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The Next Generation Inflow Control, the Next Step to Increase Oil Recovery on the Norwegian Continental Shelf

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Abstract

One of the challenges on the Norwegian shelf is declining oil production and relatively low recovery rate. At current estimate, less than half of the oil will be remaining in the reservoir after shut down. A major challenge is to improve recovery from existing fields by developing and implementing new technologies that make mature and marginal fields more profitable. It's vital to develop technologies that can increase recovery before fields shut down. In most fields on the Norwegian continental shelf is the draining mechanism of pressure support from gas and / or water. This means that after a period of production, all wells will have gas and/or water breakthrough. As the breakthrough expands the production have to be limited due to excessive gas and/or water production. This means that production from the well have to be choked or stopped, even there is oil left along the wellbore. Inflow Control Device (ICD) and Autonomous Inflow Control Device (AICD) developed and installed by Hydro and Statoil have shown that the oil production and recovery can be increased significantly with better inflow control along the well. However, neither ICD nor AICD is able to shut off the unwanted gas and water production completely. The newly developed and patented Autonomous Inflow Control Valve (AICV) can shut off the unwanted fluid completely. This technology will probably be the next major step for increased oil recovery on the Norwegian Continental Shelf, in new and old wells. The new completion technology is presented and experimental test results with gas, oil and water are presented together with reservoir simulations that confirm that the AICV will give significantly increased recovery in field suffering from gas or water breakthrough.

Introduction

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 and 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 in some parts of the well, Al-Khelaiwi et al. (2005). The negative effects of breakthrough may be delayed by ICD, Krinis et al. (2007). 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 Krinis et al. (2007).

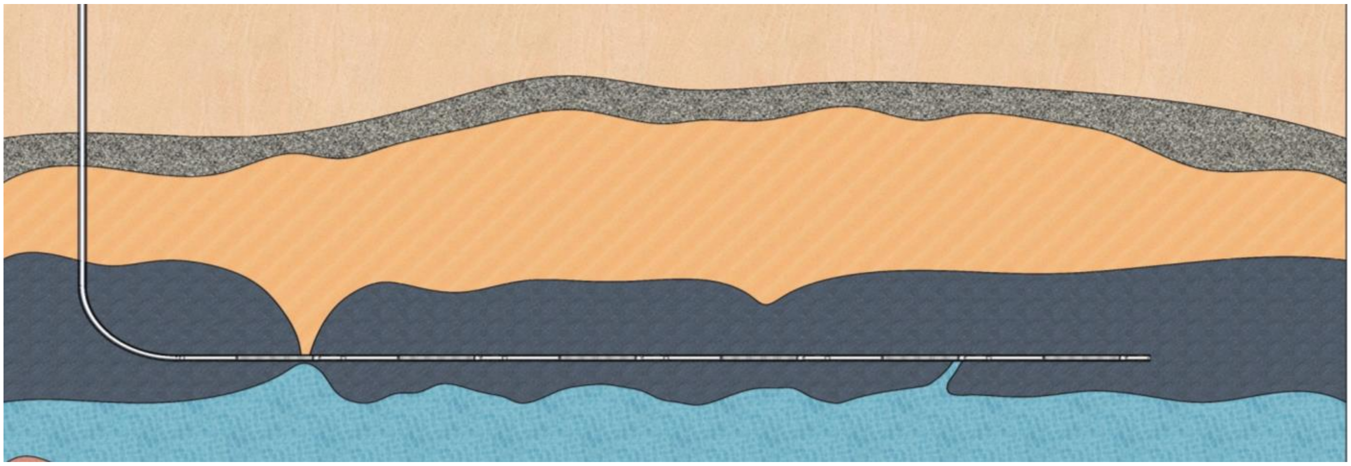

Figure 1: Sketch of typical gas and water breakthrough in a horizontal well.

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 developed the autonomous RCP, Mathiesen et al. (2011). Halvorsen et al. (2012) has shown that wells completed with AICDs increase the oil production and recovery compared to wells completed with passive ICDs with more than 20%. The AICD 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.

The Autonomous Inflow Control Valve (AICV) combines the best from ICD, AICD and ICV. The technology is patent pending, Mathiesen et al. (2013).The valves are placed along the well in the same way as the ICDs. The new AICV closes autonomously and completely shut-off the unwanted fluid production at breakthroughs locally in the well. 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 eliminates the gas and water breakthrough problems.

The AICV Technology

The AICV technology utilize that laminar and turbulent flow elements have different flow behavior. The technology consists of two different flow elements placed in series. The first one is a laminar flow element and the second is a turbulent flow element. The fundamental principle is presented below.

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

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

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 element can be a thin plate orifice, and the pressure drop may be expressed as:

$$\Delta p = k \cdot \frac{1}{2}\rho v^2 \qquad [2]$$

where k is a geometrical constant and ρ is the fluid density.

Figure 2 shows example of pressure drop versus the velocity in a laminar flow element for heavy oil, water and gas, respectively. Figure 3 shows the pressure drop versus the velocity in the turbulent flow element for heavy oil, water and gas. The figures illustrate that the different flow restrictors have different behavior for the three different fluids.

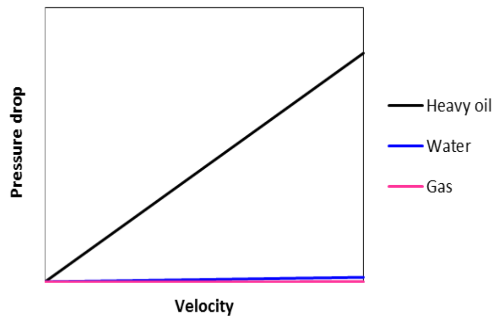

Figure 2: Pressure drop in laminar flow element.

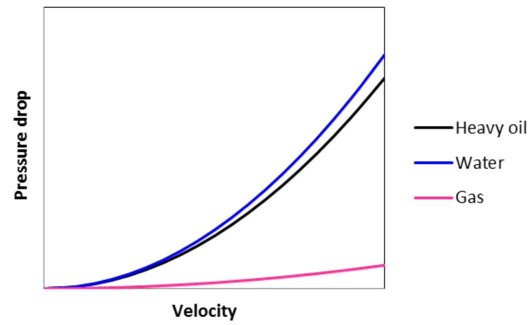

Figure 3: Pressure drop in turbulent flow element.

Figure 4 illustrates how a fluid F flows into a flow conduit 3a at a first pressure p1, through a laminar flow element 1 and into a chamber B where it attains a second pressure p2, and then flows through a second turbulent fluid flow element 2 before it exits the flow conduit at a third pressure p3. When the fluid flow rate and fluid properties (e.g. viscosity, density) are constant, the pressures (p1, p2, p3) are constant, and p1 > p2 > p3, Mathiesen et al. (2013).

In the laminar flow element, 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 element is almost independent of viscosity, but proportional to the density and to the fluid velocity squared. Therefore the pressure p2 in the chamber B, between the laminar and the turbulent flow elements, 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 p2 for heavy oil, due to the high viscosity of the oil. The pressure at p2 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, which in turn move a piston and/or a valve (not shown in Figure 4).

The AICV uses a minor pilot flow to flow through the laminar and turbulent flow elements. 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.

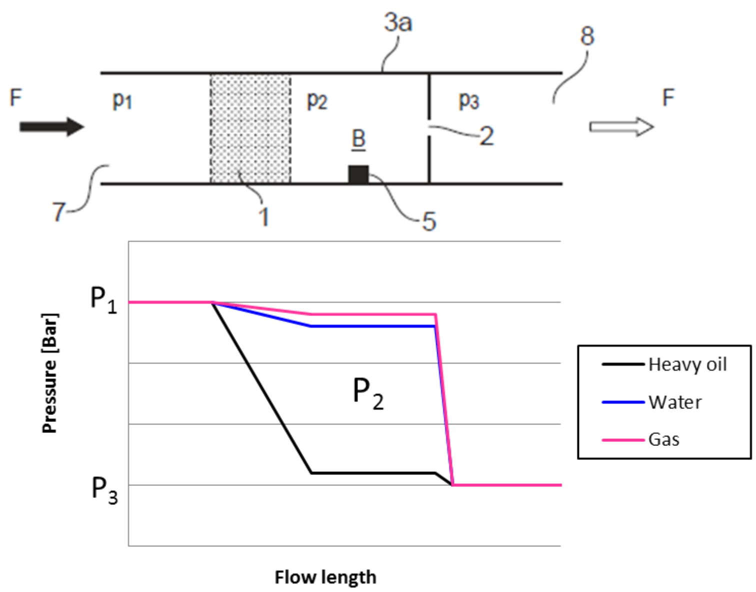

Figure 4: Combination of laminar and turbulent flow restrictors in series, Mathiesen et al. (2013).

Figures 4a and b show drawings of the AICV in open and closed position respectively. The thin blue lines show the pilot flow path, the thickest blue arrow presents the inlet of the main flow to the valve, and the two horizontal arrows show the outlet of the main flow to the base pipe. The thin blue vertical arrow presents the outlet of the pilot flow. The force F1 on the upper part of the piston (p1·A1) is acting downwards and the force F2 below the piston (p2·A2) is acting upwards. When the net force (F1-F2) is positive, the valve is in open position and if the net force is negative, the valve closes. The inlet pressure, p1, is always higher than p2, and A2 has to be larger than A1. The ratio between A1 and A2 is a design parameter and the optimum ratio is dependent on the properties of the oil and the water.

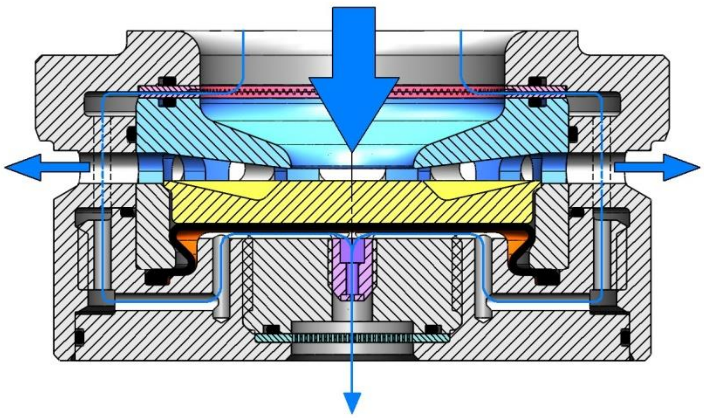

Figure 4a: A drawing of the AICV in open position.

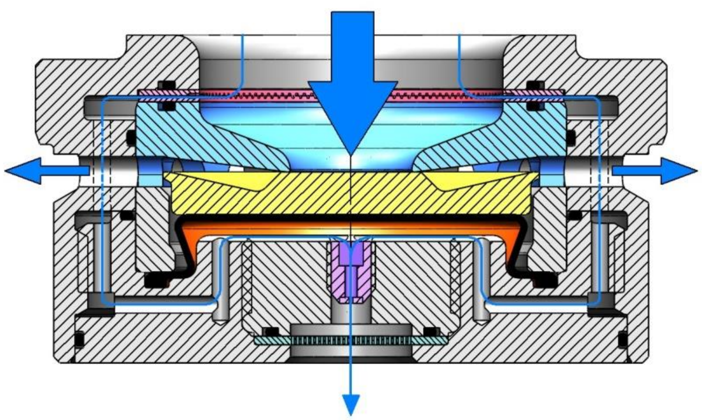

Figure 4b: A drawing of the AICV in closed position.

Experimental Flow Performance Curves

In horizontal wells uneven drainage profile along the well occur due to hetrogenites in the reservoir and frictional pressure drop due to the flow inside the base pipe. ICDs balance the flow by creating an additional pressure drop betwwen the reservoir and into the base pipe. The ICD strength can be varied. The ICD strength can be shown with flow performance curves where the flow rates is plottes versus pressure drop, e.g. Lee et al. (2013).

The AICV can be applied for different applications, the most obvious applications are:

1. Stop water and/or gas in heavy oil reservoirs
2. Stop gas in light oil reservoirs with gas cap/drive

The AICV can be easily design for each application, i.e. the laminar and turbulent flow element are modified for different application. The combination of the flow elements will give the flow rate of the closed AICV. The flow rat of the unwanted (gas/water) fluid will be typical 1 % of the oil flow rate. Depending on the reservoir and reservoir strategy the ICD strength can be adjusted.

Water/Gas Shut-Off in Heavy Oil Reservoirs

Figure 5 shows the flow performance curve for gas, water and heavy oil (50 cP). All meassurements is performed at single phase conditions with various differential pressures at typical reservoir pressure, i.e 100 bar.

The oil curve show that the ICD strength is low for oil, at 1 m^3/h the pressure drop is 1.5 bar. At the same pressure drop the water rate is less than 20 l/h. The gas rate is somewhat higher, due to the lower density, approximately 75 l/h. All water and gas is flowing trhough the minor pilot flow, since the valve will be in closed position with these fluids. These phase filter effect will eliminate the gas and water breakthrough problems. The valve is also reversible. This means that if the has closed for water/gas, and the AICV sees oil again, the valve will autonomously open and oil production continues in order to maximize recovery.

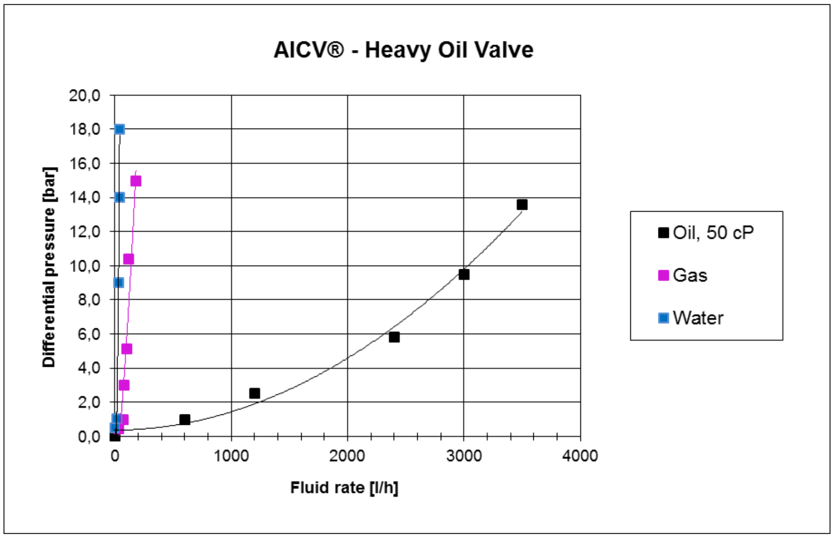

Figure 5: Flow performance curve for AICV, heavy oil valve.

Gas Shut-Off in Oil Reservoirs with gas cap/injection

Figure 6 shows the flow performance curve for gas and typical light oil (1 cP). All meassurements is performed at single phase conditions with various differential pressures at typical reservoir pressure, i.e 100 bar.

The oil curve show that the ICD strength is low for oil, at 1 m^3/h the pressure drop is 1 bar. At the same pressure drop the gas rate is approximately 40 l/h. All gas is flowing trhough the minor pilot flow, since the valve will be in closed position with gas flowing. These phase filter effect will eliminate the gas breakthrough problems in fields with gas as gas cap or injection. The valve is also reversible. This means that if the has closed for gas, and the AICV sees oil again, the valve will autonomously open and oil production continues in order to maximize recovery. This is particularly important in field with gas cap where the oil drainage will form a gas cone.

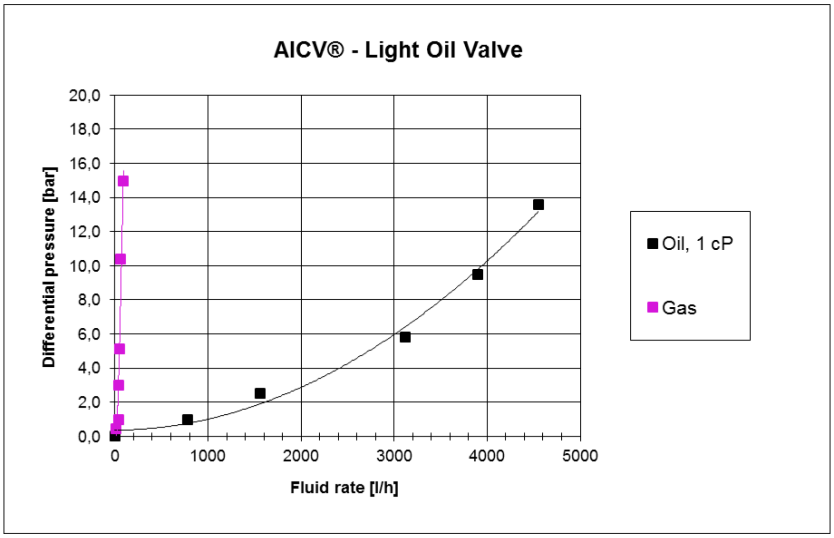

Figure 6: Flow performance curve for AICV, light oil valve.

Gas breaktrhough simulation

Akre et al. (2013a) performed simulation of the AICV in a field sufferting from gas breakthrough. Two cases for a thin oil rim with gas cap wre simulated. Case 1 was with conventional passive inflow control device and Case 2 was with the AICV. The simulations were performed with OLGA and ROCX. The simulation is dynamic, which means that the choking was 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 was controled with a set point of 200 for the GOR in both cases. The horizontal well in the simulation model was 3000 meter long with 30 evenly spaced zonal isolations. The pressure drop in the well due to friction was include. 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 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 8 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. More details of the simulations can be found in Aakre et al. (2013a).

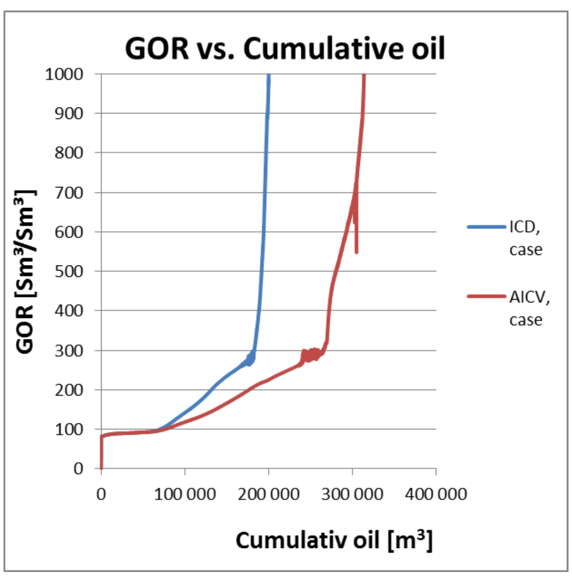

Figure 7: Cumulative oil production versus gas oil ratio

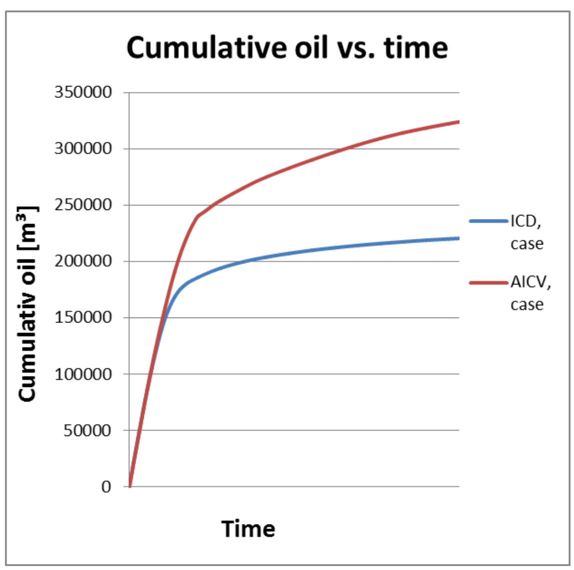

Figure 8: Cumulative oil production with time

Water breaktrhough simulation

Aakre et al. (2013b) used OLGA/Rocx and studied the effect of AICV completion on increased oil recovery for an heavy oil reservoir with water drive. A 3D mesh with rectangular cells was created. The heavy oil viscosity was 100 cP and the density is 987 kg/m^3. Figure 9 shows a part of the reservoir. The reservoir length (x-direction) is 1000 m, the width (y-direction) is 89 m and the height (z-direction) is 60 m. The generic reservoir model is heterogeneous with permeability varying from 500-5000 mD. On the left hand side the colors indicates the permeability in the y-direction. The permeability in the different zones is 500 mD (dark blue), 1000 mD (light blue) and 5000 mD (red). The figure on the right shows the initial oil saturation. Blue represents 100% water and red 100% oil.

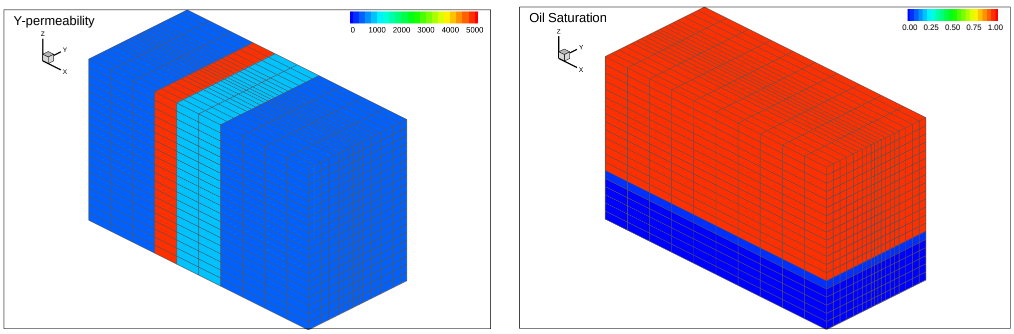

Figure 9: Reservoir conditions, permeability to the left and oil saturation to the right.

Two cases were simulated, where the first case is an open-hole simulation without any inflow control or zonal isolation, the second case is simulation with AICV completion. The well bore section consists of ten inflow ports, with no flow restrictions in the first case and with AICVs in the second and third case. The distance between the inflow ports is 100 m. In the AICV-completion cases, each zone is isolated with packers. The boundary conditions are 136 bar water drive from the bottom of the generic reservoir model and a total production rate of 6400 bbl/d of oil. The restricted production rate illustrates the capacity to a down-hole pump and/or the processing plant. Both cases were run for 400 days.

In Figure 10 the comparison between accumulated oil productions for the two cases, open-hole well and well with AICV completion is presented resepectively. The production is equal for the two cases the first 20 days of production, but after water breakthrough, the accumulated oil production increases much faster when AICV-completion is used. The total oil production after 400 days is 580 000 bbl without AICV and 940 000 bbl with AICV. This shows that AICV-completed wells have the potential to produce at least 360 000 bbl oil extra which implies 62% increase in oil production.

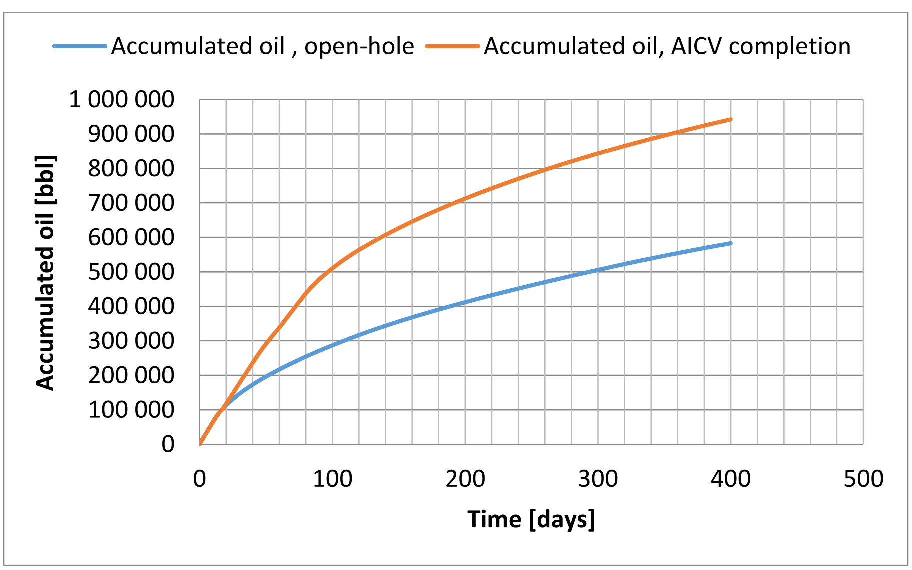

Figure 10: Comparison of accumulated oil production with and without AICV completion.

Conclusions

The paper has pointed out thatn either ICD nor AICD are able to shut off the unwanted gas and water production completely. The newly developed and patented Autonomous Inflow Control Valve (AICV) can shut off the unwanted fluid completely. This technology will probably be the next major step for increased oil recovery on the Norwegian Continental Shelf, in new and old wells. The new completion technology is described and experimental test results with gas, oil and water were presented together with reservoir simulations that confirm that the AICV will give significantly increased recovery in field suffering from gas and water breakthrough.

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