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Smart Well With Autonomous Inflow Control Valve Technology

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Abstract

A smart well concept with autonomous inflow control valve (AICV) is presented. AICV utilized the best from smart wells (ICV) and inflow control devices (ICD). The technology is presented, discussed and compared against other conventional inflow control technologies, id est (i.e.) passive ICD. The flow characteristics are presented and implemented in reservoir model simulations. Significant increased production and recovery are shown for the application in a thin oil rim with gas cap and heterogeneous reservoir. The AICVs are autonomous, i.e. self-regulating and do not required any external control or force. This makes them simple and robust, and a large number of control valves can be mounted in the well, i.e. one in each screen. When water and/or gas breakthrough occur the valves in the breakthrough zone will autonomously shut-off. This provides the operator with a significantly more efficient production and increased recovery. The AICV technology also enables opportunities to drill longer wells and achieve maximum reservoir contact of each well. In addition, the AICV removes the risk, cost and requirement for separation, transportation and handling of unwanted fluid.

Introduction

Traditionally, oil reservoirs were accessed by drilling vertical wells. This is simple and straight-forward technique, but with limited reservoir contact per well. Therefore, in order to access more reservoir contact, techniques and devices have been developed to drill horizontal wells, i.e. turning the well from vertical to horizontal oriented [1]. Multi-lateral wells have been installed by several oil companies to maximize the reservoir contact.

A major challenge in oil production is to maximize the oil recovery of the reservoir. Today, only a limited part of the oil in a given reservoir is actually recovered and produced before the field is shut down. There are strong incentives for developing new technology in order to increase oil production and recovery. Two factors are of particular importance in order to increase production and recovery from a reservoir:

- Obtaining maximum reservoir contact
- Preventing negative effects of gas and/or water breakthrough

Good reservoir contact may be achieved by drilling long horizontal and/or multi-lateral wells. The pressure drop inside the well is caused by the fluid friction within the pipe, and is proportional to flow rate, fluid density, diameter and length of the well. Hence, longer wells give increased pressure drop, and increased pressure difference between the toe and heel section of the well. This creates non-uniform oil production along the well and results in an early breakthrough in the heel section, as indicated in Figure 1. Permeability differences or heterogeneities along the well may also result in early breakthrough [2] in some parts of the well.

The negative effects of breakthrough may be delayed by ICD, [3]. Well completion with ICDs consists of a large number of ICDs disposed at regular intervals along its entire length. The ICDs causes a flow restriction of the fluid flowing from the reservoir and into the well, and will make the inflow profile more uniform. The ICDs are ports having a fixed flow area. The result is a significant increase in the recovery compared with wells without ICDs [3].

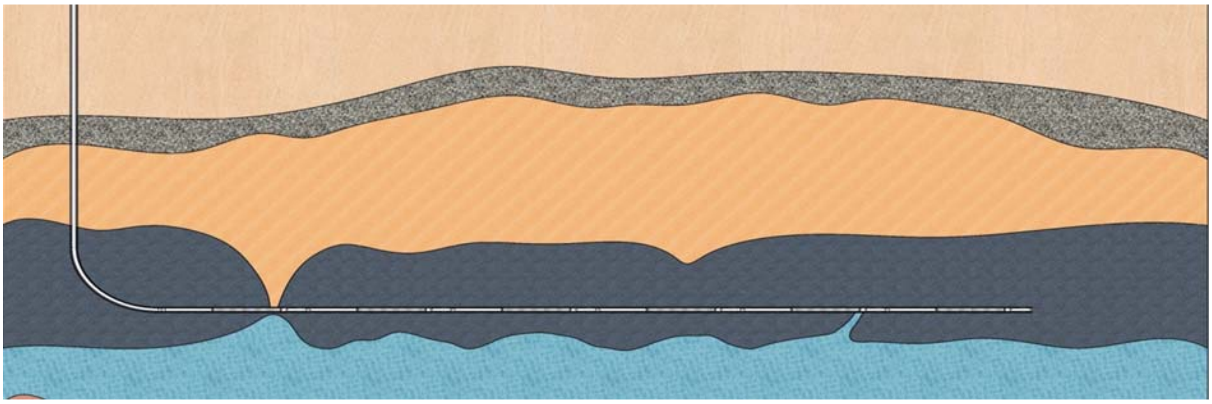

Figure 1: Sketch of breakthrough of water and gas in a horizontal oil well

Autonomous Inflow Control Devices (AICD) is devices that can adjust the choking of the fluids depending on which phase being produced. They are placed along the well in the same way as the ICDs. Statoil has shown that wells completed with AICDs increase the oil production and recovery compared to wells completed with passive ICDs [4]. TheAICD restricts the gas compared to the oil production, and these wells have a significantly lower gas/oil ratio (GOR) development than wells completed with conventional ICDs.

An alternative solution is Inflow Control Valves (ICVs) or ‘smart wells’. These do not choke initial oil production significantly, and can stop gas and water completely at a breakthrough point, but are controlled from the surface and can only be operated over a limited number of zones (e.g. 5 per well). However, ICVs are relatively expensive, have additional components such as flow meters and pressure / temperature sensors, are complex installations requiring power and data cabling fitted within the pipe well, can be operational unstable and required remote monitoring and control from the surface.

AICV combines the best from AICD and ICV. They are placed along the well in the same way as the ICDs. The new AICV closes autonomously and almost completely shut off the unwanted fluid production at breakthroughs. At the same time oil production will continue from the other inflow zones along the well, ensuring optimum oil production and recovery. The AICV is completely self-regulating, and does not require any form of control, electronics or connection to the surface. This provides the operator with a significantly more efficient production and increased recovery. The AICV technology also enables opportunities to drill longer wells and achieve maximum reservoir contact of each well. In addition, the AICV removes the risk, cost and requirement for separation, transportation and handling of unwanted fluid. The technology makes it possible to maximize the well production, and far more efficiently than ever before. The AICV eliminate the gas and water breakthrough problems.

Technology

The AICV technology utilize that laminar and turbulent flow restrictors have different flow behavior. The 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.

The laminar flow restrictor can be a pipe element, and the pressure drop may be expressed as:

$$\Delta p = \frac{32 \cdot \mu \cdot v \cdot L}{D^2} \tag{1}$$

Where, μ is the fluid viscosity v is the fluid velocity, L and D is the length and diameter of the pipe respectively.

The turbulent flow restrictor can be a thin plate orifice, and the pressure drop can be expressed as:

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

where k is a geometrical constant and ρ is the fluid density. Figure 2 shows the pressure drop versus the velocity in the laminar flow restrictor for heavy oil, water and gas respectively. Figure 3 shows the pressure drop versus the velocity in the turbulent flow restrictor for heavy oil, water and gas. The figures illustrate that the different flow restrictors have different behavior for the three different fluids.

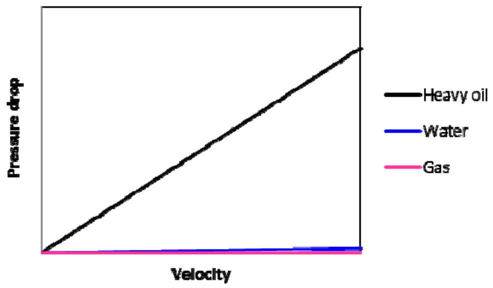

Figure 2: Pressure drop in laminar flow restrictor.

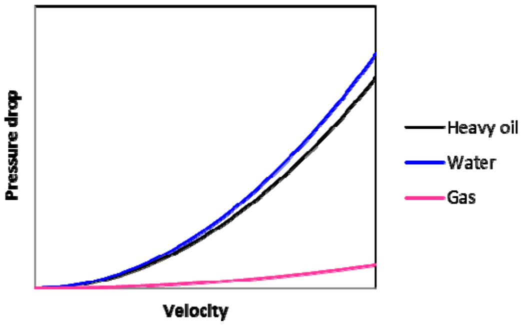

Figure 3: Pressure drop in turbulent flow restrictor.

Figure 4 illustrates how a fluid F flows into a conduit 3a at a first pressure p_1, through a laminar flow restrictor 1 and into a chamber B where it attains a second pressure p_2, and then flows through a second turbulent fluid flow restrictor 2 before it exits the conduit at a third pressure p_3. When the fluid flow rate and fluid properties (e.g. viscosity, density) are constant, the pressures (p_1, p_2, p_3) are constant, and $p_1 > p_2 > p_3$.

In the laminar flow restrictor, the fluid will undergo a pressure drop according to Equation 1, from which it may be derived that the change in pressure across the restrictor is proportional to the fluid viscosity and the fluid velocity. In the turbulent restrictor, the pressure drop is described by Equation 2. The change in fluid pressure across the restrictor is almost independent of viscosity, but proportional to the density and to the fluid velocity squared.

Therefore the pressure p_2 in the chamber B, between the laminar and the turbulent restrictor, will change if the properties (viscosity or density) of the fluid changes. This is illustrated graphically in Figure 4 in the pressure plot for heavy oil, water and gas respectively. The plot shows low pressure at p_2 for heavy oil, due to the high viscosity of the oil. The pressure at p_2 is higher for water and gas due to the relative lower viscosity. This difference between the pressures occurring in chamber B when the viscosity changes is used to perform work, for example actuate an actuator [5], which in turn move a piston/body and/or a valve (not shown in Figure 4).

The AICV uses a minor pilot flow to flow through the laminar and turbulent flow restrictors. The pressure between these two elements is used to actuate a valve that is parallel to the pilot flow. The main flow is flowing through this valve. The AICV can be designed to let approximately 99% of the total flow go through the valve [5]. In open position the valves can be designed to have no significant pressure drop, such that the initial production can be maximized.

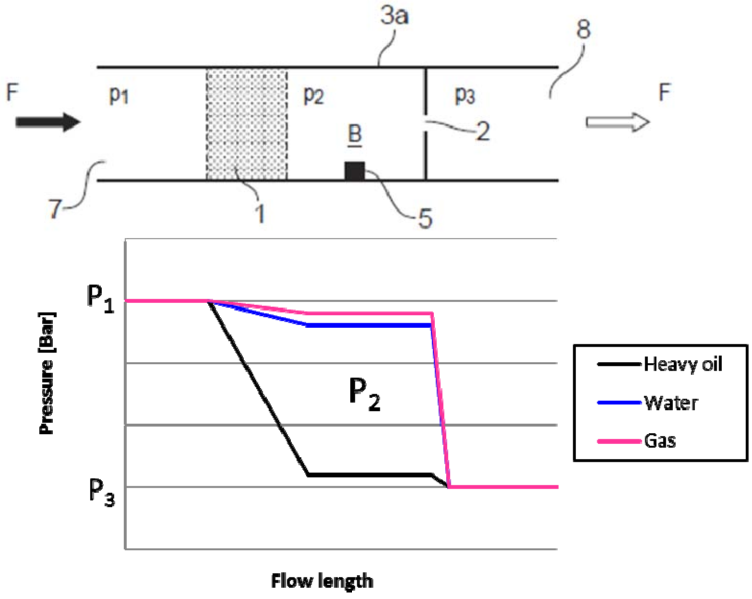

Figure 4: Combination of laminar and turbulent flow restrictors in series, [5].

Figure 5 show AICV together with 1 Euro coin. The dimension of the AICV shown in Figure 5 has a diameter of 4 cm and a height of 2.5 cm. The AICV can be designed with other dimensions and configurations. Figure 6 show a drawing of how the AICV is mounted in the screen assembly.

Figure 5: Photo of AICV together with 1 euro coin.

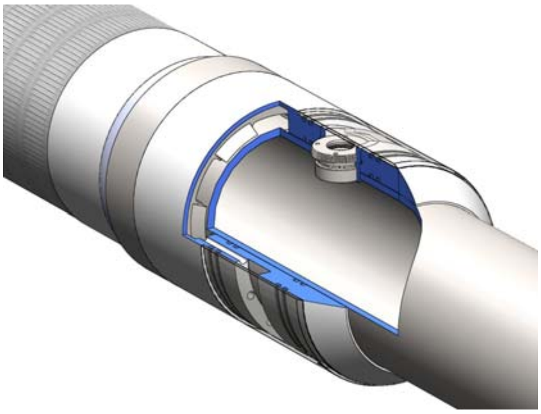

Figure 6: Drawing of AICV mounted in the screen

Simulation

Long horizontal wells are beneficial in rim oil reservoir with gas cap, [1]. Long wells and thus large reservoir contact, increase the recovery and production rate [2]. In these long wells gas breakthrough will occur some were in the well, typically in the heel of the well [6]. Nevertheless breakthrough can occur elsewhere in the well due to permeability differences or heterogeneities along the well [2]. Breakthrough limits the oil production and the recovery [3].

Two cases for a thin oil rim with gas cap are simulated. Case 1 is with conventional passive inflow control device and Case 2 is with the AICV. The simulation is performed with OLGA and ROCX. The simulation is dynamic, which means that the choking is regulated with respect to the GOR in the well. This is also typical in the real case. Due to gas handling capacity it is inevitable that the well have to be choked back when the gas rate reach a certain level. In this simulation the choke is regulated with a proportional controller with the set point of 200 for the GOR in both cases. The minimum possible opening of the choke is set to 10% opening for both cases.

The horizontal well in the simulation model is 3000 meter long with 30 evenly spaced zonal isolations. Thus each zone is 100 meter long, and annulus flow inside each zone is allowed. The pressure drop in the well due to friction is calculated by OLGA, and the pressure profile along the well is input to the reservoir simulation in ROCX. The ICD and AICV have the same strength regarding oil performance. The simulation for the AICV is done with a 95% choking of gas. I.e. 95 % of the gas is shut-off at gas breakthrough. Figure 7 shows the oil flow and gas flow through the ICD and AICV for each 100 meter long inflow zone versus the differential pressure.

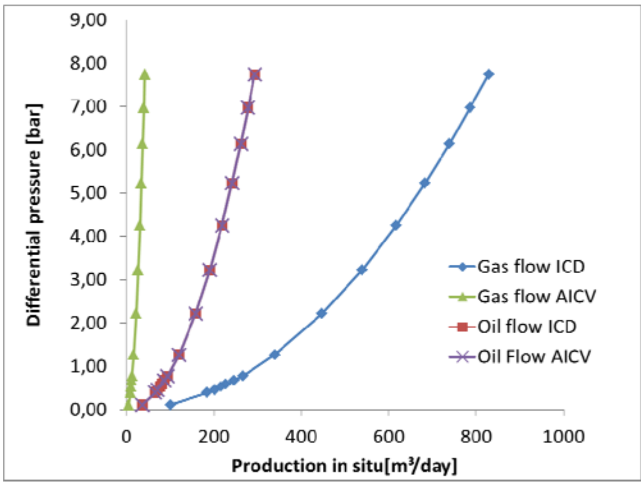

Figure 7: Oil and gas flow through the ICD and AICV versus differential pressure.

The properties of the cases are summarized in table 1.

Table 1: Properties

Well length [m]	3000
Open hole diameter [cm]	20
Screen OD [cm]	15.24
Oil column height [m]	20
Reservoir porosity [%]	30
Permeability range [mD]	100-1000
K_v/K_h [-]	0.5
Gas cap pressure [bar]	130
Temperature [°C]	100
Oil viscosity [cP]	0.9
PID controller type	P
Set point GOR	200
Minimum opening of choke during simulation [%]	10

The production starts with a low gas oil ratio (GOR), i.e. the solution GOR for both ICD and AICV case.
Figure 8 shows how an ICD completed well is choked related to the GOR development. It can be seen that at the initial production the choke position is fully open, i.e. the coke position is 1. After a while the gas enters the well and the GOR increases. When the GOR passes 200 the simulation controller start to reduce the choke opening and chokes the well. The controller continuous to choke until the choke position has reaches its minimum. After this the valve position is constant at its minimum opening and the GOR gradually increases.

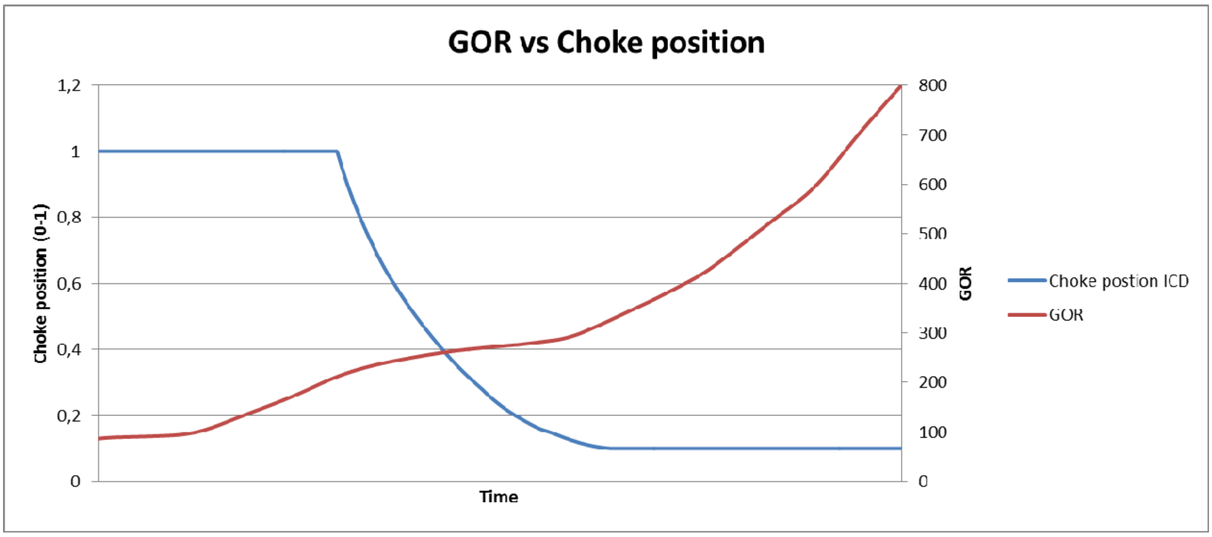

Figure 8: Gas oil ratio development related to choke position

The choking influences the pressure in all the producing zones of the well. In Figure 9 the pressure profiles in the well at two different choke positions (i.e. at two different production time) are presented. For both cases the pressure in the toe (at 0 meters) is higher than in the heel. This is due to friction loss along the well. Fluid is entering the well from the reservoir in the whole interval from 0 m to 3000 m. Thus at the toe, the pressure difference from the well to the reservoir (draw down) is lower than the pressure difference at the heel. At 50% choking, the pressure is higher in the whole well, compared to the case with fully open choke. This shows that when choking the well the draw down along the entire well will be reduced.

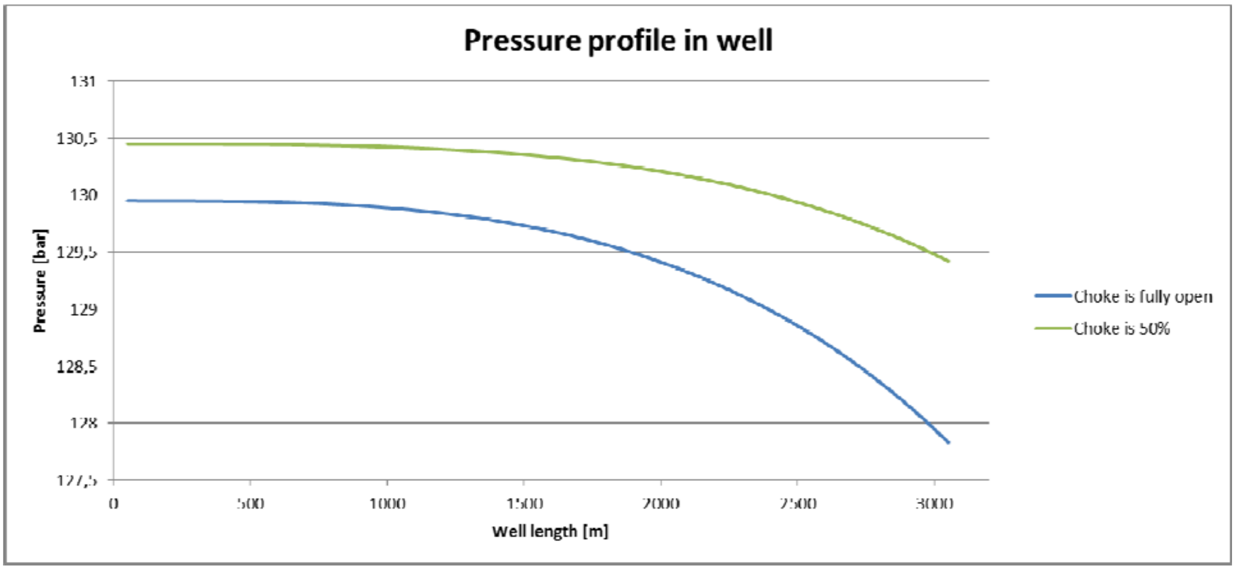

Figure 9 Pressure profile in the well for two different choke openings

Figure 10 shows the choke position versus time for the two cases, with ICD and AICV respectively. This shows that the two cases have the same initial production. Both cases have fully open choke at the start of the production. After a while the gas breakthrough occurs and the GOR increases. The gas breakthrough starts in one zone in the heel of the well. The AICV chokes the gas production from that zone locally. Hence, the GOR will remain low and the choke position is fully open. In the case with the ICD the local devices in this zone have no gas production restriction. Thus the GOR increases and the choke starts the choking. As can be seen in Figure 10, the ICD case begins the choking earlier than the AICV case. This choking leads to reduction of the draw down in the gas producing zone, and reduction of the oil production. The choking will reduce the gas production from the other zones as well.

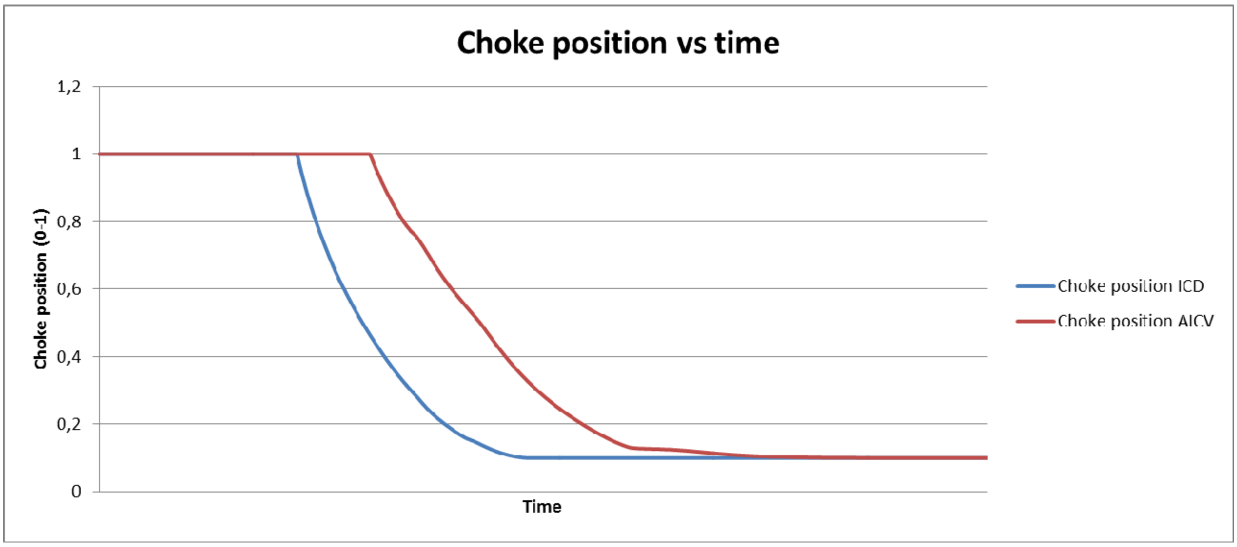

Figure 10: Choke position versus time

Figure 11 shows the cumulative oil production versus GOR. Both cases have the same profile in the start of the production. Initially, the GOR is the solution GOR. In the ICD case the GOR development increases more rapidly than the AICV case. Figure 12 shows the cumulative oil production versus time. It can be seen that both cases have the same development in the startup. Due to the gas breakthrough the cumulative oil production in the ICD case decreases earlier than in the AICV case. The simulations show that the recovery with AICV is increased with approximately 30% ore compared to passive ICD.

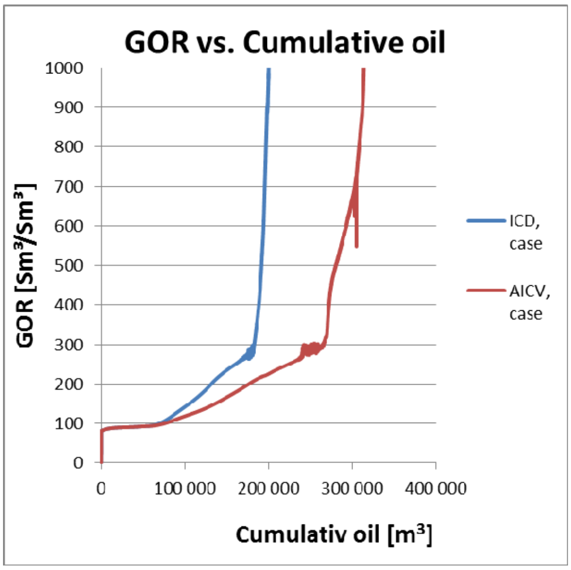

Figure 11: Cumulative oil production versus gas oil ratio

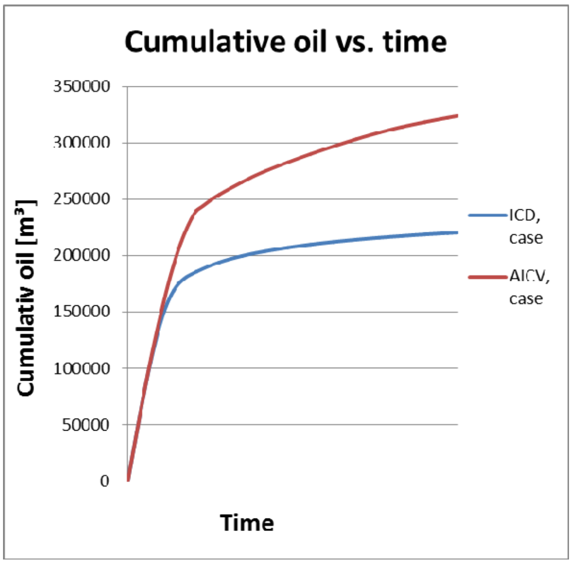

Figure 12: Cumulative oil production with time

Conclusions

The AICVs are autonomous, i.e. self-regulating, and do not require any external control or force. This makes the AICVs simple and robust and a large number of control valves, typically one in each screen, can be mounted. In open position the valves has no significant pressure drop which reduces the initial production. When the water and/or gas breakthrough occur the valves in the breakthrough zone will autonomously close. This provides the operator with a significantly more efficient production and increased recovery. The AICV technology also enables opportunities to drill longer wells and achieve maximum reservoir contact of each well. In addition, the AICV removes the risk, cost and requirement for separation, transportation and handling of unwanted fluid.

Two cases for a thin oil rim with gas cap are simulated. Case 1 is with passive inflow control device and the Case 2 is with the new AICV. The simulation is done with OLGA and ROCX. The simulation is regulated with respect to the GOR in the well, as in the real production cases.

In the ICD case the GOR development increases more rapidly than the AICV case. The ICD case begins the choking earlier than the AICV case. This choking leads to reduction of the draw down in the gas producing zone, and reduction of the oil production.

The simulations show that the oil recovery with AICV is increased with approximately 30% compared to passive ICD.

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