Nearwell Simulation of a horizontal well in Atlanta Field in Brazil with AICV® completion using OLGA/Rocx

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Abstract
Brazil has had special attention in the world oil scenario due its crescent findings in oil reservoirs. The horizontal drilling has being applied due to its higher recovery rate. The early water and/or gas breakthrough characteristic of the horizontal well can be avoided with a new inflow control technology, the Autonomous Inflow Control Valve (AICV®). AICV® are capable of closing for unwanted fluids and keep open for oil.

In this paper, a computational study of a heavy oil reservoir is modeled using Rocx coupled with OLGA, which simulated the well. The horizontal well is simulated with both AICV® (300 days) completion and openhole with gravel pack completion (200 days).

In the AICV® completion the valves closes first according to the highest permeability zone and then following the heel-to-toe effect.

The water breakthrough is delayed with AICV® completion, extending the lifetime of the well and reducing the costs related to oil/water separation.

Keywords: increased oil recovery, AICV, heavy oil, heterogeneous reservoir.

1 Introduction

Brazil has experienced a significant number of discoveries in oil and gas reserves. The discovery of high quality oil (about 30º API) in the pre-salt layer has led to the production level of 520.000 barrels of oil per day achieved in July 2014 based on 25 installed wells (Team, 2014). Although Brazil has extensive production in electric energy from hydropower and other sources, 48.5% comes from fossil fuels and most of that comes from heavy oil reservoirs. More than 90% of Brazil's oil production is offshore and in deep waters (EIA, 2014). The offshore fields are distributed at two main depths called the Post-salt and the Pre-salt layers. The post-salt layer is located in depth up to 2000m and the pre-salt layer in depth up to 7000m. Offshore post-salt layers have heavy oil (<20º API) and pre-salt layers have oil quality higher than 30º API. Heavy oil has become an important resource with the decline in conventional oil reserves. However, the low mobility of the viscous oil makes it more difficult to be extracted. In the process of extracting oil from the reservoirs, much of the oil remains in the reservoir and the principal factor is the water and/or gas breakthrough that limits the recovery of the oil in place. To mitigate this low recovery factor, technologies such as it Inflow Control Devices and different methods for Improved Oil Recovery (IOR) and Enhanced Oil Recovery (EOR) (Carlson *et all*, 1992) have been developed.

In this work the efficiency of the AICV® was studied and simulated by using the OLGA/ Rocx software. The results were compared with the production in an openhole gravel pack completed well in Brazil. The AICV reduces the effect of early water breakthrough in heterogeneous and fractured reservoir in addition to reducing the heel-to-toe effect. The oil in the reservoir is considered as heavy oil with high viscosity. Drilling of horizontal wells has increased in the world due to the advantages regarding higher recovery factor. These types of wells are well suited for reservoirs with thin oil column due to the increased contact area between the reservoir and the well. The chosen well is located in the Santos basin, in the post-salt layer.

2 Atlanta Field

The Atlanta field is located in the Santos basin about 185 km from the coastline, as can be seen in **Figure** . The development area is 115,920 km^2 (ANP, 2009). The volume of oil in place is 1500 millions of barrels and the volume of recoverable oil is 260 millions of barrels which gives a recovery factor of only 17%. (QGEP, 2013). Santos has some oil in the post-salt layer and has the largest reservoirs in the pre-salt layer.

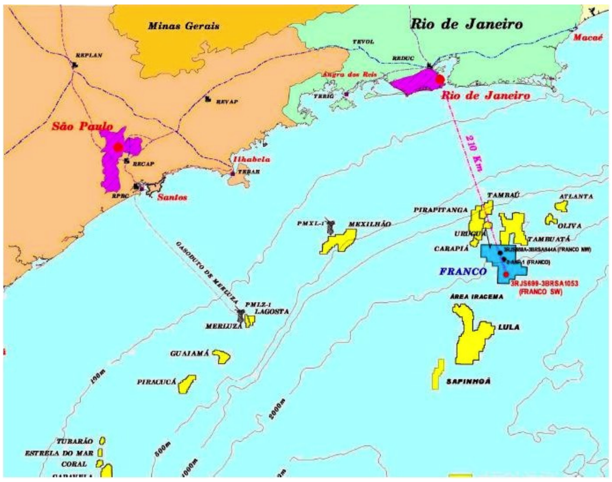

Figure 1: Localization of the Atlanta and Oliva Field. (QGEP, 2013)

The reservoir rock is Eocene turbiditic sandstone, which has a high porosity and high permeability. The sand is non-consolidated. The quality of the oil is 14° API and is considered as heavy oil. The reservoir characteristics are summarized in Table 1. The reservoir counts with an aquifer and high rock compressibility, and those characteristics will be the agents to the primary drive (Gaffney, 2014). The recovery mechanism is a combination of simple depletion (fluids expansion and porous media contraction) and water cap drive. **Table 2** shows the fluid and rock properties for the field.

Table 1: Reservoir Characteristics

Water depth	1550 m
Well depth	2316 m
Oil in place	210 millions of barrels
Recovery factor	17%
Rock compressibility	8.7E^{-4}/bar
Completion	Open-hole with Gravel packing
Start of production	2017

Table 2: Fluid and rock properties

Reservoir	Turbidity Sandstones
Porosity	36%
Thickness	115 m
Temperature	41° C
Oil Density	14° API
Viscosity	228 cP
GOR	7.5 m^3/bbl
Pressure	239 bar
Permeability	5 D

The well considered in this study is the second one drilled in the Atlanta Field as a part of the Early Production System. Figure 2 shows the porosity map and the location of the well. A fracture at position 180 m from the vertical well 3-SHEL-8 has been considered. The length of the well is 650m and it has a slight inclination of 34 m in the pressure nod. The depth is 2300m. The reservoir is considered heterogeneous.

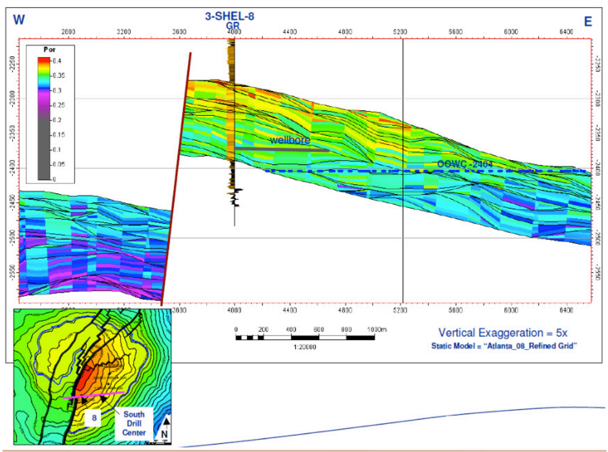

Figure 2: Porosity map and the location of the well. (QGEP, 2013)

Figure 3 shows a sketch of the well completion, which is open-hole with gravel-pack. The well includes an electrical submersible pump (ESP) to supplement low pressure and high frictional losses. The completion is consistent with sandstone rock with high porosity and high permeability and the gravel-pack prevents premature screen out and erosion.

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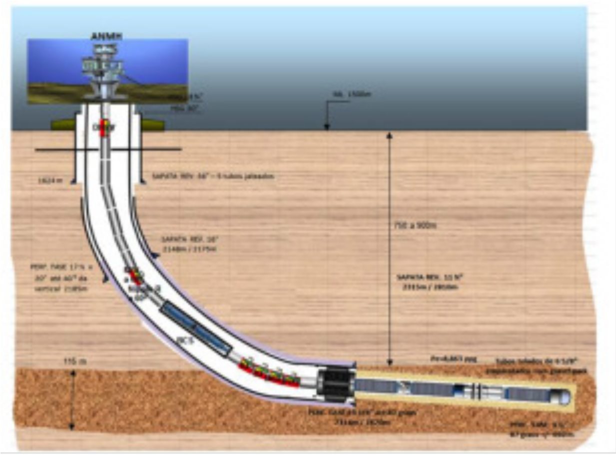

Figure 3: Sketch of the completion (QGEP, 2013)

3 Theory

3.1 Permeability

The permeability is the characteristic of the rock and indicates how easy the fluid flows between interconnected pores. The permeability is measured in Darcy (D) or milliDarcy (mD), and the higher the permeability is, the easier it is for the fluid to flow. Permeability can be expressed by Darcy's law:

$$Q = -\frac{kA}{\mu}\frac{\Delta p}{L} \quad (1)$$

where Q is the flow rate, k is permeability measured in Darcy, A is the cross sectional area, Δp is the pressure drop across the length L and μ is the viscosity.

The permeability can be further specified as effective, absolute and relative. The effective permeability is the capacity of the rock to let one fluid flow in the present of others fluids. It is dependent of the reservoir fluid saturation and the wetting characteristics of the formation (Ahmed, 2006).

The relative permeability measures how one fluid can hinder the others when two or more fluids flow at same time through a porous media. The relative permeability $k_{r,i}$ is the ratio of permeability of one phase ($k_{e,i}$) related to the absolute permeability (k). It is a dimensionless measure of the effective permeability of that phase. The equation for the relative permeability is:

$$k_{r,i} = \frac{k_{e,i}}{k} \quad (2)$$

During the production of oil, the saturation of each phase changes. Accordingly, the effective and the relative permeability also change. To be able to simulate oil production correctly, the software uses as input the accurate correlation for the relative permeability versus saturation. The relative permeability curves can be inserted manually or the known correlations can be used. Corey correlation was used in this work.

3.2 Oil viscosity

The viscosity is the measure of the fluid internal resistance to flow. It is the most important fluid property influencing on the recovery factor. The temperature of the fluid influences the viscosity and it is directly proportional with the production costs.
The heterogeneous reservoir has zones with higher permeability, resulting in higher flow in these zones – the "highways". This causes occurrence of water and/or gas conning in these zones – a fluid with lower viscosity runs faster and enter the high permeability zones, which leads to an early water and/or gas breakthrough, reducing the reservoir recovery and the well performance.

3.3 Horizontals wells

The horizontal well technology is widely used nowadays. Horizontal wells have superior production and recovery performance compared to conventional vertical wells (Porturas *et all*, 2009). Horizontal wells are commonly used to increase the production in reservoirs with thin oil column and for reservoirs with water and/or gas cap drive (Ahmed, 2006). By using horizontal wells in these cases, breakthrough of water and/or gas will be delayed due to the reduced drawdown. These types of wells improve the reservoir performance by increasing the contact area between reservoir and a long wellbore. Increased contact area results in increased production rate in reservoirs with heavy oil. Horizontal wells also open up for increased oil production in fractured reservoirs with low permeability and low porosity. The disadvantage in sandstone reservoirs is that the flow gets uneven leading to cresting/coning effects (Ferro, 2010). In carbonate reservoirs, the variations in the permeability and fractures can lead to water or gas coning. (Ferro, 2010)
One of the challenges related to long horizontal wells are the heel-to-toe effect. The heel-to-toe effect is a result of the pressure losses in the well due to friction.

During production, the drawdown (i.e. the differential pressure that drives fluids from the reservoir into the wellbore (Schlumberger, 2014)) changes differently along the well, causing uneven flow. In the toe the drawdown is low compared to the heel. Figure 4 shows the the differential pressures as a function of the distance from the heel.

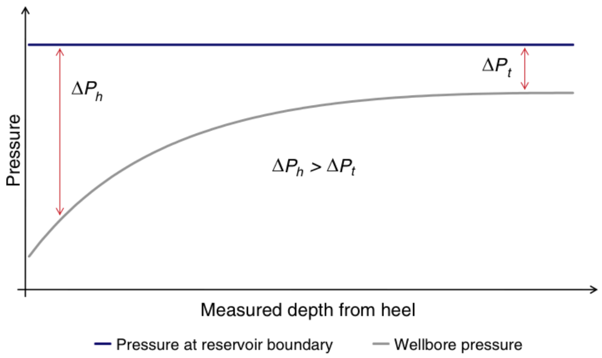

Figure 4: Heel-toe effect (Birchenco *et all*, 2009)

The higher driving force in the heel causes early water and/or gas breakthrough to the wellbore. The water or gas coning occur due to the lower viscosity and higher mobility of these phases compared to the oil. Water coning is shown in the Figure 5.

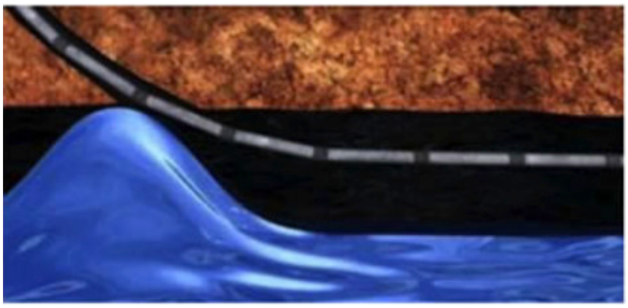

Figure 5: Water conning due to heel-to-toe effect. (AAPG, 2010)

The problems related to horizontal wells can be mitigated by varying the perforation density or by increasing the number of perforations in the toe to equalize the flow in the well extension. In addition flow restrictions as Inflow Control Devices (ICD), Inflow Control Valves (ICV), Autonomous Inflow Control Devices (AICD) and Autonomous Inflow Control Valves (AICV®) can be used. These devices works by restricting the flow according to its the position along the well. Inflow controllers can be passive or active. This work has focused on the Autonomous Inflow Control Valve, which is a suitable technology for the case of the Atlanta Field.

3.4 AICV®

Autonomous Inflow Control Valve is a technology developed for different oil qualities, from ultra light oil to extra heavy oil. The technology is the only one to the authors' knowledge that can autonomously stop the inflow of unwanted water and/or gas in a zone and reopens again when it feels oil. (Aakre *et all*, 2015). With AICV®, the flow of low viscous fluids (water and gas) to the well stops autonomously in the zones where breakthrough occurs. Meanwhile, oil keeps being produced in the other zones of the well. Wells with AICV-completion have the potential for optimum oil production and recovery. The AICV® works in a self-regulating way, without any control or surface connection. Implementation of AICV® allows for drilling of longer horizontal wells and the costs related to treatment of unwanted fluids produced together with the oil, will be significantly reduced. (Inflow Control, 2015). The valve works with a pilot flow through a laminar and a turbulent elements. The flow reacts differently in those elements, creating a pressure drop accordinly in the elements, identifying which fluid is running through the valve. Figure 6 shows picture and drawing of the AICV®.

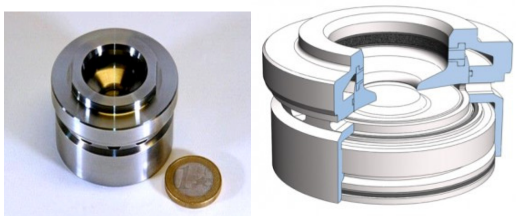

Figure 6. The AICV® (Aakre et al, 2015)

4 Simulations

Simulations with OLGA (wellbore) coupled with Rocx (reservoir) were performed to estimate the oil production using the actual completion (openhole with gravel packing) and AICV® completion. The grid chosen for the reservoir simulations is shown in Figure 7. The mesh is equally divided into grids in the x and z direction and a finer mesh towards the position of the wellbore is chosen in the y direction.

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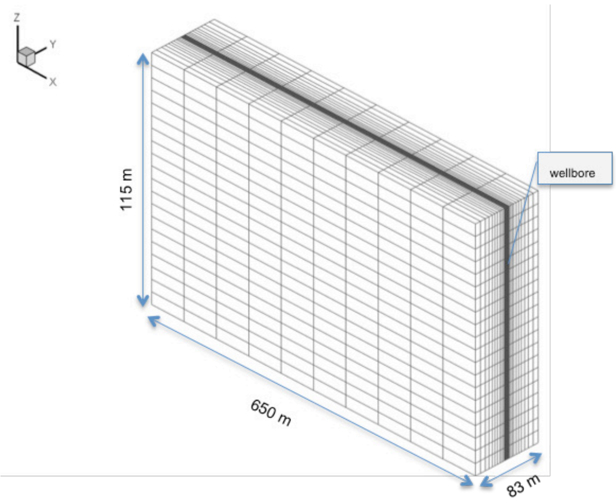

Figure 7 Reservoir section with grid and well position.

The Rocx software defines the near-well reservoir and OLGA uses the data from Rocx and simulates the flow in the wellbore. In the simulation the elements of the real completion as packers, choke devices, wellbore and inflow controllers are substituted by valves and PID controllers. The properties used in Rocx are listed in the Table .

Table 3: Reservoir and fluid properties

Properties	
Oil viscosity	228 cP
Pressure water drive	239.73 bar
Temperature	41ºC
Oil specific gravity	0.866
Porosity	38%
Permeability	5 D
Permeability in the fracture	50 D
Wellbore pressure	220 bar

4.1 OLGA settings

OLGA is applied to simulate the multiphase flow in the wellbore. The settings and the layout for OLGA were included according to the technology of the completion. In both cases the wellbore was divided in ten zones to locate the zone with highest permeability (fracture) and to facilitate the comparison between the two cases. The settings to OLGA/Rocx are given in Table 4.

Table 4: Settings in OLGA/Rocx

	Open-hole	AICV®
Extension	650 m	
Diameter	0.24 m	
Number of sections	10	20
Water cut	0.8	0.5
Drive pressure	20 bar	
Valve diameter	7 cm	2 cm

In the outlet node (pressure node) a PID controller was installed to choke the total production when the water cut exceeds 0.8. The oil flows by water drive mechanism to the well in the whole extension of the reservoir, as can be seen in Figure 8. Ten nearwell oil sources distributed uniformly along the well were defined as the input from the reservoir (defined in Rocx) to the wellbore (defined in OLGA. Figure 9 shows the layout used in OLGA.

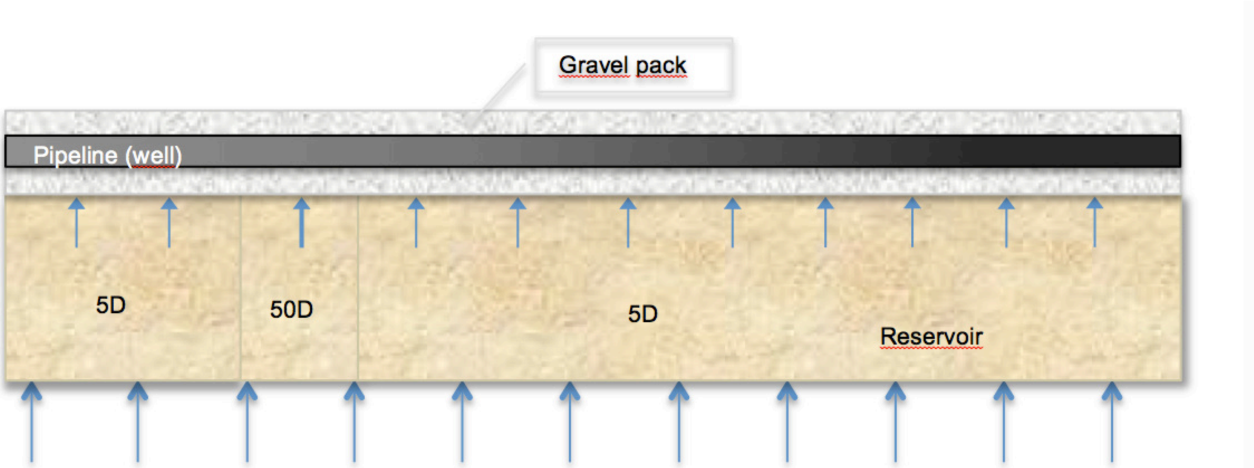

Figure 8: Section of the reservoir and the pipeline for the Openhole completion

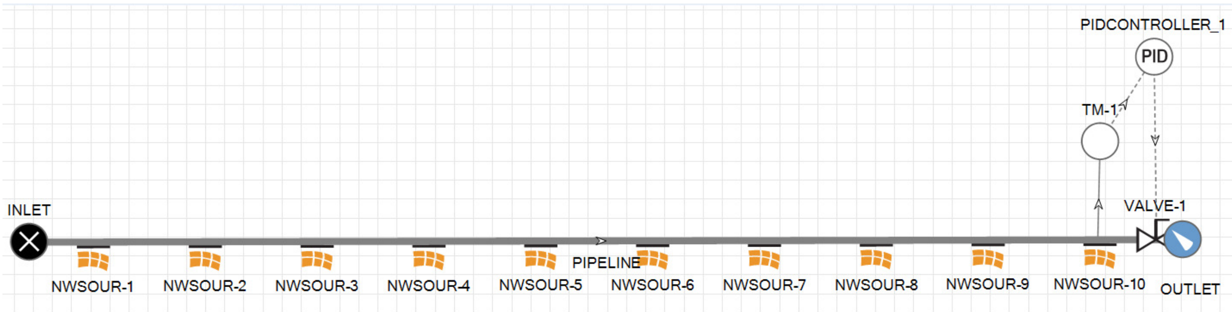

Figure 9: System layout for openhole completion.

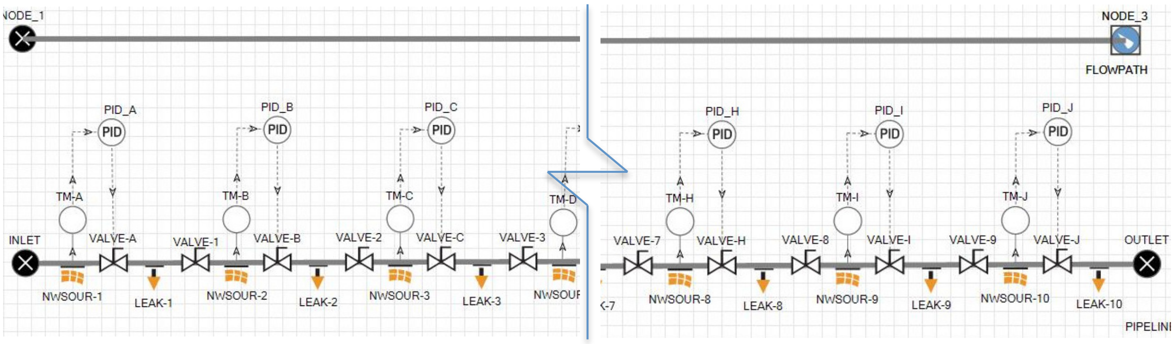

Figure 10: System Layout for AICV® completion

4.2 AICV® completion

In order to simulate a more complex system, OLGA needs a pipeline to simulate the annulus and a flowpath to simulate the well. This configuration is presented in Figure 10. The case with AICV® completion was made by dividing the well into twenty sections to locate the elements. Valves 1, 2, 3, 4, 5, 6, 7, 8, and 9 are closed and located in the odd sections. These valves act like packers which isolate the different zones from each other. The valves A, B, C, D, E, F, G, H, I and J are the AICV®'s and are located in the even sections. The mechanism of the AICV® is here presented by a transmitter with water cut as variable and a PID controller to activate the valve to close when the set point for the water cut is reached. The nearwell source illustrates the flow from the reservoir into the annulus and the leak illustrates the flow of the fluids from the

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annulus into the well. Figure 10 shows the location of the elements. The distance between the AICV®'s is 65m. Figure 11 shows the division of the annulus (pipeline) and reservoir into ten zones where the fracture (50D) is located in the third zone.

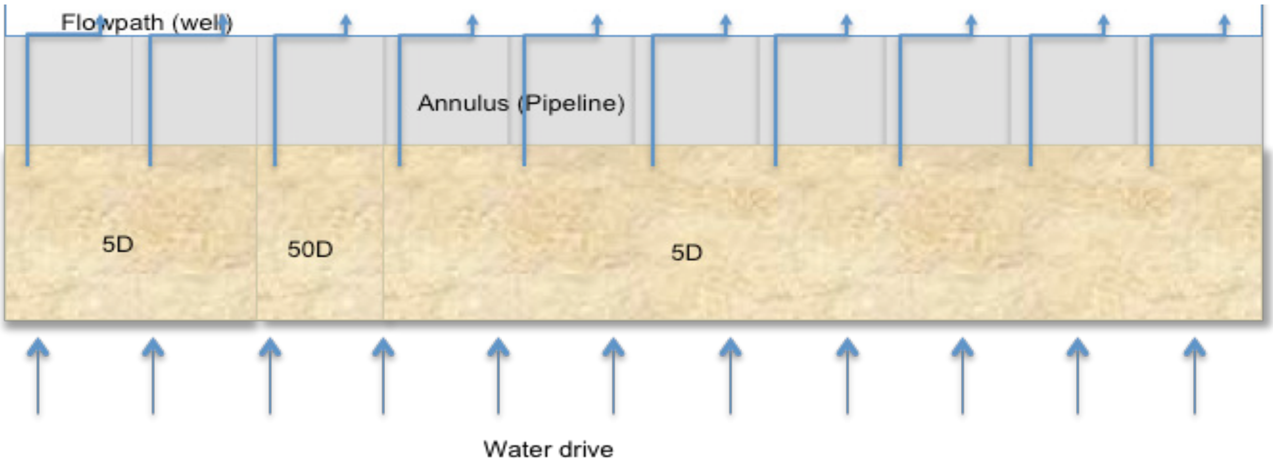

Figure 11: Section of the reservoir and the pipeline for the AICV completion

The set point for water cut was set to 50% for each of the zones. When the water cut set point is reached in a certain zone, the corresponding valve closes to 0.8% and the others remain open, producing oil until the set point value is reached. The opening of 0.8% corresponds to a minor flow which will flow through a closed AICV®. This minor flow is necessary to make it possible to identify which fluid is surrounding the valve, and thereby make the valve capable of opening again when it feels oil.

5 Results and discussion

The results of the computational study made to compare the performance of open-hole with gravel pack and AICV®-completion are presented. The goal of this study is to compare performance curves for the two cases and to show the potential improvement in oil recovery when AICV® completion is used. The simulations were performed for the period of 300 days for the AICV® well and 200 days for the open-hole well. Different time periods were used because those periods were illustrative for what happened in the two cases.

PID controllers were used together with valves to simulate the functionality of the AICV®s. For the open-hole completion a PID controller was used in the outlet of the flowpath to ensure choking at high flow rates of water. Figure 12 shows a summary of the results with open-hole and AICV® completion. For the open-hole well the accumulated production of water is higher than the oil production after 128 days. After that the production is choked, and at day 170, the accumulated oil production increases insignificantly whereas the accumulated water production is increasing with a significantly higher rate..

5.1 AICV®

The heel-to-toe effect was not the reason for the early water breakthrough in this case. The main contributor to the water coning was the "highway" from the fracture located in zone 3 in the reservoir. Figure 13 shows the closing time for the AICV® in the different positions. As can be seen, the AICV® in the high permeable zone (zone 3) closes after 40-50 days. Zone 2 and 4 (as presented in Figure 11) are influenced by the fracture in the neighboring zone (zone 3) and therefore the breakthrough occurs earlier at these locations than in the other zones with the same permeability. The AICV®s in the remaining zones are closing following the heel-to-toe effect. Figure 13 also shows the volumetric flow rate of oil as a function of time. Initially the production rate is about 220 m^3/day, and decreases to 60 m^3/day as the valves are closing. It can be noticed that after 280 days all the valves are closed. If the simulation was performed for a longer period it is expected that the valves would open after encountering oil again.

5.2 Comparison of AICV® and Open-hole completion

Figure 12 shows oil and water production for a well with AICV completion compared to and openhole well. The dashed lines represent the openhole case and the continuous lines represent the AICV® completion case. The blue and the green lines show the water and oil production respectively. After 170 days of production in the openhole completion case, the water cut

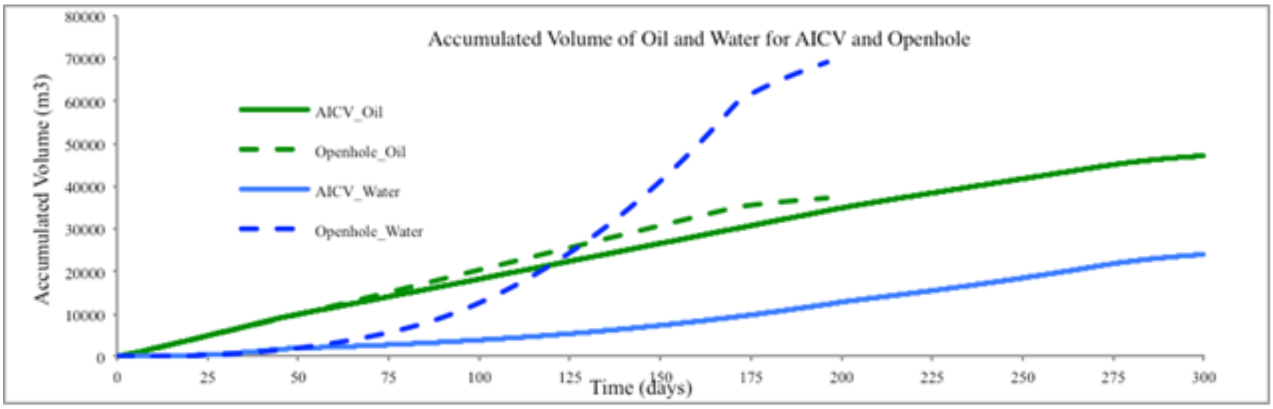

Figure 12: AICV® and Openhole**:** Accumulated oil and water

exceeds 70% and the valve starts to choke. The AICV® -completed well is still producing oil through 3 valves after 200 days. The result indicates that the lifetime of a well can be significantly extended when using AICV-completion. The accumulated oil is higher for the open-hole well until the production rate is choked down. After that, the well is mainly producing water. The amount of water produced in AICV®-completed well is much lower, which will have a positive effect on the costs for separation in surface installation.

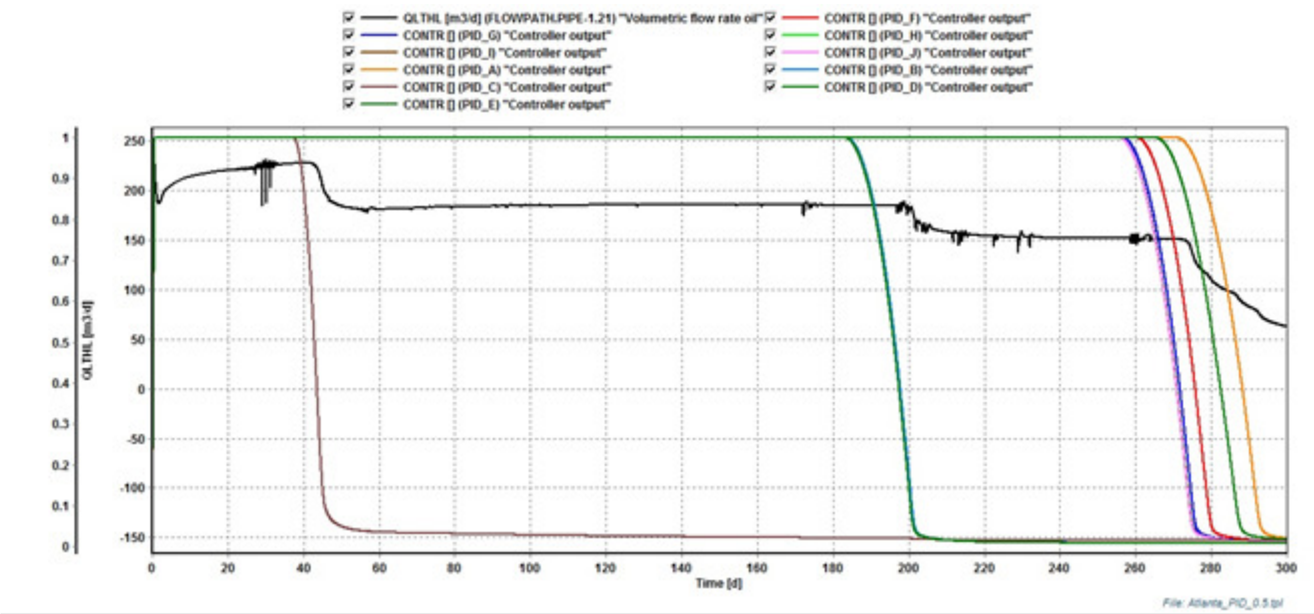

Figure 13: Volumetric oil rate and AICV® Closing sequence

6 Conclusion

The following concluding remarks are listed below.

- Brazil has a wide field to implement new technologies as AICV® especially in the pre-salt layer with thin oil column.
- Open-hole completion is well suited to sandstone, but suffer with early water and/or gas breakthrough due to fractures in the reservoir and/or uneven drawdown pressure along the reservoir characteristic for horizontal wells.
- The open-hole completion requires higher separation of the water from the oil on the surface

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facilities. This result in requirement of larger separation installations and higher costs.

- The well with AICV® completion produces 45000m^3 oil compared to 35000 m^3 with open-hole until the valves close.
- The production of water is much higher for openhole: 70000 m^3 against 20000 m^3 for AICV®, a reduction of 71%.
- Increase of 28.5% in total oil production with the AICV® technology.
- The dependency of viscosity on relative permeability for heavy oil must be further studied.

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