Evaluation of completing horizontal oil wells with inflow control devices

G. Abdurrahman, S. Eljareh.

(1 Faculty of engineering /University of Ajdabiya. 2 Faculty of engineering & Petroleum /University of Benghazi)

Abstract.

Oil production in horizontal wells currently has challenges such as excessive water production, which reduces the cumulative oil recovery, this occurs due to water coning in the reservoir which resulted to earlier water breakthrough in the wellbore. Various Down hole Flow control Devices (DFCs) including ICDs, AICDs, and AICVS are typically installed in the horizontal section of oil wells to mitigate the problem. The study of autonomous ICDs was done by comparing the long term flow performance of such devices against passive ICDs. The study was carried out with a reservoir model representing one horizontal well with three completion alternatives: open hole, ICD, and AICDs which were perforating in numerical reservoir model, these cases were run in the Eclipse simulator and their results were compared with the open hole. The results showed that the installation of Autonomous ICDs (AICDs) allowed producing more oil when compared against using passive ICDs. As it was found in three cases, for well X2, production with AICD increased the overall oil recovery by 257% and reduction of water cut to 42% as compared against an open hole completion, whereas production with ICD increased the overall oil recovery by 192% and reduction of water cut to 50% as compared against an open hole completion. The results proved that the installation of ICDs increased the net revenue comparing to open hole completion.

Key words: Inflow control devices, Horizontal wells.

الملخص:

إنتاج النفط في الآبار الأفقية يواجه عدة مشاكل أهمها الزيادة الكبيرة في إنتاج المياه المصاحبة حيث يؤثر على إنتاج النفط، العديد من الأجهزة المستخدمة في استكمال الآبار للتنقيط والحد من هذه المشكلة. في هذه الدراسة تم القيام بدراسة بين أجهزة التحكم في التدفق العادية والأجهزة المفتوحة من حيث معدل الإنتاج ونسبة المياه حيث تم بناء نموذج كمبيوتر بواسطة برامج البتل 2016 بتحري على برامج واحد مع تطبيق أنواع مختلفة من الاستكمال وهو الاستكمال المفتوح والاستكمال بواسطة اجهزة التدفق العادية وأجهزة التحكم في التدفق الذاتية. النتائج أظهرت إن استخدام أجهزة التحكم في التدفق الذاتية تساعب النتيجة كيف أكبر من النقط المفتوح للمقارنة مع الأجهزة العادية حيث وصلت نسبة الزيادة في الإنتاج بمعدل 257% باستخدام الأجهزة الذاتية ونسبة المياه خفضت إلى 42% بينما في حال استخدام الأجهزة العادية كانت نسبة الزيادة في الإنتاج 192% ونسبة المياه المنتجة كانت 50%. وظهرت النتائج أيضاً أن استخدام أجهزة التحكم في التدفق توفر الربح الصافي بالمقارنة مع استخدام الاستكمال المفتوح.
1. Introduction

1.1 Background

The challenges introduced by reservoir heterogeneity with horizontal wells tend to increase with increasing well length (Birchenko et al, 2011). Completions with long intervals often have significantly uneven specific inflow distribution along their length. These inflow variations cause premature water or gas breakthrough and should be minimized (Hallundbæk and Hazel, 2016). Advanced well completions have been demonstrated as solution to these challenges. Inflow Control Devices (ICDs) is an established type of advanced completion that provide passive inflow control (Henriksen et al, 2006). ICDs are widely used and can be considered to be a mature well completion technology. One of the challenges is the variation in rock properties.

Fluid specific inflow rate tends to increase with increasing well length (Krinis et al, 2009).

Inflow control devices (ICDs) were introduced during the 1990’s. ICDs are well completion devices which have been developed for the purpose of balancing fluid inflow along the wellbore and delay production of water and gas by introducing an extra pressure drop in the zones with low pressure drops. Figure (1) shows the inflow control devices.

![Figure (1): Schematic diagram of orifice ICD (Birchenko, 2010)](image)

1.1.1 Types of inflow control devices

There many types of ICDs which are used in the oil field depending on the manufacturer, and mechanism of performance. In this Thesis, the ICDs will be discussed based on their performance mechanism, including friction mechanism, restriction or combination of friction and restriction mechanism to generate pressure drop.

i. Channel-type (Helical channel) ICD

The channel-type ICD shown in Figure (2) is the type of ICD that uses surface friction to generate a pressure drop. The fluid flows through the channel type ICD by passing through the channel with a defined length, and then to the opening before entering the wellbore. The pressure drop in the channel type ICDs depends on the length of the channel and the diameter of the openings.
Figure (2): Helical-channel type ICD (Shevchenko, 2013)

**ii. Orifice/Nozzle type ICD**

Nozzle type ICDs shown in figure (3) provides the fluid restriction to generate a desired pressure drop. Fluid is forced to pass through a small opening (orifices) in a pipe to generate flow resistance. The pressure drop is generated due to the generated flow resistance.

Figure (3): Nozzle type ICD (Shevchenko, 2013)

**iii. Tube and Hybrid channel types of ICDs**

Tube-type is the type of ICD which combine the restrictive and friction mechanism to create the pressure drop as shown in figure (4). The hybrid channel is the type of ICD which combine the restrictive, some friction and a tortuous pathway mechanism to create the pressure drop of the fluid flowing through the device. These types of ICD combine the technology of Nozzle type ICD and channel types ICD in order to mix the advantages of all two types (Zeng, et al., 2013).

Figure (4): Section view of Tube type and Hybrid channel ICDs (Zeng, et al., 2013)

1.1.2 Autonomous inflow control devices

**i. ER-AICD type:**

The ER-AICD is the type of AICD which use the electrical resistivity mechanism depicted in Figure (5). The AICD has two flow paths, namely main flow path which most of the fluid is passing and secondary flow path. The secondary flow path contains a sensor which detects viscosity of the fluid and sends an electrical signal to a solenoid which has an electromagnetic effect to open the valve of the main flow path for highly viscous fluid such as oil and close valve of the main flow path for low viscous fluid such as water and gas.
The main disadvantages of ER-AICD are not working in the high temperature environment since they consist of electronics devices and valves which are affected by temperature.

ii. Fluidic diode type

The fluidic diode type AICD also is called Equi-flow AICDs. This kind of AICD does not contain a movable part; it is functioning depending on the changes of fluid properties (James, et al., 2017). It is functioning by directing different fluids to different pathways depending on the properties of fluids as shown in figure (6).

Important fluids properties for the AICD to operate are density, viscosity and flow rate. The inertial forces are created by densities and flow rates of the flowing fluids, whereas viscosities and flow rates create the viscous forces. AICD is working by balancing inertia and Viscous forces in the fluids.

iii. RCP-AICD

Figure (7) shows the RCP-AICD, another kind of AICD used to restrict fluids of low viscous fluid such as water and gas. The AICD uses the Bernoulli principle which is expressed in the following equation (1):

\[ P_1 + \frac{\rho v_1^2}{2} = P_2 + \frac{\rho v_2^2}{2} + \Delta P_{friction} \]  

(1)

The low viscosity fluid is passing through AICD with the higher speed than high viscous fluid. The higher speed of fluid causes the pressure at the flowing side of the disc to be lower compared against the pressure on the other side of the disc (Stagnant pressure). The pressure difference on these two sides causes the disc to move towards
the seats and reduce the flowing area. When the flowing area is reduced the unwanted fluid production (gas and water) will also be reduced.

Figure (7): RCP valve (AICDs) (Halverson, et al., 2012)

1.2 Objective of the study

The main objectives of this paper are to evaluate the viability and feasibility of completing the horizontal well with DFCs (ICDs and AICDs) by using Petrel 2016 software.

1.3 Significance

The water preferentially precedes in the form of a cone, as such its name. It yields associated problems of reduced efficiency of depletion mechanism, early abandonment of affected wells, reduced field recovery, reduced field profitability and an extra cost for handling produced water.

2 Methodology

2.1 Simulation model

The simulation was done using Petrel 2016.3 version and ran using the Schlumberger Eclipse 100 simulator. The main benefits highlighted by the simulations runs performed are the water breakthrough management and production optimization capabilities obtained by adopting Smart well Technology. The value proposition of the technology is measured using three key parameters; reduced water production, economic oil production rates.

2.2 Model description

The reservoir model is a carbonate reservoir based on the Libyan oil field located onshore in the north of Libya (Sirte basin). The heterogeneous properties of the model make it an ideal candidate for simulating intelligent well operations.

The reservoir is one region with a water oil contact (WOC) of 8450 ft. The average reservoir pressure is 3000 psi with initial water saturation of %35.

Table 1: Reservoir properties

<table>
<thead>
<tr>
<th>Field property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Dimensions</td>
<td></td>
</tr>
<tr>
<td>Model length (DX)</td>
<td>10000ft.</td>
</tr>
<tr>
<td>Model width (DY)</td>
<td>10000ft.</td>
</tr>
<tr>
<td>Reservoir top</td>
<td>8315 ft.</td>
</tr>
</tbody>
</table>
2.3 Fluid Properties Description

This section deals with fluids filling the reservoir rocks. Oil, gas and formation water properties are covered under pressure-volume-temperature section PVT, the black oil model is the most common where the oil properties such as formation volume factor Bo, solution gas oil ratio Rs and oil viscosity. Table(2) explains PVT properties.

Table 2: Reservoir fluids properties

<table>
<thead>
<tr>
<th>Volume factor (RB/STB)</th>
<th>Oil gravity (API)</th>
<th>Saturation pressure psi</th>
<th>Solution GOR (SCF/STB)</th>
<th>Oil viscosity</th>
<th>Water viscosity</th>
<th>GOR @bubble point (scf/stb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.262</td>
<td>35.5</td>
<td>2450</td>
<td>1.4</td>
<td>0.48</td>
<td>500</td>
</tr>
</tbody>
</table>

2.4 Well geometry

Table (3) Well geometry

<table>
<thead>
<tr>
<th>Initial completion</th>
<th>6/4/2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well datum (ft.)</td>
<td>8380</td>
</tr>
<tr>
<td>Horizontal section (Open hole) (ft.)</td>
<td>8806-11002</td>
</tr>
<tr>
<td></td>
<td>6 ( \frac{1}{8} )</td>
</tr>
</tbody>
</table>
2.5 Simulation cases

i. Without ICD completion

The second simulation run was performed to model the reservoir behavior without intelligent technology. In this case, the wells were operated under the same constraints as the base case model. However in addition, the producers were set to a maximum water cut of 50%. Production started in September 2019 to January 2029 to predict the behavior of wells without any ICDs.

ii. With ICD completion

Unlike the historic case and without ICD case, the intelligent modifications employ down hole control of each segment. The goal is to optimize production by accelerating and maximizing oil production, while minimizing water production. Down hole control was simulated by installing the Inflow Control Devices (ICDs), as shown in figure (8).

iii. With AICD completion

In this case AICD completions were run instead of nozzle ICDs as shown in figure (9) and many parameters were changed to compare the results with nozzle ICDs.
3. Results and discussion

In this simulation, the effect of ICD completion on oil, water production was investigated. Also, a base case without ICD completion was considered as reference. Results of interest are the relation between oil and water production and well completion strategies.

i. Without ICD case (open hole completion)

- **Oil production**

  Oil production was very low and reached to 100STB/D as shown in figure (10).

![Figure (10): Oil production for well X2](image)

- **Water cut & production**

  Water cut was high and reached to about 98% and more water was produced as shown in figure (11) and the water production rate was high as shown in figure (12).

![Figure (11): Water cut for well X2](image)

![Figure (12): Water production for well X2](image)

ii. with ICD completion

- **Oil production**
Oil production was optimized and increased to 900 STB/D with ICD completion comparing with open hole completion as shown in figure (13).

- **Water cut & production**

  The performance of ICDs was expressed by the restriction of water inflow in the wellbore. Figure (14) shows the results of produced water (WC) Water cut decreased to 50% where the water production decreased.

iii. With AICD completion case

i. **Oil production**

  Oil production rate was successfully increased to 1200 STB/D and optimized with AICD completion as shown in figure (15).
ii. Water production & water cut

The performance of AICDs was expressed by the restriction of water inflow in the wellbore. The results of produced water (WC) Water cut decreased to 40% where the water production decreased as shown in figure (16).

![Water cut for well X2](image)

Figure (16): Water cut for well X2

4.5 Economic impact of DFCs on the horizontal well

Economic impact of DFCs on the horizontal well was evaluated according to the cumulative increase of produced oil then calculate the net revenue. This evaluation was done by comparing the revenue obtained from the increased oil due to ICDs and AICDs completion and the cost of the devices as shown in equation (2). The oil price and cost of ICDs used to evaluate the Net revenue are shown in Table 4-3, as discussed in chapter three where as the net revenue is:

\[
\text{Net revenue} = (P \times \Delta q) - \text{CDFCs} \quad (2)
\]

Where \( P \) is the oil price, \( \Delta q \) is the oil increased due to DFCs installation, and CDFCs is the cost of ICDs.

The sensitivity analysis on the oil price was done so as to overcome the uncertainty of the oil price which is changing regularly, so the oil price was increased and decreased by 40% as shown in Table (4).

| Table (4): Parameters for economic evaluation |
|----------|----------|----------|-----------|
| **Name** | **Unit**  | **Value** | **Reference** |
| Oil price per bbl. | USD | 43 | Oil price.com 2020 |
| Cost of ICD per joint | USD | 28000 | (Nnakaihe, et al., 2017) |
| Cost of AICD per joint | USD | 33000 | (Halliburton ,2019) |
| Price variation (uncertainty) | USD | assumed | 40% |
| DFCs Price variation (uncertainty) | 10% | assumed | |

Table (5) shows the results for the completion where the installation of ICDs in the X2 well resulted to the increase of cumulative oil production by 159326 STB after one year when compared against the open hole, whereas the installation of AICDs
resulted to the increase of cumulative oil production by 272236 STB when compared to the open hole.

**Table (5)** shows results of the increase of cumulative oil production

<table>
<thead>
<tr>
<th>Date</th>
<th>Oil increment by AICD (STB)</th>
<th>Oil increment by ICD (STB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>272236</td>
<td>159326</td>
</tr>
<tr>
<td>2021</td>
<td>575451</td>
<td>383825</td>
</tr>
<tr>
<td>2022</td>
<td>918535</td>
<td>658071</td>
</tr>
<tr>
<td>2023</td>
<td>1287258</td>
<td>958385</td>
</tr>
<tr>
<td>2024</td>
<td>1672378</td>
<td>1271459</td>
</tr>
<tr>
<td>2025</td>
<td>2058432</td>
<td>1588966</td>
</tr>
<tr>
<td>2026</td>
<td>2443943</td>
<td>1909128</td>
</tr>
<tr>
<td>2027</td>
<td>2826465</td>
<td>2231819</td>
</tr>
<tr>
<td>2028</td>
<td>3205502</td>
<td>2559295</td>
</tr>
</tbody>
</table>

Table (6) shows the results for the completion with oil prices around 40 USD, where the installation of ICDs in well resulted to revenue by USD 4.3 million after one year when compared against the open hole, whereas the installation of AICDs resulted to revenue by USD 8.6 million when compared to the open hole. Where the installation of ICDs in well resulted to revenue by USD 2.14 million after one year when compared against the open hole, whereas the installation of AICDs resulted to revenue by USD 4.8 million when compared to the open hole with oil prices around 26 USD. Where the installation of ICDs in well resulted to revenue by USD 6.9 million after one year when compared against the open hole, whereas the installation of AICDs resulted to revenue by USD 13.1 million when compared to the open hole with oil prices around 56 USD.

**Table (6)** Shows net revenue by different oil prices

<table>
<thead>
<tr>
<th>Date</th>
<th>Revenue by AICD (40 $)</th>
<th>Revenue by ICD (40$)</th>
<th>Revenue by AICD (56 $)</th>
<th>Revenue by ICD (56$)</th>
<th>Revenue by AICD (26$)</th>
<th>Revenue by ICD (26$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>8689474</td>
<td>4373059</td>
<td>13045264</td>
<td>6922283</td>
<td>4878158</td>
<td>2142488</td>
</tr>
<tr>
<td>2021</td>
<td>20618058</td>
<td>13153021</td>
<td>29825282</td>
<td>19294229</td>
<td>12461738</td>
<td>7779463</td>
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<tr>
<td>2022</td>
<td>34141403</td>
<td>23922853</td>
<td>48787965</td>
<td>34451995</td>
<td>20981912</td>
<td>14609854</td>
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<tr>
<td>2023</td>
<td>48590340</td>
<td>35635430</td>
<td>69086476</td>
<td>50969602</td>
<td>30168721</td>
<td>21118029</td>
</tr>
<tr>
<td>2024</td>
<td>63895146</td>
<td>47958366</td>
<td>90353204</td>
<td>68301712</td>
<td>39781845</td>
<td>30057938</td>
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<tr>
<td>2025</td>
<td>79037303</td>
<td>60458673</td>
<td>1116722225</td>
<td>85882143</td>
<td>49519247</td>
<td>38013137</td>
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<tr>
<td>2026</td>
<td>94157722</td>
<td>73065152</td>
<td>132860811</td>
<td>103411213</td>
<td>58942519</td>
<td>45837349</td>
</tr>
<tr>
<td>2027</td>
<td>109058600</td>
<td>85772760</td>
<td>153782040</td>
<td>121081864</td>
<td>68488090</td>
<td>53827294</td>
</tr>
<tr>
<td>2028</td>
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<td>98171800</td>
<td>174708154</td>
<td>139220520</td>
<td>78043071</td>
<td>62141670</td>
</tr>
</tbody>
</table>
4. Conclusion

- Reservoir model with a horizontal well (X2) has been built by Petrel 2016 and run in the Eclipse simulator for different completions including the open hole and ICDs completion.
- The installation of DFCs (ICDs, and AICDs) in the horizontal well increased the oil recovery (RF) significantly, however the installation of Autonomous ICDs (AICDs) in the horizontal well perforating the oil reservoir increased more oil when compared against the passive ICDs, and this had been proved by the results of the reservoir model.
- Well X2 whereby producing with AICDs completion increased the RF by 257% when compared against the open hole completion, while producing with the ICDs completion increased the RF by 192% when compared against the open hole completion.
- Well X2 in which after nine years open hole had a WC of 95%, a well completed with AICDs had a reduction to 42% WC, and a well completed with ICDs had a reduction to 50% WC when compared to the open hole.
- Installation of ICDs in well resulted to revenue by USD 4.3 million after one year when compared against the open hole, whereas the installation of AICDs resulted to revenue by USD 8.6 million when compared to the open hole when oil prices was 40USD.

Figure (17): Oil production of well X2

Figure (18): Water cut for well X2
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