Recovery improved in a brownfield heavy oil well, using inflow control technology

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Use of AICDs in heavy oil fields to control water can increase oil production. Using AICDs in heavy oil fields can reduce water cut. As a case study shows, the viscosity difference between heavy oil and water provides a favourable mobility ratio well-suited to this technology, and increased oil production.

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.

One of the most important aspects of heavy oil is its viscosity, which can directly impact the recovery and productivity of the reservoir. Although there is no direct relationship between density and viscosity, a reduction in API gravity scale index for heavy oil is generally accompanied by an increase in viscosity.

Heavy oil usually occurs in shallower formations in marginal geological basins formed by non-consolidated sand. Reservoirs tend to have lower pressure and temperature in comparison to a light oil reservoir. This generally results in lower recovery factors. Although this characteristic points to more complex production processes, factors such as high permeability could make the recovery process easier.

Depending on the capillary pressure, gravitational and viscous forces, and the interaction between these elements during oil flow, oil is generally retained in the reservoir. The porous media may then be measured by the mobility ratio. The mobility of the fluids in porous media is defined by Darcy’s Law, which defines a direct relationship between pressure, permeability and mobility, depending on viscosity and velocity. Due to an unfavourable mobility ratio for heavy oil flow compared to water, the primary recovery technique may leave as much as 70% of petroleum in the reservoir.

Application of an ICD
To increase the recovery factor and the production rates, supplementary recovery methods, which are generally termed improved oil recovery (IOR) techniques, deploy operational strategies and the supply of additional energy to the well to increase oil recovery. One of the techniques used in horizontal heavy oil wells is the application of an inflow control device (ICD). This is an engineered nozzle or high friction channel that is typically made from high erosion resistance material and installed in the base pipe to create pressure drop. It is used to control the inflow from heel to toe by applying higher pressure drop in the heel of the well to balance the inflow in the toe of the well and overcome the friction flow in the length of horizontal completion as shown in Figure 1.

The use of passive ICDs in horizontal wells has been practiced widely in conventional wells to achieve the balance flux and mitigate early breakthrough of unwanted water or gas in oil wells. The devices are, however, sensitive 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 allows water to flow much faster through the reservoir and into the wellbore. This enables water breakthrough to happen faster, displacing oil production from producing zones.

Autonomous inflow control devices (AICD) are designed to automatically react to the properties of the fluid flowing...
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 compartmentalized 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.

The AICD device in operation

AICD functions are based on Bernoulli’s Principle which, by neglecting elevation and compressible effect, can be expressed as:

\[ P + \frac{1}{2} \rho v^2 = P + \frac{1}{2} \rho v'^2 + \Delta P \]  

\[ P \] = Static Pressure  

\[ \frac{1}{2} \rho v^2 \] = Dynamic Pressure  

\[ \Delta P \] = Friction Pressure Loss

The equation states that the sum of the static pressure, the dynamic pressure and the frictional pressure losses along a flow path, and velocity. Due to an unfavourable mobility ratio for Darcy’s Law, which defines a direct relationship between during oil flow, oil is generally retained in the reservoir. The viscous forces, and the interaction between these elements Depending on the capillary pressure, gravitational and geological basins formed by non-consolidated sand.

As oil reservoirs age, the optimisation of oil recovery happen faster, displacing oil production from producing areas. There are different types of AICD but most commonly used is the Flosure AICD which comprises of three components: valve body, nozzle, and disk as seen in Figure 2.

The Flosure AICD is constructed using erosion resistant material and is engineered to fit within standard ICD housings without protrusion into the completion bore.

AICD mathematical function described by the differential pressure across the AICD versus flow rate through the device.

\[ f(\rho, \mu) = \left( \frac{\rho_{mix}}{\rho_{cal}} \right) \left( \frac{\mu_{cal}}{\mu_{mix}} \right) \left( a_{AICD} \right) q^d \]

The AICD restricts the flow rate of low viscosity fluids by increasing flow resistance. When gas or water flows through the valve, the pressure at the flowing side of the disk will be lower due to the high fluid velocity. The total force acting on the disk will move the disc towards the inlet, and reduce the flow area and thus the flow, as shown in Figure 3b. When more viscous fluids flow through the valve, the friction loss increases and the pressure recovery of the dynamic pressure decreases. The pressure on the rear side of the disk will decrease resulting in lower force acting on the disc towards the inlet, as shown in figure 3a. Thus, the disk moves away from the inlet and the flow area and the flow increases. Notably, the AICD cannot shut-off production but can only manage the rate as a function of the fluid properties.

Applications

AICDs have been installed in a range of applications and reservoir types that can be described as horizontal oil producing wells with unwanted gas or water production. This includes: sandstone; carbonate; heavy oil; open-hole and cased-hole, both as a retrofit solution and as a primary completion. The technology is applicable to both high value subsea wells producing thousands of barrels a day, and low yielding land producing just tens of barrels per day.

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. The flow path in either configuration is the same as reservoir fluids enter the completion through the 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 as shown in Figure 4.
During oil flow, oil is generally retained in the reservoir. Depending on the capillary pressure, gravitational and lower recovery factors. Although this characteristic points comparison to a light oil reservoir. This generally results in productivity of the reservoir. Although there is no direct product of the reservoir.

As oil reservoirs age, the optimisation of oil recovery operational strategies and the supply of additional energy. To increase the recovery factor and the production rates, breakthrough has already occurred through deployment as compartments and favour production from low water cut. Like ICDs, an AICD can be used in new wells to create a isolation as shown in Figure 7, or with cased and perforated existing wellbore whether that be standalone screens or AICD subs, swellable packers are installed within the existing wellbore annulus and/or the formation, a bypass valve can be installed as part of screen assembly. The technology is applicable to both high value producing wells with unwanted gas or water production.

Enhanced well performance can be achieved with AICD completed wells providing that acceptable production rates can be achieved through the AICDs throughout the life of the well. As viscosity contrast between the oil and the unwanted fluid (gas/water) is present at well conditions, some heterogeneities or non-uniformity in water production is present along the wellbore and there is the ability to achieve adequate compartmentalization of the wellbore annulus.

The process of candidate selection starts with an evaluation of the increased or accelerated oil production and once this is determined, the well operability factors can be considered during the detailed well planning phase. One of the main factors affecting the results of this process are the reservoir fluids.

The AICD requires a viscosity contrast to provide an additional increased or accelerated oil production. This will be the case for water control in oil fields. AICD has the potential for controlling water breakthrough/water production in heavy oil applications. Comparison of the flow characteristics of AICD versus passive ICD for the reservoir fluid is the first screening stage for a new application. This is performed using regression analysis to define the AICD characteristics based on the viscosity and density of oil and water at reservoir condition.

Figure 6 shows an example for test conditions with an oil viscosity of 27cp. The single-phase oil flow rates for AICD and ICD are matched for a given pressure drop and the differences in flow characteristics are examined.

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. Based on the results, the oil-water volumetric flow ratios for 27cp oil can be calculated. At 15bar pressure drop, oil/water ratios are about six times. This means that when the zones have water breakthrough, the AICD will choke the flow rate by almost 80%.

It is observed during the test at 25% water cut, that the AICD is not effectively choking the fluid mixture due a small change of mixture viscosity and oil is still in a continuous flowing phase. When the water cut increases to 65%, the AICD starts to show increased choking. As the water cut increases to 80% and 92%, the choking behaviour is strengthening resulting in a reduction of viscosity. A viscosity contrast of approximately 3cp is required for the AICD to differentiate between water and oil. It follows that as the viscosity contrast between oil and water increases the effectiveness of the AICD increases, making this technology particularly suited to heavy oil applications.

Analysis and simulation technologies
There are multiple commercial nodal analysis tools and

dynamic reservoir simulators that are equipped with AICD function in the inflow control device option. A static reservoir simulator can be used to optimize the AICD size and number of AICDs per joint. Dynamic simulators are required to quantify the production benefits of the AICD over field life. Notably, all new wells are simulated with a static and dynamic simulator to design the AICD size and number of AICD per joint.

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.

Figure 5 shows two-phase oil/water tests performed with water cut at 25, 65, 80 and 92%. 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.

\[
\rho_{\text{mix}} = a_{\text{oil}}\rho_{\text{oil}} + a_{\text{gas}}\rho_{\text{gas}} + a_{\text{water}}\rho_{\text{water}}
\]
\[
\mu_{\text{mix}} = a_{\text{oil}}\mu_{\text{oil}} + a_{\text{gas}}\mu_{\text{gas}} + a_{\text{water}}\mu_{\text{water}}
\]

Items a, b, c, d, e, f have been implemented recently to the mixture equations, to aid better description of the mixture properties at multi-phase conditions.

**Figure 5:** Multi-phase production test results, with AICD as a function of volume flowrate and pressure drop.

**Figure 6:** An AICD performance comparison with an ICD.
Completion design
Effective compartmentalisation is critical in AICD completions to allow different choking between compartments enabling more contribution from sections with highest oil fraction.

In general terms, the more compartments that can be created the more effective the AICD performance will be as the ability to limit unwanted water production into smaller wellbore length allows greater contribution from zones with higher oil saturations.

Limitations on the number of compartments may be imposed by well operability factors such as hole condition, weight limitations or existing completions. The location of compartments can be determined by changes in reservoir factors such as natural barriers, fractures, permeability or saturation contrasts. In longer bores, may be simply spaced out along the completion.

Sensitivity studies using nodal analysis tools is required to optimize the quantity and location of zonal isolation devices. This analysis is typically reviewed once actual well data becomes available and changes can be made at the rig site. Zonal isolation is typically achieved using swellable rubber mounted onto sleeves that can be slipped over the completion tubing and secured in place providing a flexible solution to compartmentalisation.

For retrofit applications in inner string consisting of installing AICD sub, swellable packers are installed within the existing wellbore. In this case, compartmentalization is driven by the existing wellbore whether that be standalone screens or gravel-packed completion along with packers for zonal isolation as shown in Figure 7, or with cased and perforated wells.

![AICD Diagram](image)

**Figure 7:** A retrofit AICD completion in an existing, stand-alone screen, with the production flow paths

The quantity and sizing of AICDs (driven by changes to the inlet port) will depend on the overall flow rate, formation productivity and the well length. Each AICD has a flow capacity as a function of its inlet port diameter and total capacity of the completion must be equal to or greater than the target production rate for a given flowing condition. The initial and maximum oil and liquid production targets will be simulated to determine the quantity and size of AICDs required to ensure maximum well deliverability is achieved.

The evolution of water cut over time is a critical factor for AICD completion design to maximize oil production. Value is derived from the application of AICD if water breakthrough can be delayed and if water saturation development is non-uniform along the wellbore. During early production, prior to water breakthrough, AICDs should be used to optimize 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. Once water saturation is uniform along the wellbore the AICDs are no longer able to improve production performance.

The AICD also acts as a check valve, preventing flow from the production conduit to the formation (injection direction). During deployment, this allows circulation through the completion without deploying a wash pipe and allows a hydraulic packer to be set. In later life, 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.

Reducing water cut – a case study
AICDs have been used in brownfields across Europe, 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 8. 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.

![Graph](image)

**Figure 8:** One of the first AICD retrofit installations offshore China boosted oil output significantly.

One of the key challenges in successfully implementing AICD in this field, as with many late field life applications, was the limited availability of well performance data, production logs and dynamic reservoir models. To demonstrate the potential value of AICD technology, a series of hypothetical scenarios were created, and a statistical approach adopted.

In the case where water saturation was at 96% across the producing section the AICDs cannot add value, but in scenarios where variation in water cut increases value can be demonstrated provided the additional pressure drop
resulting from the AICD does not limit well production (Figure 8). In this case, progressive cavity pumps were used to drive production and therefore the low reservoir energy was not a limiting factor. Similarly, a statistical approach was adopted to evaluate the success of AICD application with the range in increased oil production of zero to 165% but with an average of 44% immediately following installation.

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. The trial well was flowing with initial water cut of 96% similar to the well in the area. After installation of AICD, the well is producing with 93% water cut. It is envisaged that the water is coming from wet sand in the heel of the well and the AICD is choking the high-water zone area. The water cut reduction enabled a resultant increase in the oil production from 43m3/d to 55m3/d, or 28%. 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.

The use of AICDs requires a thorough understanding of the technology, well performance and downhole fluid properties that will impact the design and determine the ultimate recovery. The reservoir model with also have at least some degree of uncertainty that needs to be addressed using sensitivity analysis to ensure the AICD will perform in the well in all scenarios.