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The Autonomous RCP Valve - New Technology for Inflow Control In Horizontal Wells

Vidar Mathiesen, Haavard Aakre, Bjørnar Werswick, Geir Elseth, Statoil ASA

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Abstract

Horizontal wells with one or more branches have been used to maximize reservoir contact by Statoil and other oil companies for more than a decade. Frictional pressure drop and variation in permeability and mobility will naturally lead to non-uniform inflow profile along a well. Eventually, this will result in gas and/or water breakthrough, which may reduce the well performance and recovery significantly. The breakthrough typically occurs in the heal region of the well and in regions with high reservoir permeability. Inflow Control devices (ICDs) are flow resistance elements installed along the producing zone of a well to counteract the non-uniform inflow, hence improving the well performance. The technology is regarded as standard technology by the industry and classified as passive inflow control, since the geometry of the devices is fixed or preset prior to installation. Passive inflow control is applied to delay the unwanted gas/water breakthrough. However, once occurred, conventional inflow control will not reduce or stop the breakthrough. Statoil's new autonomous inflow control device (AICD) is an active flow resistance element distributed along the well, similar to conventional passive ICDs. Statoil's AICD will, in addition to delay the breakthrough, reduce the proportions of the breakthrough. The AICD will impose a relatively strong choking for low-viscous fluids and only minor choking for viscous oil. This is due to autonomous changes in the flow area internally in the AICD. With this technology the well performance and production can be higher after a breakthrough compared to conventional inflow control.

Statoil's AICD technology is piloted in two wells at two different fields in the North Sea. Each well is completed with 1-4 AICDs per screen joint, typically 200-400 per well. The AICD operates without need for human interventions and electric or hydraulic power. Well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well from a reservoir containing light oil. Due to the restriction of the gas inflow, the drawdown can be kept high after breakthrough to allow significant oil production from the remaining oil zones in the well.

Likewise, in a pilot well in a reservoir containing heavy oil, well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well and preliminary evaluations indicate that even water inflow is reduced. Thus the drawdown can be kept high allowing high production from the remaining oil zones.

Motivation

Horizontal wells with one or more branches have been used to maximize reservoir contact by Statoil and other oil companies for more than a decade [1-4]. Statoil started production from Troll in the fall of 1995. The thin oil layer was between 22 and 26 meters in the Troll oil province and 11 and 13 meters in the Troll gas province. In order to start profitable oil production from this thin layer, it was necessary to develop advanced drilling and production technology. Hence, the oil production wells drilled in Troll were horizontal wells, and most of the wells were controlled by inflow control devices which are friction elements distributed along the well for improving the well performance [5]. The technology is regarded as standard technology by the industry and classified as passive inflow control, since the geometry of the devices are fixed or preset prior to installation.

Horizontal wells are characterized by an uneven drainage profile from the heel of the well to the toe, even when equipped with conventional passive ICDs. Frictional pressure drop and variation in permeabilities and mobility will naturally lead to a non-uniform inflow profile along a well. Eventually, this will result in gas and/or water breakthrough, which may reduce the well performance and recovery significantly. The breakthrough typically occurs in the heal region of the well and in regions with high reservoir permeability. Passive inflow control is applied to delay the unwanted gas/water breakthrough but this device will not reduce or stop the breakthrough.

The new autonomous inflow control device (AICD) from Statoil will, in addition to delay the breakthrough, reduce the consequences of the breakthrough. The AICD valve chokes the flow of low-viscous fluids and favours the viscous fluid. With this technology the well performance and production can be higher after a breakthrough compared to conventional inflow control.

While static ICDs can be selected and installed with optimal inflow control properties at the beginning of the production life time of the well, the properties of the well will change over time in a manner that is difficult or impossible to foresee. Since the ICDs are static, there is no easy way to adjust the inflow characteristics of the ICDs after the initial installation. Hence the drainage characteristics that were correct and optimal during the first part of the production lifetime, becomes more and more off with time as the well starts to mature. Another important drawback with conventional fixed opening ICD is that this technology has no ability to close off the internal flow area or flow opening in the event of water or gas breakthrough.

The RCP Technology

The described autonomous inflow control device is developed by Statoil, and is called the Rate Controlled Production (RCP) valve. The technology is patented [6] in all relevant countries.

In Figure 1 an example of a well installation is shown. The fluids are flowing from the reservoir through the screen and then into the inflow chamber where the RCP is mounted. Typically, one RCP valve is installed for each screen section. However, for certain applications up to four valves may be mounted per screen section.

In Figure 2, a picture of the RCP valve is shown, whereas a schematic sketch is given in Figure 3. The flow path is marked by arrows. The outer diameter of the RCP valve is typically 80 mm and the valve consists of only one movable part, the free floating disc. In Figure 3 the disc rests at the seat allowing maximum flow area for the passing fluid. The valve is autonomous, i.e. the valve operates entirely without the need for human interventions and it does not require electric or hydraulic power. The position of the disc depends on the fluid properties and the flow conditions. The performance of the RCP valve is based on the Bernoulli principle. By neglegting elevation and compressible effects the Bernoulli equation can be expressed as:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 + \Delta p_{\text{friction loss}} \tag{1}$$

The equation states that the sum of the static pressure, the dynamic pressure and the frictional pressure losses along a streamline is constant. This phenomenon is utilized in the RCP valve.

The RCP valve restricts the flow rate of low viscous fluids. When gas flows through the RCP valve, the pressure at the flowing side of the disc will be lower due to the high gas velocity. The total force acting on the disc will move the disc towards the inlet, and reduce the flow area and thus the flow. When more viscous fluids flow through the RCP valve, the friction loss increases and the pressure recovery of the dynamic pressure decreases. The pressure on the rear side of the disc will decrease resulting in lower force acting on the disc towards the inlet. Thus the disc moves away from inlet and the flow area and the flow increases. The result of this is that heavier oils will flow through the valve with less rescistance compared to lighter oils. A fixed geometry device like a nozzle or an orifice will have an opposite behaviour.

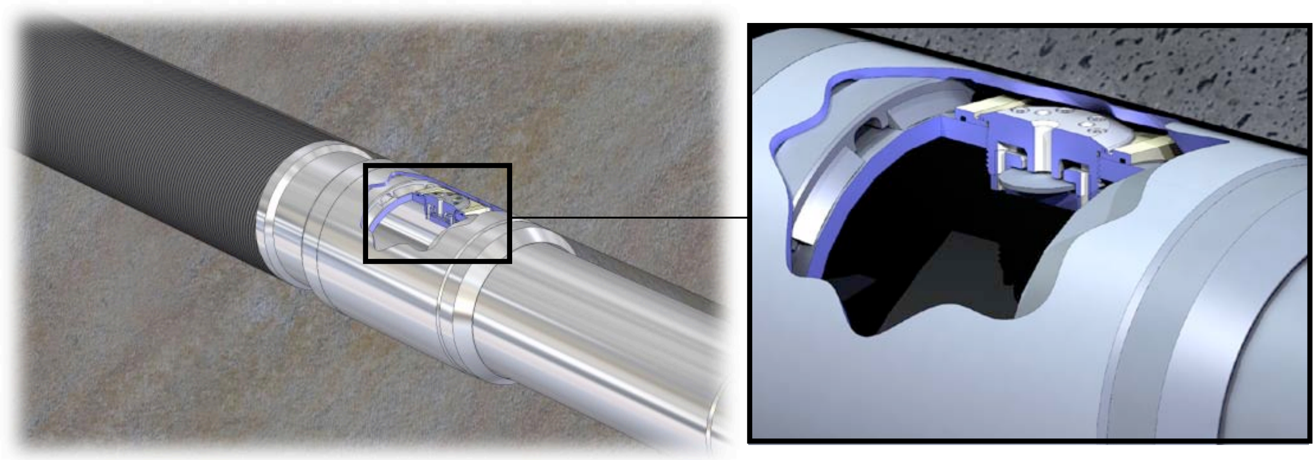

Figure 1: Statoil's RCP valve conneted to the base pipe in a sand screen joint in the well.

Figure 2: Statoil's RCP valve

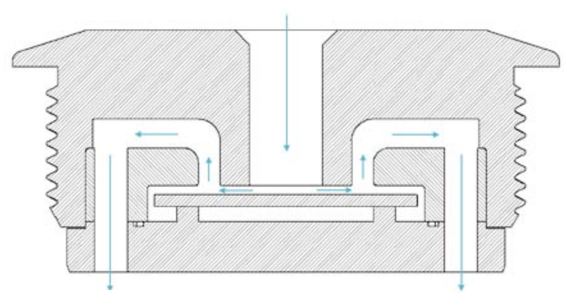

Figure 3: Schematic sketch of Statoil's RCP valve

Uniform Inflow Profile Effect

Horizontal wells are characterized by an uneven drainage profile from the heel of the well to the toe due to frictional pressure drop and variation in reservoir permeability. The principle of an ICD is to restrict the flow rate by creating an additional pressure drop. This will give a more uniform production profile in the wellbore from the toe to the heel, and the water and gas breakthrough will be delayed. The pressure drop over standard ICDs is proportional to the square of the volume flow. In Statoils AICD the flowrates will be controlled by the movable disc, and this makes the flow characteristics different from the standard ICDs. The pressure drop over an RCP valve is typically proportional to the volume flow to the fourth power.

The design of a passive inflow control element like the ICD is critical since this is not adjustable after the installation in the well. The reservoir conditions and production vary during the life time of a well hence the effect of the ICDs will change during the same life time. A well installed with AICDs has the capability of selective choking of the reservoir fluids, and the consequence is that the performance of the AICDs is more robust towards varying reservoir conditions. Figure 4 shows a comparison of typical flow characteristics for an AICD and a fixed geometry device having dp vs flow rate function close to the power of 2, similar to an orifice. The comparison is made using viscous oil (12cP). At a differential pressure of 5 bar the flow rates are equal. The experimental AICD data are obtained from tests performed in Statoil's multiphase flow test laboratory in Porsgrunn. As can be seen from the figure, the flow rate through the fixed geometry device is more sensitive to changes in differential pressure. Even with a very high differential pressure, the AICD will keep the flow rate low and an early gas or water breakthrough will be delayed compared to a fixed geometry device. The AICD give a more uniform massflow over a range of drawdown. The total flow rate into the well can be adjusted by the number of valves.

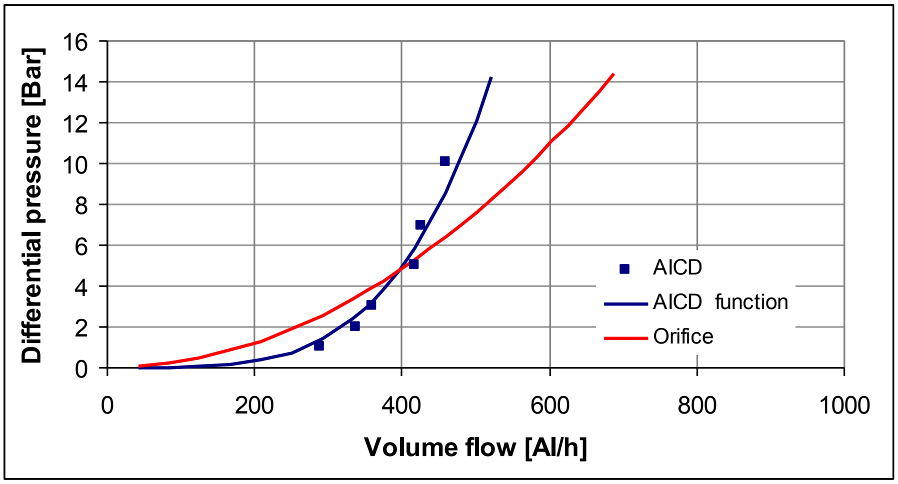

Figure 4: Comparison of oil flow rates (12 cP) through Statoil's AICD and a fixed geometry device similar to an orifice.

Selective Choking Effect

The second advantage of AICD compared to a conventional ICD, is that the AICD chokes for low viscous fluids after breakthrough, such as gas in light oil production and both gas and water in heavy oil production. Due to the movable disc in the AICD, the flow area changes depending on type of fluid and flow conditions. This implies that the AICD is phase selective. With this technology the well performance and production can be increased after a breakthrough compared to wells without Statoil's AICDs.

Figure 5 shows a typical flow rate profile for water, gas and oil through an AICD. The data is given for oil (460 cP), water and air. The curves represent the flow rates of single phase oil, single phase water and single phase gas as a function of differential pressure. The flow rates through the valves are dependent on the design parameters of the valve. The design of the RCP valve can be adjusted to fit the current oil field. Since the AICD is controlled by the viscosity of the fluid, the valve reduces the inflow of gas from a reservoir containing light oil. In a reservoir containing heavy oil the valve will reduce unwanted water production as well. Based on the results given in Figure 5, the oil-water and oil-gas ratios for 460 cP oil are calculated and presented in Figure 6. The oil/water and oil/gas ratios are about 6.5 and 3.5, respectively. The experiments are performed in Statoil's multiphase flow test laboratory in Porsgrunn.

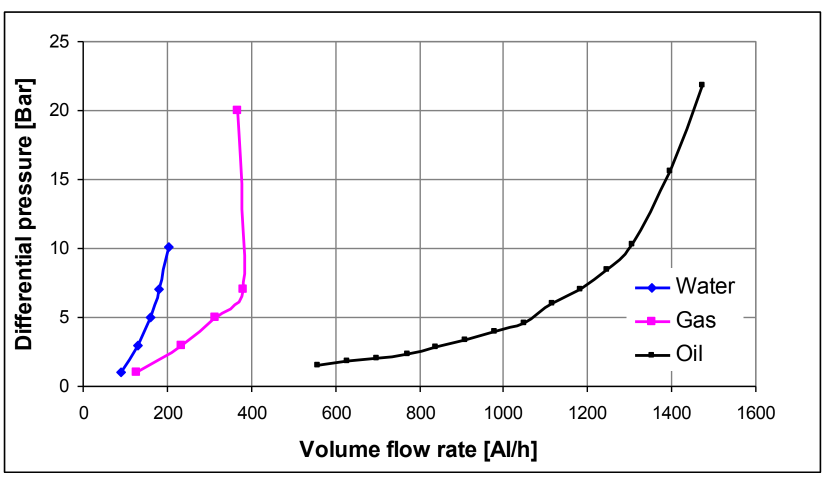

Figure 5: Volume flow of oil (460 cP), water and gas through RCP as a function of differential pressure.

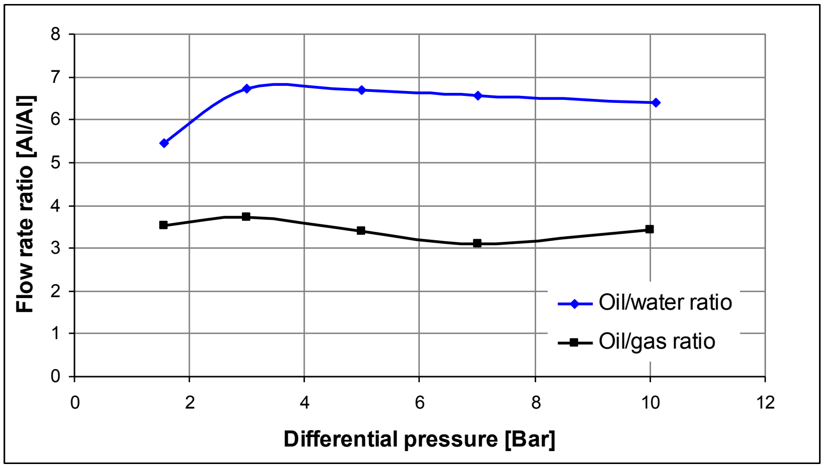

Figure 6: Oil /water and oil/gas ratios as a function of differential pressure. The oil viscosity is 460 cP.

RCP function

Several experimental series with oil, gas and water are performed to validate the functionality of the RCP valve. Based on the experimental data a function for the RCP has been developed. The RCP model has been implemented in the reservoir simulation tool Eclipse. The RCP model is a general expression for differential pressure across the valve as a function of fluid properties and volume flow. The function is expressed by:

$$\delta P = f(\rho,\mu) \cdot a_{AICD} \cdot q^{x} \tag{2}$$

where $f(\rho,\mu)$ is an analytic function of the mixture density and viscosity, a_{AICD} is a user-input 'strength' parameter, q is the local volumetric mixture flow rate and x is a user input constant. RCP valves will have different design for different oil fields. The model constants x and a_{AICD} are dependent on the RCP design and the fluid properties. Based on the experimental data the flow constant and calibration properties in the RCP model can be defined. Typically, the value for x varies between 3 and 4.

The function $f(\rho, \mu)$ is defined as:

$$f(\rho,\mu) = \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^{y} \tag{3}$$

where y is a user-input constant and ρ_{cal} and μ_{cal} are the calibration density and viscosity respectively.

The mixture density and viscosity are defined as:

$$\begin{aligned} \rho_{mix} &= \alpha_{oil}\rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \\ \mu_{mix} &= \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{gas}\mu_{gas} \end{aligned} \tag{4}$$

where α is the volume fraction of the phase. The function is validated against several experimental data series performed with different oils with a range of viscosities. Figure 7 shows an example of RCP function compared to data from tests performed in Statoil's multiphase flow test laboratory in Porsgrunn.

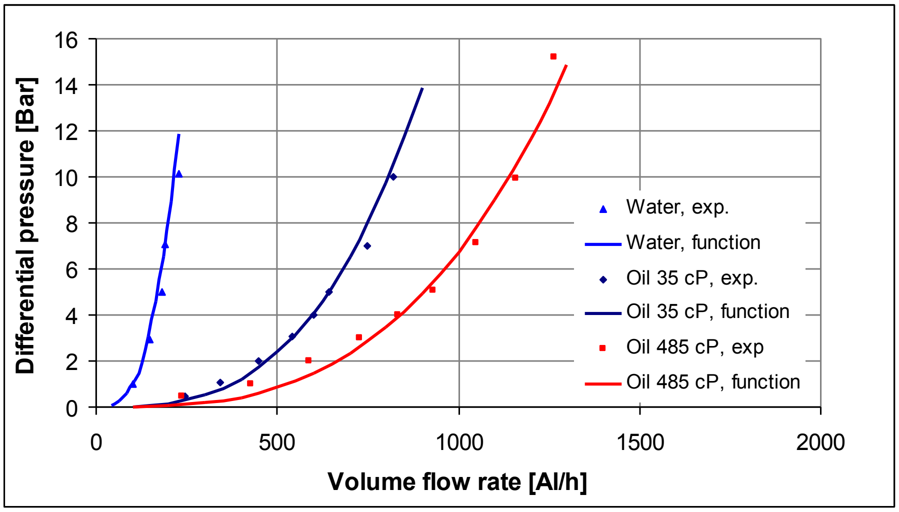

Figure 7: Comparison of the RCP valve function with experimental data.

Zonal isolation

Water or gas breakthrough will first appear in one part of the well, usually in the heal area or in zones with high permeability. When water or gas reaches the annulus between the base pipe and the reservoir in one zone of the well, the AICDs in this particular zone will choke. Hence it is important that the different zones are isolated from each other to avoid annular flow of low-viscous fluid. Without zonal isolation, the annulus may be filled with water or gas soon after the first breakthrough. Hence and all the AICDs may start choking and the oil production will be significantly reduced. Zonal isolation will isolate the water or gas producing zones and the rest of well will still be able to produce oil at the same flow rate as before the breakthrough. The optimal configuration or distribution of the AICDs combined with zonal isolation in the wellbore will be field specific. Figure 8 shows a schematic illustration of AICDs and zonal isolation.

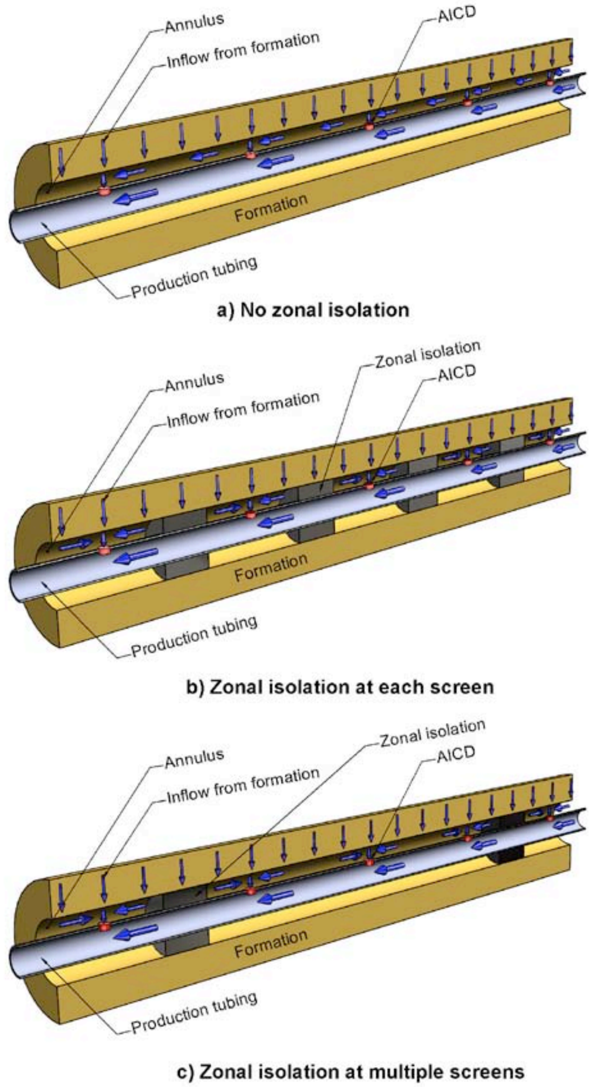

Figure 8: Schematic illustration of AICD configurations and zonal isolation

Application Area

The new autonomous inflow control device is capable of delaying the breakthrough of gas or water and to reduce the consequences of the breakthrough. The valve operates entirely without the need for human interventions and it does not require electric or hydraulic power. These characteristics have the potential of giving the AICD an advantage compared to other inflow control devices. In all types of oil fields, the RCP valve will be capable of choking for gas. In fields with heavy oil, the valve will choke both for gas and for water. With this technology, given a proper distribution along the well and combined with zonal isolation, the well performance and production can be increased after a breakthrough compared to conventional inflow control. The application of the RCP valve has a significant potential in fields with viscous oils since the valve chokes the low-viscous fluids and favours the viscous fluid. The flow rate through the valve increases with increasing viscosity as shown in Figure 9. The experimental results are from tests performed in the Statoil multiphase flow test laboratory in Porsgrunn. It is observed that the flow rate increase through the valve for increasing viscosity, ranging from 0.46 cP (water) to 485 cP (heavy oil).

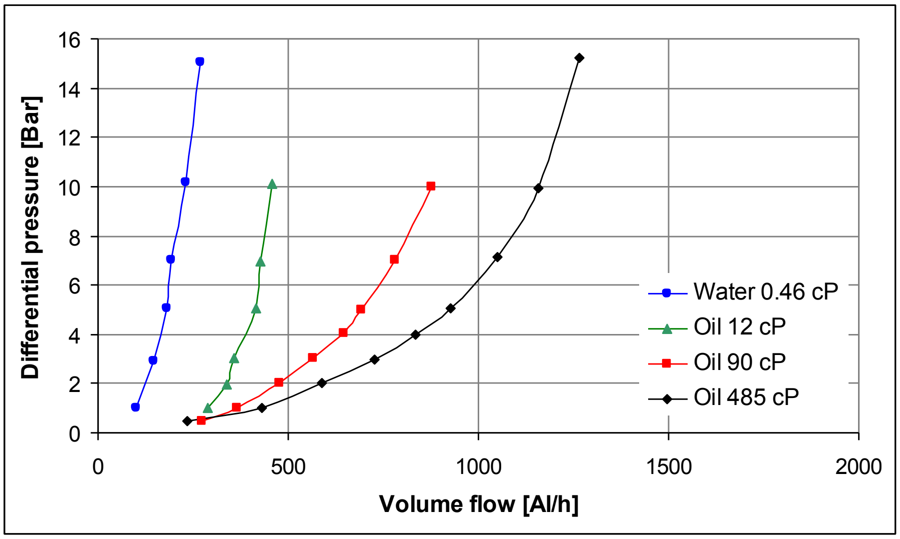

Figure 9: Volume flow vs differential pressure for water and oils with different viscosities.

Statoil's AICD technology is piloted in two wells at two different fields in the North Sea. Each well is completed with 1-4 RCP valves per screen joint, typically 200-400 per well.

Well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well from a reservoir containing light oil. In this pilot well the drawdown was initially about 20 bars. The gas breakthrough occurred after a few weeks. Due to the AICD the drawdown could still be kept at 20 bar even with gas breakthrough. In wells without Statoil's AICD the drawdown will be reduced down to 0.5-1 bar after gas breakthrough. The permeability in the reservoir changes with a factor of 20 along the well. Thus the low permeability zones will have minor production after gas breakthrough. The use of AICDs makes it possible to produce from low permeability zones, also after gas breakthrough. From these tests the hypothesis is that the well length and reservoir contact can be increased when using Statoil's AICD technology.

In heavy oil production Qin and Wojtanowicz [7] refers to instability in recovery due to dramatic loss of wells productivity at the onset of water breakthrough. In a Statoil pilot well for the AICD technology in a reservoir containing heavy oil, well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well and preliminary evaluations indicate that even water inflow is reduced. Thus the drawdown can be kept high allowing high production from the remaining oil zones.

Figure 10 shows a horizontal well without AICDs in a heavy oil reservoir. After water breakthrough the drawdown has to be reduced to avoid a huge amount of water production. In heavy oil reservoirs the mobility ratio between water and oil is typically from 20 to several 100. This implies that water travels accordingly faster in the formation assuming similar pressure gradient. Low drawdown leads to a reduction in production from oil producing zones, illustrated with arrows in the figure.

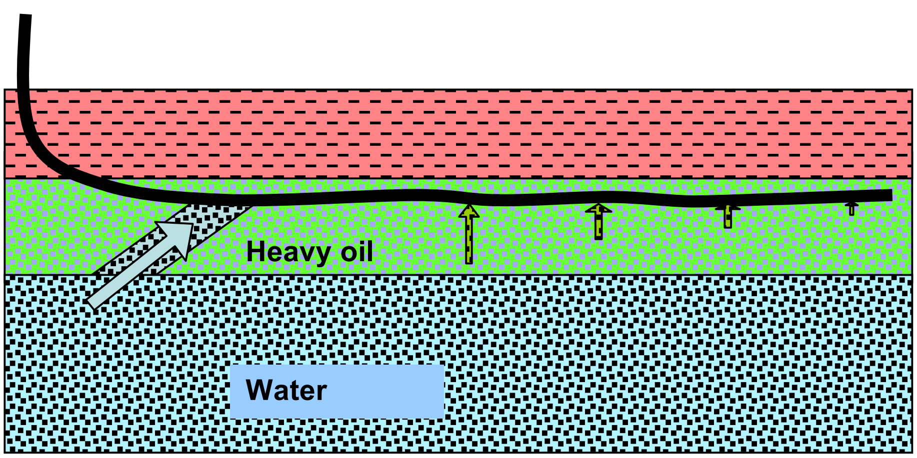

Figure 10: Production without Statoil's AICD

Figure 11 shows a horizontal well with AICDs in a heavy oil reservoir. After water break through the AICD in the zone with water will react and choke back the water flow as shown in Figure 9. The well can then produce with the same drawdown as before the water breakthrough, and the production from the remaining oil zones will be unchanged, illustrated with arrows in the figure.

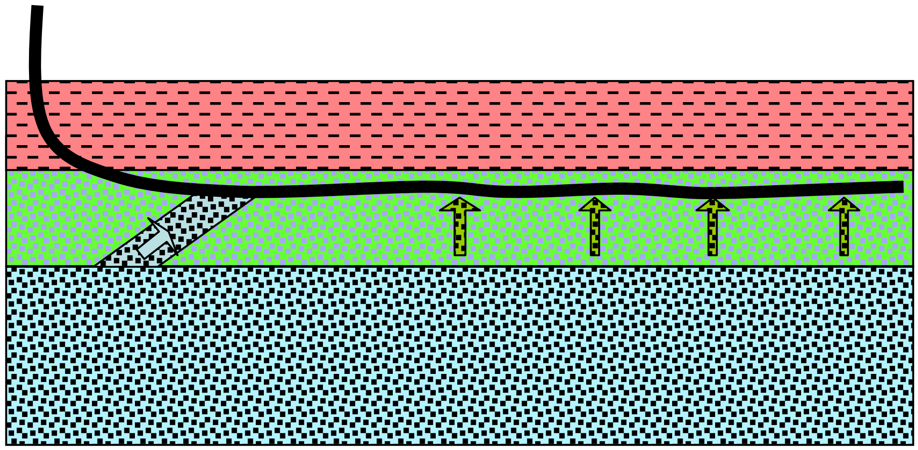

Figure 11: Production with Statoil's AICDs

The AICD technology is very applicable and important in heterogeneous reservoirs where the choking effect will give more uniform oil production from zones with highly different permeability.

Conclusions

Horizontal wells with one or more branches have been used to maximize reservoir contact by Statoil and other oil companies for more than a decade. ICDs are used in horizontal wells to improve the well performance. Frictional pressure drop and variation in permeability and mobility will naturally lead to non-uniform inflow profile along a well. This will eventually lead to gas and/or water breakthrough, which may reduce the well performance and recovery significantly. The breakthrough typically occurs in the heal region and in regions with high permeability. Passive inflow control is applied to delay the unwanted gas/water breakthrough. However, once occurred, conventional inflow control will not reduce or stop the breakthrough. Statoil's new autonomous inflow control device (AICD) is an active flow resistance element distributed along the producing interval in the well like conventional passive ICDs. Statoil's AICD will, in addition to delay the breakthrough, reduce the proportions of the breakthrough. The AICD will impose a relatively strong choking for low-viscous fluids and only minor choking for viscous oil. This is due to autonomous changes in flow area interally in the AICD. With this technology the well performance and production can be higher after a breakthrough compared to conventional inflow control.

Several experimental laboratory tests with oil, gas and water are performed to validate the performance of the valve. Based on the experimental data a function for the RCP valve has been developed. The RCP model has been implemented in reservoir simulation tool Eclipse. The RCP model is a general expression for differential pressure across the valve as a function of fluid properties and volume flow. The differential pressure across the valve is typically proportional to the flow rate in the power of about 4. The design of the RCP valve can be adjusted to fit the relevant oil field.

Statoil's AICD technology is piloted in two wells at two different fields in the North Sea. Each well is completed with 1-4 valves per screen joint, typically 200-400 AICDs per well. The AICD operates without the need for human interventions and it does not require electric or hydraulic power. Well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well from a reservoir containing light oil. Due to the restriction of the gas inflow, the drawdown can be kept high after breakthrough to allow significant oil production from the remaining oil zones in the well.

In a pilot well in a reservoir containing heavy oil, well tests have shown that Statoil's AICD technology reduces the inflow of gas into the well and preliminary evaluations indicate that even water inflow is reduced. Thus the drawdown can be kept high allowing high production from the remaining oil zones.

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