Case Study: Utilizing of Autonomous Inflow Control Valves Helps to have Better Fahud Wells Production Performance

Abd El-Fattah, M., *InflowControl AS,* **Maamari, H.,** *PDO***.,** *InflowControl AS,* **Mathiesen, V.,** *InflowControl AS*

This paper was presented at the 10th Mediterranean Offshore Conference & Exhibition in Alexandria, Egypt, October 15-17, 2019. It was selected for presentation by MOC 2019 Programme Committee following review of information contained in the abstract submitted by the author(s). The Paper as presented at MOC 2019 has not been reviewed by the Programme Committee.

ABSTRACT

One of the largest oil fields in the Oman - Fahud - was developed in the 1960's. The field was initially produced under natural depletion supplemented by gas injection. The high offtake rates led to a rapid displacement of the gas/oil contact, thus the field has now been suffering from early gas/water breakthrough and uneven fluid influx along the horizontal wells. The reservoir which has been on production more than 50 years, with water/gas breakthrough from fractures being the major challenge which negatively affects oil production rates. Applying technology which can manage such water/gas breakthrough in a cost effective manner whilst allowing increased oil production was a key goal from operators in this field.

Passive Inflow Control Devices (ICD) were introduced to the global oil and gas market in mid/late-90's, and the first generation of Autonomous ICD that can help reduce more unwanted gas or water was first installed several years later in 2007. ICD's successfully demonstrated that they could delay the gas and/or water breakthrough within horizontal wells, but they could not choke gas when the coning/ gas-breakthrough occurred and along with limited abilities to stop choke unwanted water production. To solve this problem the Autonomous Inflow Control Devices (AICD) with a movable disc was introduced to the market and demonstrated reduction of gas production by 20-30% with similar gains in oil production [1]. In this paper the patented newest generation of Autonomous Inflow Control Valves (AICV) technology is presented. The AICV technology has a movable piston that can close and reduce the unwanted gas and water production with 95 % [2]. The application of AICVs discussed herein were deployed within a number of wells in this Omani field named Fahud which had extremely high Gas Oil Ratio (GOR) and low oil production. The novel AICV technology can differentiate between fluid types based on viscosity and density, then when undesired fluid (gas and/or water) starts to be produced, the AICV starts to choke the valve flow area gradually until completely shut-off without well intervention [3].

The unique comparison of actual well production data -before and after- installing AICVs documents the benefits of installing correctly designed autonomous inflow control. The results demonstrate the AICVs closing the zones with high gas production and favoring oil rich zones. All the wells evaluated demonstrated clearly that the extremely high GOR was reduced up to solution GOR, and at the same time the daily oil production is increased. The application of AICV technology helps in complete gas/water shut-off autonomously. The AICV technology extend the technological application of ICD's enhance the well completion by making it a completion that provides control / complete gas/water shut-off all without well intervention and zero cost gas/water shut-off operation. This is a truly reservoir centric completion design.

INTRODUCTION

Fahud was first tested on surface indication in 1957 but the second well didn't take place until 1964 based on seismic discovered oil in commercial quantities in Middle Wasia limestones. Today, Fahud is the central base of PDO's operations in the interior of Oman. The Fahud culmination is expressed as an almost un-disturbed WNW-ESE trending anticline in outcropping Eocene rocks. In the subsurface at Cretaceous level the south flank is disturbed by a fault zone parallel to the structural axis. Pressure data indicate that the reservoirs probably have a common free water level. It is assumed that communication between reservoirs exists [4]. Fig. (1) shows field general structure cross section.

The initial development was performed in the period 1967-71. The field was initially produced under natural depletion supplemented in 1968 by gas injection. The high offtake rates led to a rapid displacement of the gas-oil contact (GOC), which resulted in the early gassing out of a number of relatively downdip completions. Simulation studies and field trials were conducted, which concluded that better recoveries would be obtained through waterflooding [5].

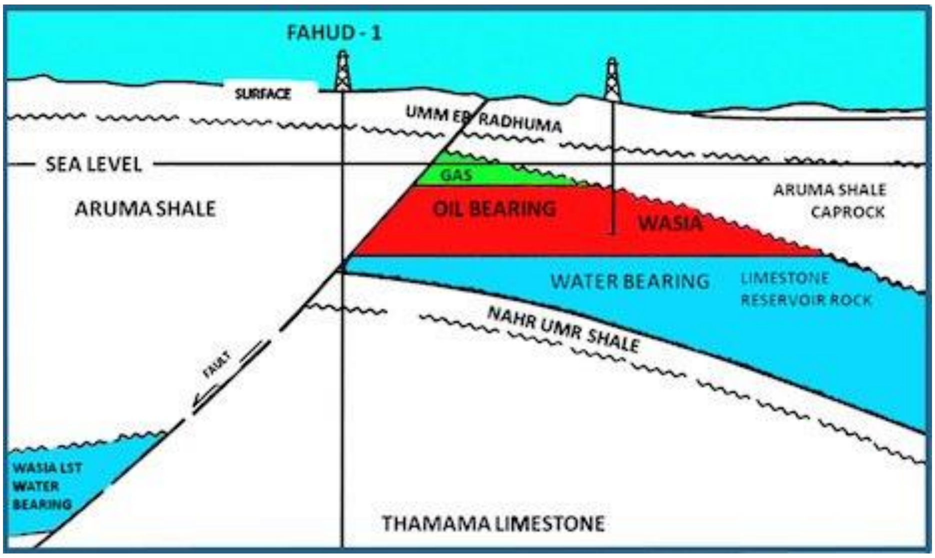

Fig 1: Fahud field general structure map

Waterflood Period-1972-80. Following the recommendations, water injection schemes were implemented in Fahud reservoirs. However, they failed to arrest either the pressure or oil production decline. Reassessment Period-1981-83. The poor performance of the waterflood led to a thorough review during which a number of thermal decay time (TDT) logs and tracer tests were conducted. It was concluded that because the reservoir rock was both fractured and oil-wet, recovery factors from waterflooding were low and could be substantially improved by reverting to full-scale gas/oil gravity drainage [5].

Horizontal wells in Fahud have in general been drilled in low offtake areas and at the same time replace gassed out vertical wells. Drilling of horizontal wells was started with short radius wells, drilled in 1984 and 1986. Side-tracking from existing wells was started in 1995 and slim-hole wells design was started in 1997, resulting in significant cost savings. Many side-tracked wells are distributed across the field and completed over various reservoirs in the field. Horizontal wells are contributing more than 80% of the total field production [6].

Water and gas production are the main challenges in the Fahud field. Although Fahud reservoirs have been on production over 50 years, early water and gas breakthrough from fractures are still one of the major production challenges significantly affecting oil production rate. Excessive water-gas production normally leads to lower oil production and poor fluid influx distribution across open hole horizontal section, in addition to by-passed oil and lower reservoir recovery. In the end excessive water-gas production will lead to wells being shut-in.

Autonomous Inflow Control Valves (AICV) completions can be considered an optimum completion solution to overcome the Fahud Assets reservoir and production challenges. AICV advance passive ICD technology to another level by making AICV valve smarter and hosting features of dynamic flow choking of unwanted phases (which is more comparable to intelligent completions flow control valves, yet the AICV does this without any control lines to surface. The AICV is a truly autonomous valves, as compared to the passive ICD (which cannot change it’s effective flow area to stop gas or water), the AICV technology has a robust, dynamic piston which can close and reduce the unwanted gas and water production by up to 95~98 %. AICV also has much better gas control performance over conventional ICD and AICD. For that reason, the Fahud Asset took the initiative to install AICVs within its asset in Oman to control wells gas and water production and allow increased oil production from previously stranded wells [2].

In this paper the AICV completed wells within Fahud field will be evaluate production performance by showing how reservoir and production challenges were overcome and how the wells oil production performance has enhanced, fluid influx balanced; less gas/water production and enhanced oil production.

Autonomous Inflow Control Valves (AICV@)

Passive Inflow Control Devices (ICD) were introduced to the market in mid-90's, to balance fluid influx across open hole section and control water production. ICD's have successfully demonstrated that they can delay the gas and/or water breakthrough in horizontal wells, but they cannot choke the gas production effectively after coning/breakthrough and limited for water production control.

Fig. (2) shows a pipe cross section with nozzle-based ICD completion, where the red arrows illustrate the fluids path. The fluid flows to the well, from the annulus via the sand screen and into the nozzle ICD. When the fluid flows through the small nozzle, pressure drop is generated as a function of fluid velocity squared, density, and geometry of the ICD. The pressure drop is almost independent of fluid viscosity. The nozzle size and then also the pressure drop for a specific fluid developed by the device is set prior to installation [7]. But once number/size of nozzle had been installed, it will remain constant flow area even if type of produced fluid changes – ***passive system***.

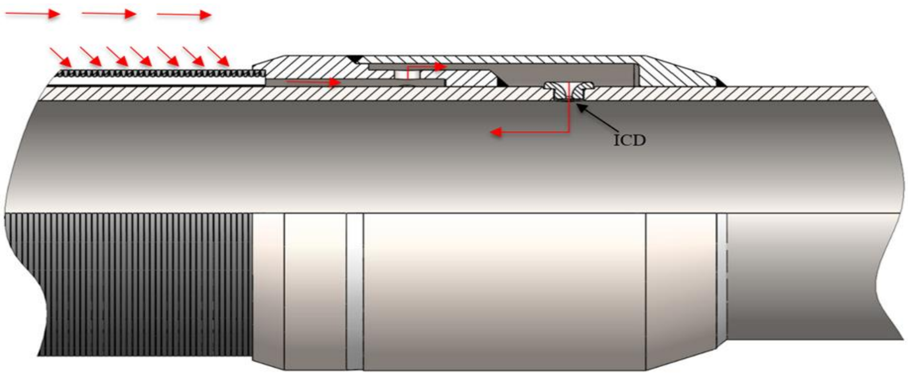

Fig 2: Flow into the sand-screen and through the nozzle ICD to inside tubing.

The pressure drop created by the nozzle is expressed by:

$$\Delta P = C \cdot \frac{1}{2} \cdot \rho \cdot v^2 \qquad (1)$$

where ΔP is the pressure drop across ICD, C is a geometrical constant, ρ is the produced fluid density and v is fluid velocity through the nozzle. Due to the density difference, the gas flow rate is significantly higher than the oil flow at the same differential pressure. For that reason, conventional ICD has no control on gas production.

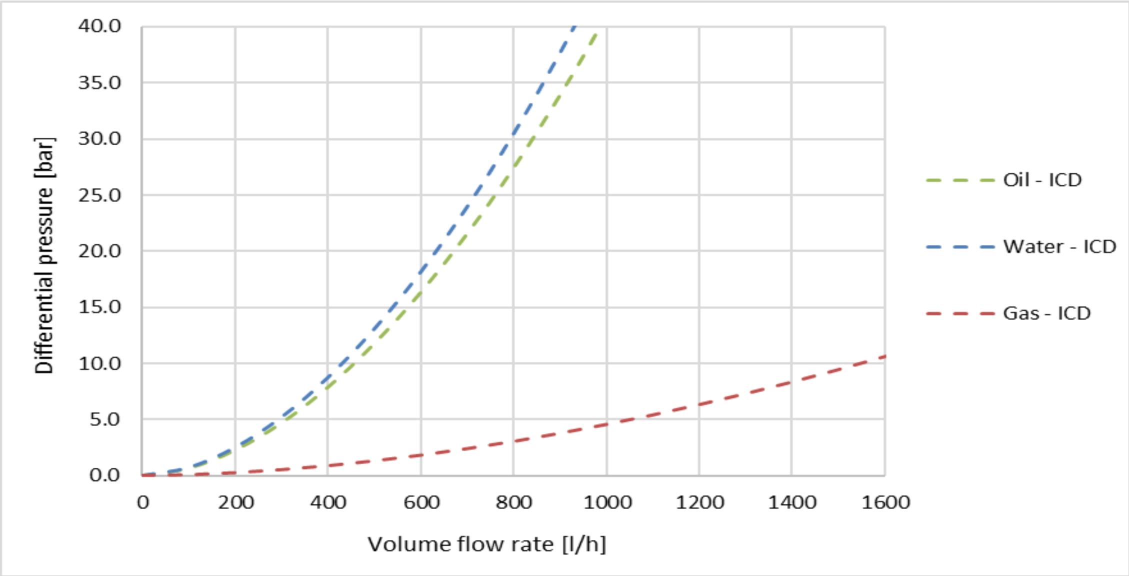

Fig 3: Performance curves of the nozzle ICD for oil, water and gas.

All passive ICDs has fixed flow area which limit adapting completion design in case of unexpected reservoir fluids saturation, pressure and permeability profiles is encountered. Also, after putting well on production and gas/water breakthrough, passive ICDs did not give a hand to control gas production as shown in Fig. (3) and only control water production to a certain degree and not complete water shut-off. The need of complete undesired fluid shut-off push to develop On/Off ICD type which is equipped with sliding sleeve. This type of On/Off ICDs enable operators to complete shut-off compartments which produce undesired fluids. Many factors limited the spread of On/Off ICDs application such as; PLT requirements to identify where gas/water is breakthrough, using Coil Tubing / Tractors with shifting tool to shut-off ICDs, in addition to the high Cost / Risk from operational point of view.

The need of Autonomous Inflow Control Device AICD become essential, where ICD can detect the type of produced fluid and have movable parts enables choking/shut-off ICD flow area when undesired fluids produced. There have been many attempts to develop AICD, the first generation of AICD which has movable parts working according to the type of produced fluid was first installed in 2007. The AICD developed by Statoil [1] is the Rate Controlled Production (RCP) valve. Fig. (4) shows fluids flow performance curve of an RCP compared to nozzle-based ICD, [2]. The flow rate of oil is equal for both devices. Due to the change in flow area for different fluids the flow rate of gas and water will be less for the RCP compared to the passive ICD type. The black arrows show the RCP improvement in the flow performance for gas and water compared to passive ICD. Due to lower flow for low viscous fluid, the gas flow rate will be lower than for the passive ICD. The improved flow performance curve for gas will reduce the well Gas Oil Ratio (GOR) [8].

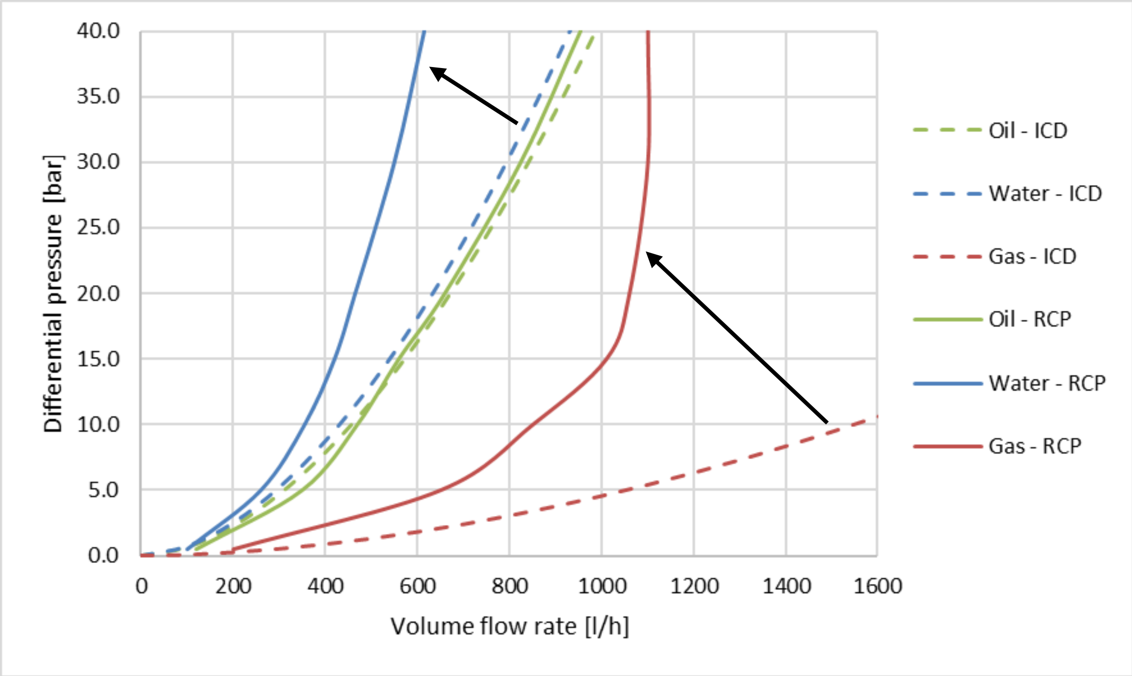

Fig 4: Performance curve of the ICD and the RCP for oil, water and gas [2].

The latest generation of AICD called Autonomous Inflow Control Valve (AICV) which can close completely for unwanted fluids. It is self-regulating, and does not require any form of control, electronic or connection to the surface. Based on the difference in the fluids properties as viscosity and density, the AICV has the feature to distinguish between the fluids, [9]. AICV performance curves compared to passive ICD one is shown in Fig. (5).

The AICV is designed to open for high viscous fluids and close for low viscous fluids. The functionality is controlled by a minor pilot flow path parallel to the main flow path, where approximately 2~5% of the total flow rate is going through. When the valve is closed, the minor pilot flow represents the total flow rate through the valve. Fig. (6) shows the main flow path in open and closed position respectively.

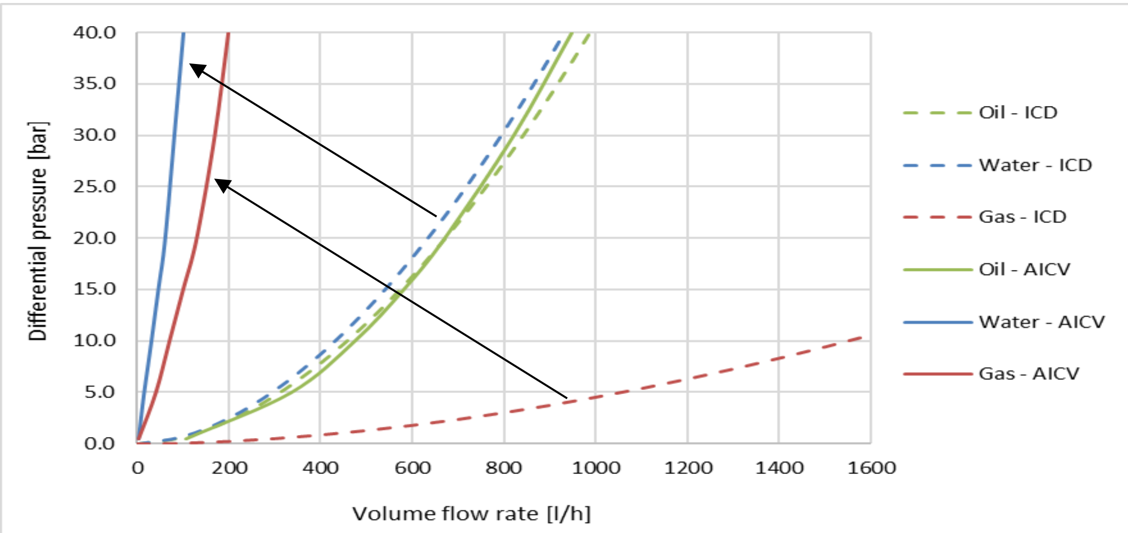

Fig 5: Performance curve of the ICD and the AICV for oil, water and gas, [2].

Pressure profile in pilot flow path is shown in Fig. (7) with expected pressure at different positions along the pilot flow for oil, water, gas or steam. When the pressure drop through the laminar flow element is high, as for oil, P2 is low and the valve will be in fully open position producing oil. For low viscous fluids, such as gas/steam, flow through the laminar restrictor causes lower pressure drop resulting to a higher P2. The high pressure will actuate the piston that will close the valve. For gas/steam and water choking or shut off applications a piston position that restricts or close low viscous fluids such as gas/steam is required. This can be achieved by modifying LFE, TFE and valve flow areas which creates different P2 pressure, different valve piston position and consequently different net forces acting on piston. Therefore, oil production can be easily adjusted by modifying different parts of AICV Fig (8).

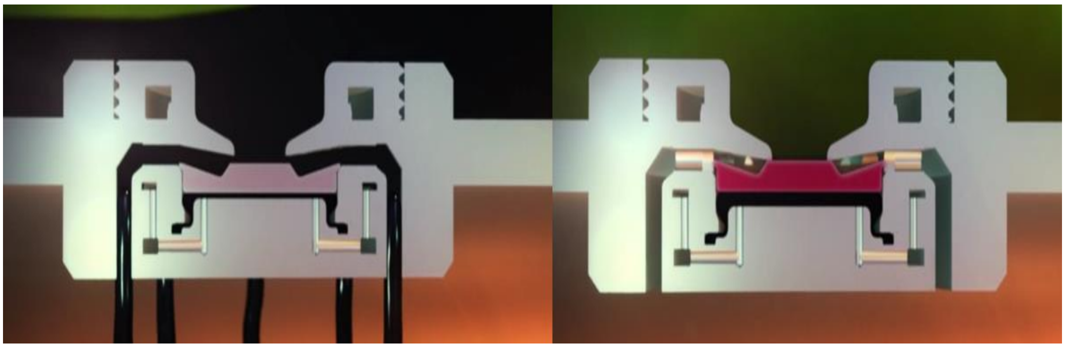

Fig 6: AICV in open (left) and closed (right) position

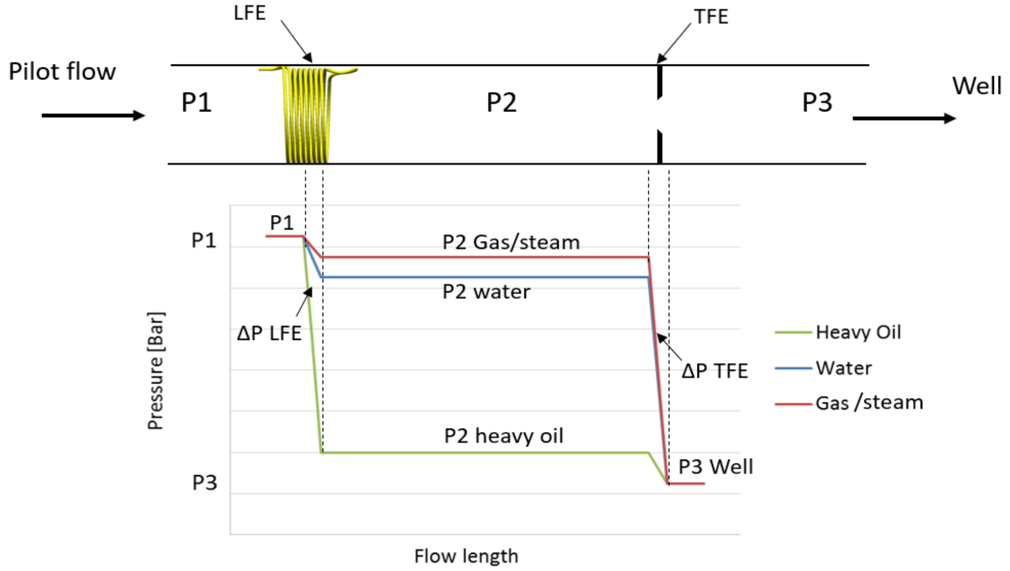

Fig 7: AICV pressure working envelope

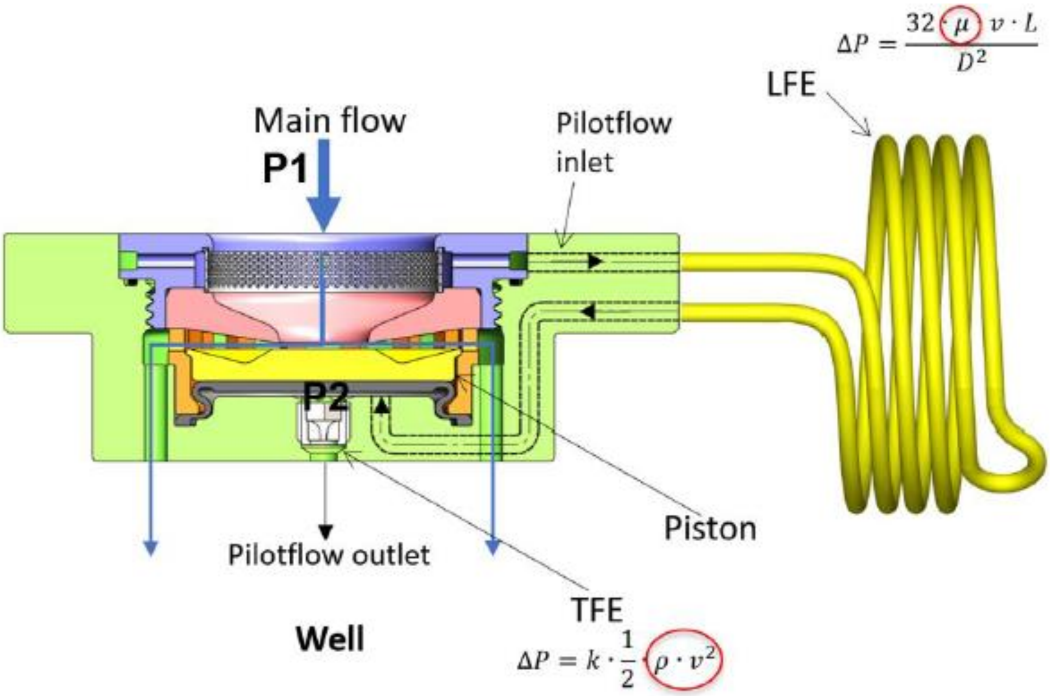

Fig 8: AICV – valve components

AICV completion design optimization

Every field and well have its own unique challenges, completion objectives, and limitations. Issues such as early water or gas breakthrough, unbalanced fluid production influx, downhole cross-flow, fractured reservoir, or surface process facility limitations are considered in the AICV completion design on a case by case basis. AICV completion design is critical for any development since it is the first Inflow Control completion technology which can autonomously provide complete water / gas shut-off without well intervention which is fully reversible also. It is also the first Autonomous Inflow Control Device which provides effective solution for high gas production and from reservoir management point of view, will enhance sweep efficiency and improve ultimate recovery of reserves.

The objectives of AICV completion in Fahud were as follows:

- Control / stop wells gas production, high GOR consumes reservoir energy and limits the well's oil production capacity.
- Control / stop wells water production.
- Balance the oil influx profile across the open hole section to delay early gas/water breakthrough and ensure that fluids contacts move evenly.

Traditionally, optimization of a passive ICD (fixed flow area) completion design is performed based on open-hole logs (gamma ray, porosity, density, resistivity, saturation) and reservoir parameters (derived permeability, relative permeability, and pressure-volume-temperature data). Any uncertainties in the data can result in flaws in the completion design. The degree of uncertainty in the data will impact the accuracy of the completion model results.

Since AICV has variable flow area, it is not a passive ICD type; it is a novel version of active ICD where the flow area autonomously adjusted according to compartment productivity and type of fluids passing through it.

AICV application decreases the risk of data uncertainty and its effect on completion performance, since the valve will autonomously adjust the flow area according to the new situation thus managing uncertainty. Also, AICV reduce the effect of completion malfunction if failed to be set in design depth.

The optimal AICV completion design resulting in limited free gas production, effective well water production control, minimal heel-to-toe effect and balanced inflow across the horizontal section in heterogeneous reservoirs is achieved by compartmentalizing the horizontal section with packers based on permeability, pressure, fluids saturation and viscosity variations and managing the pressure drawdown across the reservoir (P_r - P_{ann}) and across the completion (P_{ann} - P_{tub}).

At gas/water breakthrough in a compartment, AICV in this compartment starts to choke/reduce the flow area with increasing gas fraction or water cut as shown for water cut in Fig. (9). The valve has a reverse action. So, if fluid contacts get settled and oil accumulate around the valve again, it will re-open which helps to drain more oil from reservoir and enhance reservoir recovery factor.

In the well design process the number of AICV joints and compartments identified is an important simulation proponent. For passive ICD, the number of ICD joints or its flow area is critical because it cannot be changes once installed, and if it is over required – the benefit of using ICD completion will be decreased. In the other hand if it is less than required an extra pressure drop across completion will be generated (completion skin). AICV completion designer should ensure that number of joints can produce the required low capacity. The number of AICV joints should be slightly higher compared to passive ICD used for the same well.

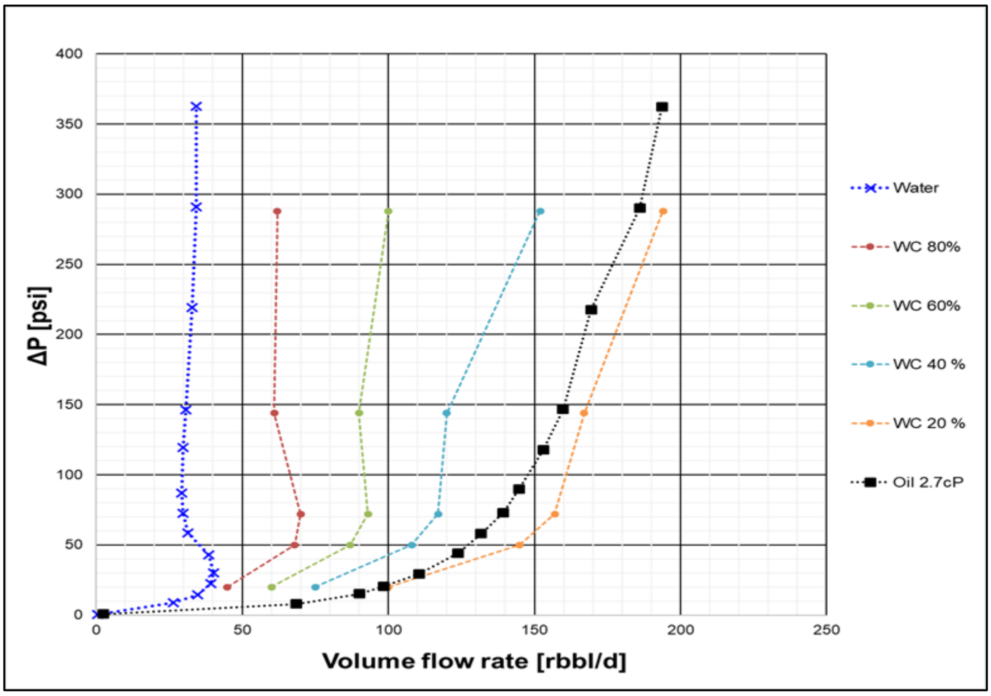

Fig 9: AICV® Performance curves for different water cut production

AICV completed wells: production performance analysis

At the time of this paper publication over twenty (20) wells had been completed in Fahud field using AICV completion to control gas and water production yet more are already planned to be deployed in addition. The Fahud Asset's typical 'default completion' design used to be a barefoot completion and there were also some cemented/-perforated wells and many pre-perforated liner completions. These types of completion did not provide any type of control to unwanted gas or/and water production, and when gas or water become in direct contact with fractures it progressed fast / direct to well bore thus gas and/or water would dominate the wells production preventing oil from being produced from somewhere else in the well due to higher gas or water mobility compared to oil.

The AICV completion proved to be a significant enhancement in reducing the un-wanted fluid production of gas and water in Fahud wells which it was deployed in. For most of the wells, the AICV completion also enhanced the wells oil production rate in parallel to reducing unwanted gas production.

The AICV managed to decrease the Fahud wells gas production by 38 ~ 86% and reach the ideal well performance shown as reference for Well-A in Fig. (10), when gas production reaches solution GOR.
Oil production in most of the wells was increased 56 ~ 61% thus achieving fantastic results as shown in well Well-B Fig. (11), where well oil production rate reaches 2.3 times the same before AICV completion installation. In case of water production; AICV completion significantly control water production such as in produced water wells for example in Well-A case water cut has controlled from 80% to 26%.

Well–A:

Well_A AICV completion had been installed for almost one year. 17 AICVs and 18 double packers (oil swell and water swell packers) had been used. Well_A production performance is shown in Fig. (10) before and after installing AICV completion. AICV completion manage to stop free gas production, control water production and increase well oil production rate.

- Reducing gas production to just solution GOR.
- Reducing water cut from around 80%, to 26%
- Increase well oil production rate (+ 56%).

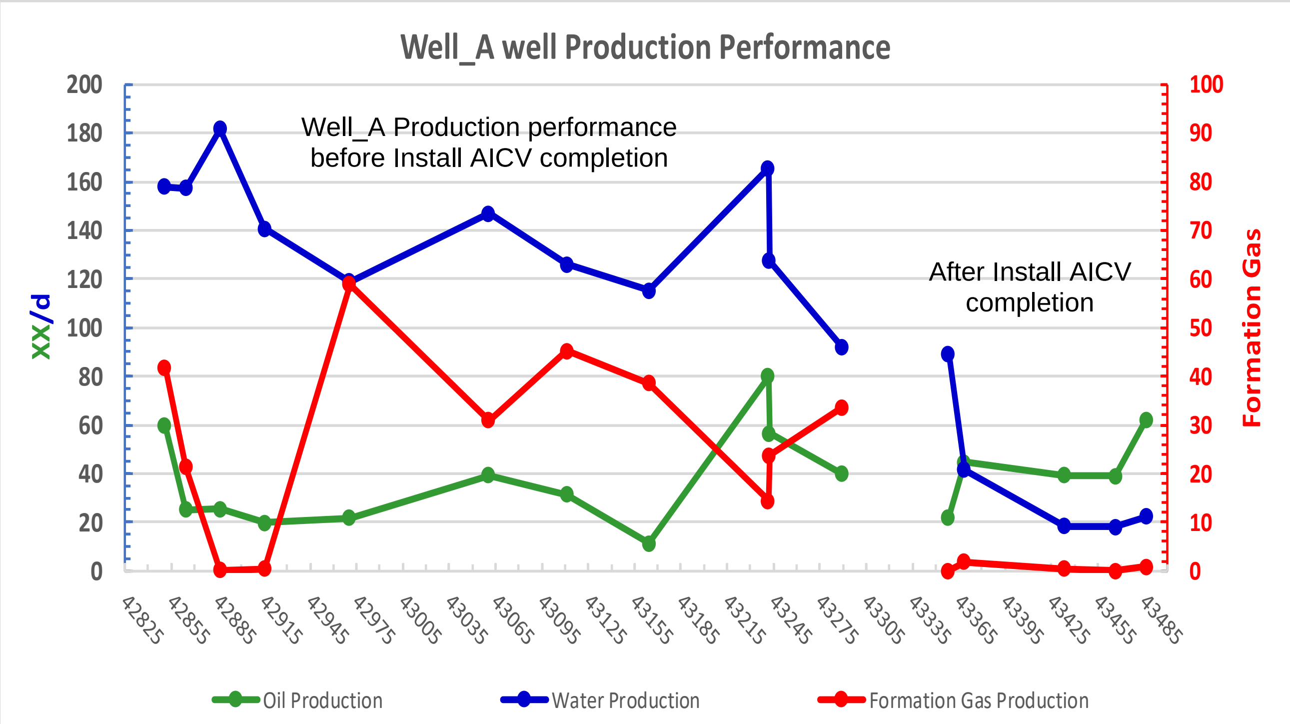

Fig 10: Well_A Production Performance before/after install AICV completion

Well–B:

Well_B AICV completion had been installed for more than one year. 17 AICVs and 18 double packers (oil swell and water swell packers) had been used. Well_B production performance is shown in Fig. (11) before and after installing AICV completion. AICV completion manage to significantly reduce free gas production, and increase well oil production rate.

- Reducing well total gas production by 83%.
- Gas production control allow to doubled Well oil production rate

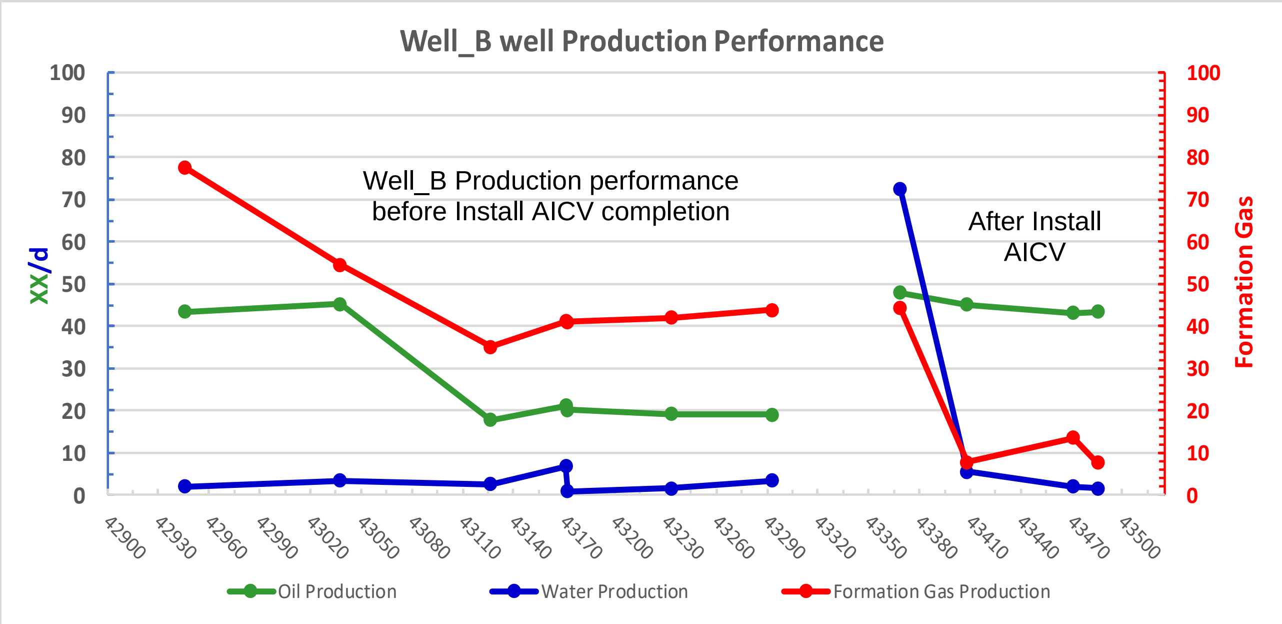

Fig 11: Well_B Production Performance before/after install AICV completion.

CONCLUSIONS

- The unique comparison of production data before and after installing AICVs shows documented benefits of installing autonomous inflow control.
- The results demonstrated the AICVs closing off zones with high gas production and favour oil rich zones.
- All the wells evaluated demonstrated clearly that the extremely high GOR (free gas production) was reduced and/or closed to solution GOR, and at the same time the daily oil production is increased.
- The application of AICV technology helped reduce operational risk as no further interventions were required to operationally try to control gas and also there was no need to run additional surveillance operations to identify the zones where gas breakthrough occurred as the AICV's autonomously handled the wells inflow based on the phases of flow at the sand phase, adjusting itself autonomously.
- The AICV technology extends the application of passive ICDs and makes it possible for operators to manage their assets which require -gas/water shut-off without well intervention and zero cost gas/water shut-off operation.
- AICV application allows operators with gassed over reservoirs to now produce more of the ROIP (remaining oil in place) thus increasing the economics of the field all without having to drill new wells, only applying retrofit completions for existing wells that suffer from high gas and/or water production.

ACKNOWLEDGEMENTS

The authors are grateful to Petroleum Development Oman (PDO) management, PDO Fahud Asset Team, and InflowControl AS for their support and contribution in this paper and allowing this work to be published. The application of AICV's by the PDO Fahud asset has proven a great milestone with the >20 wells deployed at the time of this paper, highlighting a low cost, unique solution to add additional oil production from the asset all without drilling new wells, thus extending the assets viability and total recoverability.

REFERENCES

1 V. Mathiesen, H. Aakre, B. Werswick and Geir Elseth, Statoil (2011) The Autonomous RCP Valve – New Technology for Inflow Control in Horizontal Wells, Aberdeen, UK, 6-8 Sept. 2011.

2 Anita B. Elverhøy, Haavard Aakre and Vidar Mathiesen, InflowControl, (2018). Autonomous Inflow Control for Reduced Water Cut and/or Gas Oil Ratio; Paper OTC-28860-MS; presented at the Offshore Technology Conference held in Houston, Texas, USA, 30 April–3 May.

3 V. Mathiesen, B. Werswick og H. Aakre, (2014). The Next Generation Inflow Control, the Next Step to Increase Oil Recovery on the Norwegian Continental Shelf. Paper SPE 169233, i SPE Bergen One Day Seminar, Bergen, Norway, 2 April.

4 R. H. Tschopp (Petroleum Development (Oman) Limited), 1967. Development of the Fahud Field. Paper WPC-12122; presented at the 7th World Petroleum Congress, 2-9 April, Mexico City, Mexico

5 Niel O, apos; Neill, (1988). Fahud Field Review: A Switch From Water to Gas Injection. Paper SPE-15691-PA published at the Journal of Petroleum Technology. Volume 40 Issue, publication date May 1988.

6 Shaikhan Al-Khodhori , (2001). The Challenges and Way Forward of Horizontal Dual Lateral Wells in Fahud Matrix Reservoir; Paper SPE-68204-MS; presented at the SPE Middle East Oil Show, 17-20 March, Manama, Bahrain

7 T. Ellis, A. Erkal, G. Goh, T. Jokela, S. Kvernstuen, E. Leung, T. Moen, F. Porturas, T. Skillingstad, P. Vorkin og A. G. Raffn, «Inflow Control Devices- Raising Profiles,» i Oilfield Review no.4, Schlumberger, Winter 2009/2010, pp. 30-32.

8 M. Halvorsen, G. Elseth og O. M. Naevdal, 2012. Increased oil production at Troll by autonomous inflow control with RCP valves. Paper SPE 159634. i SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 8-10 October.

9 H. Aakre, B. Halvorsen, B. Werswick og V. Mathiesen, 2013. Smart Well With Autonomous Inflow Control Valve Technology. Paper SPE 164348. i SPE Middle East Oil and Gas Show and Exhibition, Manama, Bahrain, 10-13 March.

10 Mohamed Said Al Salhi (Petroleum Development Oman) | Michiel F.J. Van Rijen (Petroleum Development Oman LLC) | Harm Dijk (Shell Intl. E&P Inc.) | Lingli Wei (Shell International Exploration). 2005. Structured Uncertainty Assessment for Fahud Field through the Application of Experimental Design and Response Surface Methods. Paper SPE-93529-MS, presented at the Middle East Oil and Gas Show and Conference, 12-15 March, Kingdom of Bahrain

11 Q. Zeng, Z. Wang, Y. Gang og J. Wei, «Selection and Optimization Study on Passive Inflow Control Devices by Numerical Simulation. SPE 167443,» i SPE Middle East Intelligent Energy Conference and Exhibition, Dubai, 28–30 October 2013.

12 H. Aakre, B. Halvorsen, B. Werswick og V. Mathiesen, «Increased oil recovery of an old well, recompleted with Autonomous Inflow Control Valve (AICV),» i ADIPEC 2013 Technical Conference, Abu Dhabi, 10-13 November 2013.