Increasing oil recovery in brownfield heavy oil wells

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Oil Review Middle East, April 2018

As oil reservoirs age, the optimisation of oil recovery becomes essential if oil production targets are to be met, not least in heavy oil fields where the challenge is greater due to the lower reservoir energy and requirement for high reservoir contact.

For many years, inflow control devices (ICDs) have been used to mitigate early breakthrough of unwanted water or gas in oil wells. ICDs are, however, passive in nature and once water or gas breaks through, the choking effect cannot be adjusted without intervention. Furthermore, the viscosity difference between heavy oil and water creates an unfavourable mobility ratio, which allowing water to flow much faster through the reservoir and into the wellbore, so that water breakthrough happens faster, displacing oil production from producing zones.

Autonomous inflow control devices (AICD) are designed to automatically react to the properties of the fluid flowing through them. An AICD restricts the flow of less viscous fluids, such as water and gas, while allowing more viscous fluids, such as heavy oil, to pass through with minimum pressure drop. When used in horizontal wells that have been compartmentalised using swell packers, AICDs restrict the flow of water in high water cut zones while allowing greater drawdown of the reservoir in high oil saturation zones, reducing water cut and improving oil recovery for the overall well.

Like ICDs, an AICD can be used in new wells to create a more balanced inflow profile along a horizontal section prior to water breakthrough. Once water breaks through in one or more zones, the AICDs restrict production from these compartments and favour production from low water cut zones. AICDs can also be used in existing wells where water breakthrough has already occurred through deployment as a retrofit string, reducing water cut to extend economic well life and improving sweep efficiency.

Applications

In sandstone reservoirs, the AICD is typically assembled as part of the sand screen joint in the lower completion. For carbonate reservoirs, the AICD can be deployed as a standalone sub, with a debris filter assembled before the inlet of the valve. Reservoir fluids enter the completion through the sand screen filter and flow along the annulus between the filter and base pipe into the inflow control housing where the AICD is mounted. The fluids then flow through the AICD and into the production conduit, moving to the surface together with the production from the rest of the well (figure 1).

Figure 1: Autonomous ICD Flow Path
Flow loop experiments were carried out with a 27cp crude oil and water to define AICD performance in heavy oil operations with varying water cuts conditions. Figure 2 shows two-phase oil/water tests performed with water cut at 25, 65, 80 and 92% (WC%). The pressure drop as a function of total volume flow rate is plotted together with the single-phase oil and water curves for reference. With this degree of viscosity contrast, water will travel faster at a similar pressure gradient compared to oil. The AICD imposes a much higher pressure drop on water and leads to a reduction in water flow. The mixture of oil and water generates a mixture viscosity depending on the fraction of each fluid. The same trends were observed with increasing water cut. As the water cut increases, the mixture viscosity will be reduced and increase the velocity of the mixed fluid flow through the valve resulting in an increase the pressure drop. The AICD mathematical function of the mixture viscosity can be simplified to be expressed by the function \( \mu_{\text{mix}} \) based on the fraction (\( \alpha \)) of each fluid.

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\mu_{\text{mix}} = \alpha_{\text{oil}} \mu_{\text{oil}} + \alpha_{\text{gas}} \mu_{\text{gas}} + \alpha_{\text{water}} \mu_{\text{water}}
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As the water cut percentage increases, this will result in reduction in viscosity and higher pressure drop. A viscosity contrast of 3cp minimum is essential for the AICD to differentiate between water and oil.

Figure 2: Multiphase production test results with AICD as a function of volume flow rate and pressure drop

Using AICDs requires a good understanding of the technology, well performance and reservoir properties. A segmented dynamic reservoir model is often employed to simulate representative reservoir performance and allow evaluation of the well with and without the AICD completion. For example, in wells without inflow control, the water may be drawn into the wellbore from the down-dip oil-water contact through high-permeability channels, reducing effective drainage of the oil up-dip. The AICD will improve the water sweep by balancing the inflow from high and low-permeability sections and creating additional pressure drop at high water cut zones. Furthermore, the AICD will allow a low mobility, viscous oil to be produced and recover the oil up-dip.

Completion Design

Annular isolation is critical in AICD completions to compartmentalise the reservoir, which allows for the segregation of flow from sections of the well with different fluid saturations. The AICDs impose a greater flow restriction on compartments with high (mobility) water saturation and allow more production from low mobility, high oil saturation compartments. Generally, swell packer placement is dependent on the permeability contrast and fluid saturation contrast between intervals in the wells. Limitations on the number of compartments may be imposed by well construction and completion factors, such as zone length, open hole drag, dogleg severity and previous operational experience. Sensitivity analysis to optimize the quantity and location of zonal isolation devices is essential for this technology. The retrofit application consists of installing AICD subs within existing stand-alone screens along with packers for zonal isolation as shown in Figure 3. The retrofit AICD application is also applicable with existing gravel pack well.

The overall flow rate, formation productivity and the well length will determine the flux rate through a single AICD valve. The initial and maximum oil and liquid production targets are used along with the produced fluid properties and reservoir data to determine the quantity and size of AICDs required to ensure the maximum well deliverability is achieved.

The evolution of water cut over time is a critical factor for AICD completion design to maximise oil production. During early production, prior to water breakthrough, AICDs should be used to optimise drainage and reduce the likelihood of water coning by ensuring that inflow between the zones is balanced. This provides a window to accelerate early oil production, and then maintain oil production from high oil saturation zones when water begins to break through other zones, until the water saturation increases uniformly along the entire wellbore.

The AICD acts as a check valve, preventing flow from the production conduit to the formation (injection direction). Where chemical treatments are prescribed to treat scale, paraffin, or asphaltene problems, requiring injection into the wellbore annulus and/or the formation, a bypass valve can be installed adjacent to the AICD to permit injection. The bypass valve can be installed as part of screen assembly (with the AICD) in the lower completion or run as a separate sub.
Case study
AICDs have been used in brownfield wells across the Middle East, China, and North America as a retrofit solution after water cut increases, most commonly when water cut has reached up to 96%.

In one of the first AICD retrofit installations on December 2014 in heavy oil environment, offshore China, designed to control water cut, it also showed a significant increase in oil production as show in Figure 4. The length of the well is 600m horizontal and completed initially with 5.5" screen with gravel pack in 8.5" open hole. Retrofit AICDs have been installed on 4" pipe joints and deployed inside existing 5.5" screen. The well was previously shut in due to the water cut exceeding 96%. Following installation of the AICD completion a reduction in water cut to 93.6% was observed. The water cut reduction enabled a resultant increase in the oil production from 43m3/d to 55m3/d, or 28%. Based on the positive results of the initial well, there have been many more wells within the field completed with AICDs as a retrofit solution or primary completion for new wells.

Conclusion
Using AICDs in heavy oil fields to control water can help reduce water cut. The viscosity difference between heavy oil and water provides a favourable mobility ratio well suited to this technology and has been shown to increase oil production. As the water is restricted upon breakthrough, the overall recovery of the well is improved when compared to operations using conventional methods and passive ICDs.