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A Stochastic Approach for evaluating where On/Off Zonal Production Control is efficient.

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Abstract

Intelligent wells offer an efficient downhole completion able to increase oil production and reduce water or gas production, and to mitigate the unwanted fluid breakthrough thus reducing the production uncertainty. The flexibility of down-hole, active flow control allows field development optimisation on a day-by-day basis without costly and time consuming well intervention operations. The installation of On/Off, interval control valves (ICVs) is a simple and effective example of an active intelligent well (IW) completion. Many IW completions employ On/Off ICVs because they are efficient, (relatively) cheap and are more reliable than the more complex infinitely variable or multi- position, discrete ICVs. A clear understanding of the area in which On/Off ICVs provide sufficient zonal control will allow reducing a project’s capital investment while minimising possible future risks of production loss.

This paper provides a stochastic, Monte-Carlo simulation-based approach for identifying the application area of On/Off ICVs by analysing how the completion performance is affected by changes in the inflow over a broad range of zonal reservoir and fluid properties such as
productivity index, water cut, gas-oil ratio and layer pressure. The analysis confirms that On/Off control provides an optimal solution for the wide range of reservoir and fluid properties when the well is being produced by natural flow or gas-lift and the instantaneous oil rate maximisation is the control objective. It also shows that a multi-position valve is marginally better only in the cases of an intelligent well producing from multiple reservoirs with significantly different zonal pressures or gas-oil ratios. Let alone it is uncommon to have accurate, zonal water cut measurements which are required to take advantage of the better performance of multi-position ICVs.

This paper confirms that On/Off control strategy has a wide application area where it achieves the maximum, or near maximum, instantaneous oil rate value. It also provides guidelines for identifying whether On/Off ICVs are applicable in a particular case. The resulting methodology can thus be used to guide informed choices on the ICV completion types.

Highlights

- We critically review the intelligent well (I-well), downhole flow control options
- We propose a fast, analytical method of modelling intelligent well performance
- We propose and verify a fast, robust, optimal I-well control method
- We compare statistically the applicability of various I-well completion options
- We propose applicability criteria for the most reliable I-well completion option
Keywords

Intelligent Well; Smart Field; Inflow Control Valve; Well Completion Optimisation; Well Flow Performance Modelling

1. Introduction

Intelligent wells have a wide application area and showed benefits in a number of field cases since 1997, when the first intelligent well was drilled in the Snorre field (Skarsholt, Mitchell et al. 2005). Examples of the IW successful application include increased oil production due to optimal downhole control (Akram, Hicking et al. 2001, Glandt 2005), commingled production from several layers (Jackson-Nielsen, Piedras et al. 2001, Glandt 2005), successful oil rim developments (Sinha, Kumar et al. 2001, Jansen, Wagenvoort et al. 2002, Skilbrei, Chia et al. 2003) and sweep efficiency improvement (Sigurd 2000, Arenas and Dolle 2003, Abduldayem, Shafiq et al. 2007).

All these results have been achieved due to the inherent flexibility of an intelligent well’s zonal production or injection.

Active controlled ICVs can be divided into three types:

1. On/Off valves with only two positions: fully open or fully closed.
2. Discrete valves with a fixed, normally 10 or fewer, number of positions.
3. Infinitely variable valves which can have any position between fully open and closed. These valves provide the most flexible control.
ICVs may be controlled from the surface using hydraulic, electric or combined hydraulic-electric control elements. All control strategies can be divided into two main types: “proactive” and “reactive” (Ebadi and Davies 2006). “Reactive” optimization requires the IW to respond to the actual well flow performance, e.g. by controlling actual zonal flow rates. The advantage of this approach is that it requires only the instantaneous production data and does not require knowledge of the inter-well geological properties. By contrast, a “proactive” strategy can change the invading front’s behaviour; delaying the unwanted fluid’s breakthrough and increasing the sweep efficiency. A “proactive” strategy can thus be more beneficial than a “reactive” one, giving an increased total oil production. However, it is difficult to apply to a realistic, full-field model since the computational time required for proactive optimisation is high.

Reservoir uncertainty is a second challenge for the proactive optimisation strategy. This strategy requires selective zonal control to start early in the well’s or field’s productive life. If effective, this choking may delay the breakthrough of unwanted fluids; but it may also lead to a decreased early oil production.

The accuracy of the initial reservoir simulation model will also strongly influence the total oil production achieved. For example, an inappropriate (early) choking strategy based on an inaccurate model can lead to a decreased oil production and an earlier breakthrough of an (unwanted) fluid. A control strategy based on a model which is inaccurate is likely to give a non-optimum production control strategy.

In addition, the discount coefficient used in NPV calculations reduces economic benefit of the proactive strategy. The later extra oil produced may be worth less than the early-time production loss; even if the proactive control increases the recovery factor.

Instantaneous, reactive control strategy is therefore the most widely used one.

On/Off ICVs powered by a hydraulic control element is the most reliable and cost efficient combination for such active flow control. Zandvliet et al. (Zandvliet, Bosgra et al. 2007, Zandvliet 2008) demonstrated that the On-Off solution is only slightly suboptimal for the
water flooding optimisation problem, but can still be regarded as optimal from a practical point of view. However, their result strongly depends on the particular case being studied and the chosen input parameters.

In this paper we aim to investigate the application of the active production control at different conditions and provide answers to the following questions:

- At which conditions do On/Off valves provide maximum instantaneous oil production?
- What is the range of the cases where On/Off valves provide optimal reactive control?
- What is the loss associated with On/Off valves if they do not achieve maximum instantaneous production?
- How to identify if On/Off valves are sufficient for a particular case?

2. **IW Methodology Adopted in This Study**

The objective function and constraints of production optimisation vary from one case to another. Maximum revenue is often the aim of the operator, while maximisation of the oil production and recovery factor is normally a subject of a government consideration.

Instantaneous oil rate is a subject of the optimisation in our study and often leads to close to the maximum values for both revenue and recovery factor in a liquid production case with no free gas in a reservoir.

Maximisation of oil rate during the plateau period is relatively simple: wells and intervals with the highest water rate should be choked. An after plateau period is normally the longest period of the field production live while the wellhead pressure often becomes a main constraint. In our study we will focus on oil rate optimisation during this period.
We will answer the above listed questions by modelling ICV performance for a specified range of cases covering a wide spectrum of production scenarios. Theoretically, the number of all possible variants is infinite. Hence our analysis must be reduced to a feasible number of cases without distorting the general conclusions.

The wells considered in this study have:

- The length of production interval much less than the total well length;
- Liquid production at the downhole conditions;
- Linear, liquid inflow performance relationship for each well zone;
- Pressure constrained production.

2.1 **IW modelling**

Consider a production well with N zones completed with ICVs. The well is controlled by a constant well head pressure (WHP). The inflow into the tubing is controlled by ICVs (Figure 1). The new liquid production rate, or operating point, after choking some of the ICVs is given by:

\[
Q_{\text{new, liquid}} = Q_{\text{liquid, open}} - \Delta Q_{\text{liquid, choked}} + \Delta Q_{\text{liquid, friction, completion}} + \Delta Q_{\text{liquid, gravity, completion}}
\]  

(1)

where \( Q_{\text{liquid, open}} \) is the liquid rate when all chokes are fully open.

\[
\Delta Q_{\text{liquid, choked}} = \sum_{i=1}^{N} (1-a_i) Q_{i,\text{liquid, open}}
\]  

(2)

where \( \Delta Q_{\text{liquid, choked}} \) is the change in the liquid rate of zone \( i \) due to the additional pressure drop across the ICV and \( a_i \) is a coefficient varying from 0 (when the ICV is fully closed) to 1 (the ICV is fully open). \( N \) is the number of zones, each of which is separately controlled by an ICV.
\[ \Delta Q_{\text{BHP}}^{\text{Liquid}} = \sum_{i=1}^{N} J_i \cdot \Delta P_{\text{BHP}} \] is the change in the liquid production in the fully open zones due to a change in the bottom hole pressure when the density of the fluid components changes; where \( \Delta P_{\text{BHP}} \) is the change in the bottom hole pressure and \( J_i \) is the productivity index of zone \( i \).

\[ \Delta Q_{\text{friction, completion}}^{\text{Liquid}} = \sum_{i=1}^{N} J_i \cdot \Delta P_{\text{friction, } i} \] - is a change caused by friction pressure changes in downhole completion area (at production interval);

\[ \Delta Q_{\text{gravity, completion}}^{\text{Liquid}} = \sum_{i=1}^{N} J_i \cdot \Delta P_{\text{gravity, } i} \] - is a change due to density changes in downhole area.

\[ i \in \{1..N\} \] – number of the production zone / ICV

In vertical wells the thickness of the perforation intervals is much smaller than the total well’s length from a well head and these two components: \( \Delta Q_{\text{gravity, completion}}^{\text{Liquid}} \) and \( \Delta Q_{\text{friction, completion}}^{\text{Liquid}} \) are relatively small. Therefore, equation 1 can be written as:

\[ Q_{\text{new}}^{\text{Liquid}} \approx Q_{\text{Open}}^{\text{Liquid}} - \Delta Q_{\text{choked}}^{\text{Liquid}} + \Delta Q_{\text{BHP}}^{\text{Liquid}} \] (3)

The well outflow performance will define the BHP change due to the ICV(s) operation. This performance cannot be generally approximated by a simple formula, but has to be modelled using complex, multi-phase flow correlations. We therefore need to model a theoretically infinite number of well cases to be able to evaluate the performance of various types of zonal control. We apply two approaches to make this task feasible:

1. We develop an approach to acceptably represent the inflow performance of a well with 3 or more zones as a 3-zone well. This will be described in the next section.

2. We use Monte-Carlo simulation to model only a statistically representative ensemble out of all possible well cases with the wide range zonal and fluid properties. The range and distributions of the properties is described below.
2.2 Reduction of a Number of Realisations

2.2.1 Partially Choked Zones

The number of realisations becomes infinite if valve positions of non-operating zones have any intermediate value. Such situation may be replaced with the case where all non-operating valves are fully open.

Statement 1

If the maximum oil rate is achieved at partially choked positions for several valves, there is a corresponding case, were all valves are fully open except one valve which should be partially choked.

The proof of this statement can be found in Appendix A.

Based on this statement we need only investigate cases with one operating valve; the other valves being fully open.

2.2.2 Converting the performance of a well with more than 3-Zones into an equivalent 3-Zone well

We have shown that it is necessary to control only one zone, with any other zone(s) being either fully open or closed, to maximise instantaneous oil production. According to equation 3, the well’s liquid production after choking one ICV (numbered as ICV1) can be expressed as:

\[
Q_{\text{new, liquid}} = a Q_{1, \text{liquid}}^i + \sum_{i=2}^{N} dP_i \cdot J_i + \sum_{i=2}^{N} J_i \cdot \Delta P_{\text{BHP}}
\]

(4)

where \(dP_i\) is a drawdown in layer \(i\).
The water cut and GOR of the other zones (i.e. Zones 2-N), whose performance is described by the second and third terms in the right-hand side of this equation, do not depend on the ICV1 position. They are constant at any ICV1 position providing there is no cross flow between the zones. The composite inflow performance of these N-1 zones for a given BHP value can be described by as little as 1 or as many as N-1 zones due to the linearity of their individual inflow performances. We aim to describe them by as little number of equivalent zones as possible to simplify the well control problem while also keeping acceptable representation accuracy in the vicinity of the given BHP value. Appendix B provides a detailed explanation of how to describe N-1 fully open zones by as little as two equivalent zones with an acceptable accuracy. There is no need to increase the number of equivalent zones, while representation of N-1 fully open zones with one equivalent zone is not possible if the representation conditions listed in Appendix B are to be met. The algorithm shown in Figure 2 can be used to convert any number of zones into 3 zones (i.e. 1 zone with a controlled ICV and 2 equivalent zones to represent the rest, fully open zones) so as to simplify well modelling when achieving the particular objective in this study: maximising instantaneous well oil rate.

Note that the above representation of a multiple-zone well with a 3-zone well has to be done at each optimisation time-step, followed by the instantaneous oil optimisation routine (explained below) at this time-step. As the fluid and reservoir properties change during the well production life, the 3-zone well representation will also be changing reflecting the production dynamics.
A Case Study

The application of the algorithm is demonstrated with a case study where an example well with 5 zones will be converted into 3 equivalent zones. The reservoir and fluid parameters are summarised in Table 1. Productivity indexes, reservoir pressures, water cuts and gas-oil ratios are different in this case; while the oil density is assumed to be the same for all zones. This assumption is caused by technical limitation of the commercial software used for this analysis. This software is currently unable to assign different PVT properties of fluid properties for different layers. However, this is not a strong limitation in practice since the commingled production from reservoirs with significantly different PVT properties is uncommon.

The algorithm was implemented in an Excel spreadsheet for calculation of the parameters required when describing any number of zones with the 3-zones equivalent. Zone 1 is the operating zone with the highest water cut and so it will be controlled, hence its parameters are left unchanged. All other zones were amalgamated into the 2-zone equivalent. The result is summarised in Table 3.

Weatherford’s Wellflo software was used to model both scenarios. The choke position of zone 1 is simulated using different productivity indices for this zone from 0.01 (fully closed) to 104 (fully open). The difference in the liquid rates, oil rates and GOR for a naturally flowing well for both scenarios as a function of the choke position is shown in the Figure 3.

The difference is negligible, being less than 0.1% for all parameters. Therefore, the 3 layer case accurately describes original 5 layer model for the given BHP value. The same analysis was done for production employing both Gas Lift and ESP. A gas injection rate of $70 \times 10^3$ sm$^3$/day for the gas-lift case was chosen, since this value provided the technical maximum oil production for the original case with fully open ICV’s (Figure 4).
In ESP case pump was chosen and optimised to cover the whole production interval depending on the choke position (Figure 5).

The maximum difference from the original case for all scenarios is summarised in Table 3. For all cases the absolute difference from the original value is less than 0.1%; implying that the 3-zone well sufficiently accurately described the original 5-zone case (note that this small mismatch can also be caused by numerical errors, rounding the input values of water cut and GOR for the 3 zones and the small difference in pressures that inevitably occurs along the length of the completion).

This case illustrates that it is reasonably accurate to model a multi-zone well as a 3-zone well for the sake of the optimisation problem discussed in this paper.

3. Input Data

The following parameters were used for the analysis:

Well:

- Deviated well; MD = 2750 m, TVD = 2300 m (Figure 6)

- Tubing diameter – 5.5 inches (0.14 m);

PVT Properties:

Oil Gravity = 845 kg/sm³

Gas Gravity = 0.9 kg/m³

PVT Correlations:

- Standing (FVF, Pb)

- Beggs et al (viscosity)

Reservoir Parameters:
Productivity Index: 2 - 231 m³/day/bar

WC: 0 - 100%

Reservoir Pressure: 150 - 250 bar

GOR: 9 - 585 m³/m³

Both natural flow and gas lift well production scenarios were investigated. The THP was fixed at 10 bar.

The modelling workflow is summarised in Figure 7. Commercial well modelling software was used to model well outflow performance for various water cuts and GORs used in the well production system.

Statistical approach has been used to investigate application area of on/off control.

4. Statistical Approach

As mentioned above, it is impossible to model all the possible combinations of reservoir and fluid properties in a multi-zone well in order to evaluate the zonal control types’ applicability. We use here a Monte-Carlo simulation with uniformly distributed fluid and zonal properties to sample a statistically representative ensemble of combinations (models). The productivity index, WC, reservoir pressure and GOR were uniformly distributed for 2- and 3- zone well cases with the following range of parameters:

The selected range of properties covers a wide range of oil fields and can be extended or changed if required.

An example of input parameters for 3 zones case is shown in Table 5:

The results were analysed under the following headings:

- [No On/Off] - percentage of cases where On/Off does not give maximum oil production
- **[Diff]** – average difference from the optimum for the cases where On/Off does not give the maximum oil production rate (Figure 8)

Note that the resulting percentages will be generally speaking specific to the case study specification and the input distributions. The qualitative conclusions, however, are expected to be general.

The use of a statistical approach implies that the result will more accurately represent the total assembly of all cases as the number of analysed cases increases. Figure 9 shows how the [No On/Off] value depends on the number of cases calculated. The variation decreases then stabilises with the increasing number of calculated scenarios.

This behaviour is explained by *Central Limit Theorem* theory (Cramer 1946). The relationship between the number of cases and stochastic error is explained in Appendix C.

Figure 10 shows how the statistical error reduces with the number of cases. For the sample of 10,000 cases the maximum error for [No On/Off] is 5% and for [Diff] is about 10%, which implies that for all possible here scenarios the fraction of cases where On/Off ICVs are unable to deliver the maximum instantaneous oil rate is $10\% \pm 0.5\%$ with 95% certainty.

Table 6 shows that statistical error for 10,000 realisations is small for all four considered completion scenarios. We have thus used a sufficient number of cases to describe all possible scenarios for the chosen intervals.

5. **Results**

5.1 **On/Off Control Application Area**

On/Off control strategy delivers maximum oil production in approximately 90% of the cases in all our scenarios (Table 7).
Figure 11 shows that, even if the value provided by the On/Off ICV is not optimal, the difference from the maximum oil production is less than 1% for most cases. Therefore, the practice of using On/Off valves may be still feasible; even if they do not provide the absolute optimal value.

The next important question is how to identify for a particular case if the On/Off ICV is sufficient or whether the more complex discrete position or infinitely variable ICV completion is required. We will answer this question by identifying which parameters have the highest impact on the mismatch from the optimal value.

5.2 Correlation of the Difference from Optimal Value with Input Parameters

The correlations of the difference from optimal value for the 2-zone scenario with the following parameters were investigated:

- $J_2$ – productivity index
- $\text{Pres}_1$ – layer 1 reservoir pressure
- $\text{Pres}_2$ – layer 2 reservoir pressure
- $\text{WC}_1$ – zone 1 water cut
- $\text{WC}_2$ – zone 2 water cut
- $\text{GOR}_1$ – zone 1 gas-oil ratio
- $\text{GOR}_2$ – zone 2 gas-oil ratio
- $\text{Qliq}$ – well’s liquid rate
- $\text{Qoil}$ – well’s oil rate
WC – well’s water cut

GOR – well’s gas-oil ratio

Pbhp – bottom hole pressure

Qliq1 – zone 1 liquid rate

Qliq2 – zone 2 liquid rate

GOR1-GOR2 – difference in gas-oil ratio between zone 1 and zone 2

|dGOR| - absolute difference in gas-oil ratio between zone 1 and zone 2

GOR1/GOR2 – zone1 to zone 2 gas-oil ratio

Pres1-Pres2 - difference in reservoir pressure between zone 1 and zone 2

|dPres| - absolute difference in reservoir pressure between zone 1 and zone 2

Pres1/Pres2 – ratio of reservoir pressures

WC1-WC2 - difference in water cut between zone 1 and zone 2

WC2/WC1- ratio of water cuts

OilDens – oil density

LiqDens - liquid density

Pgrav – well’s tubing gravity pressure

Pfric - well’s tubing friction pressure

Pfric/Pgrav– ratio of friction pressure to gravity pressure

The highest correlation is observed with the difference in Gas-Oil Ratio:
Figure 13 shows that the difference is higher than 1% for the cases with significant difference in GOR, such as $|\Delta GOR| > 100 \text{ sm}^3/\text{sm}^3$.

Another parameter which has a high correlation with the oil rate mismatch is the difference of reservoir pressure (Figure 13). Therefore, there is a higher risk to have optimal position at an intermediate choke position, and higher difference in oil rate, if the difference of GOR and reservoir pressures is significant.

5.3 Risk Analysis

The probability to have a mismatch with the optimal value at certain conditions was investigated. The parameters $|\Delta GOR|$ and $(\text{Pres}_1 - \text{Pres}_2)$ were selected as input parameters for this investigation since they show a good correlation with the difference from the optimal value (Figure 12). The first and last 25% of cases for each parameter were analysed, covering the following values of $|\Delta GOR|$ and $(\text{Pres}_1 - \text{Pres}_2)$ (Table 8):

The number of cases providing the specified mismatch values for each situation is summarised in Table 9.

This table shows that only 4 out of the 554 cases with a mismatch greater than 1% have $|\Delta GOR| < 70 \text{ sm}^3/\text{sm}^3$. By contrast, almost 70% of these cases have a GOR difference of greater than $300 \text{ sm}^3/\text{sm}^3$. Also the percentage of cases with a significant difference in GOR constantly increases with increasing difference from the maximum oil rate. A similar situation is observed for an increasing difference in the zonal reservoir pressure.

The above statistical analysis shows that if the difference between GOR is less than 70 sm$^3$/sm$^3$, then On/Off ICVs will provide the maximum oil rate within ±1% at a confidence level of almost 100%.
Higher GOR differences increase the probability of a greater mismatch. The On/Off strategy still shows optimal result in 72% of all the cases for $|\Delta GOR| > 300 \text{ sm}^3/\text{sm}^3$, while in 80% of cases the mismatch is less than 1% (Figure 18).

5.4 Further Recommendations to Evaluate the Feasibility of Zonal On/Off Control in a Specific Well Model

From a practical point of view it is important to know the potential difference of the maximum instantaneous well oil rate achieved by the On/Off control from its absolute maximum value for a particular case with certain layers GORs. It is also important to predict how this difference depends on the reservoirs pressure and water cut changes. We provide below some recommendations how to evaluate such differences:

1. The maximum difference is observed in the vicinity of the so-called “Critical Water Cut” value, i.e. the threshold WC value above which a watered zone should be completely closed. The CWC approach’s background and definitions can be found in (Grebenkin and Davies 2012).

2. We have observed that two conditions should be satisfied simultaneously so that the On-Off zonal flow control strategy can show sub-optimal results:
   - Zonal reservoir pressure differential is such that the cross-flow between the well zones is possible;
   - A zonal water cut equals its CWC.

3. Where the well/reservoir model is uncertain, we recommend carrying out the proposed analysis for the range of expected well/reservoir properties (e.g. using the common P10/P50/P90 approach) to fully assess the risks.
6. Conclusions

1. A methodology to find the application area for On/Off zonal control strategy has been developed for a liquid producing well. It is only applicable to the control objective considered here: maximisation of the instantaneous well oil production rate.

2. It was shown that a multi-zone I-Well can be described by a 3-zone well within the scope of this study objectives. An acceptably accurate algorithm describing inflow performance of an IW with over 3 zones as an equivalent 3-zone IW in the vicinity of a given BHP value has been developed. The parameters of such equivalent well change and have to be calculated at every control time-step during the well production life.

3. A wide range of input parameters have been investigated:
   - Productivity Index: from 1 to 231 sm$^3$/day/bar
   - WC: from 0 to 100%
   - Reservoir Pressure: from 150 to 250 bar
   - GOR: from 9 - 585 sm$^3$/sm$^3$

   Both natural flow and gas-lift scenarios have been analysed. On/Off ICVs provided the maximum oil rate in about 90% of cases with a mismatch of less than 1% for 95% of the considered cases with a given input parameters distribution. The ESP scenario was not analysed because the optimum ESP pump range has to be found for each case which is a time-consuming task.

4. A methodology has been described for finding whether an On/Off ICV reactive control strategy is applicable. On/Off ICVs provide the optimal production rate if the zonal GOR difference is less than 70 sm$^3$/sm$^3$. The maximum, yet usually insignificant, mismatch of On/Off control-achieved well oil rate from its maximum
possible value is only observed when a zonal water cut value is close to its Critical Water Cut (CWC) value.

Note that the above assumptions and modelling approaches have been derived in order to evaluate and/or find the optimal zonal control scenario to maximise instantaneous well oil rate. If another well control optimisation objective is envisaged we recommend modifying the presented workflow to address this new objective.

In summary, the reactive, On/Off zonal flow control strategy has a wide application area in liquid production wells providing the maximum (within 1%), instantaneous oil production rate target.

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Appendix A. Converting from choked zones to fully open

Statement 1

If the maximum oil rate is achieved at partially choked positions for several valves, there is a corresponding case, were all valves are fully open except one valve which should be partially choked.

Proof

Based on the equation 3 the maximum oil rate can be described as:
\[ Q_{\text{max}} = \sum_{i \in \text{Ch}} a_i \cdot Q_{i,\text{Liquid}} (1 - WC_i) + \sum_{j \in \text{Ch}} Q_{j,\text{Liquid}} (1 - WC_j) + \Delta P_{\text{BHP}} \cdot \sum_{j \in \text{Ch}} J_j (1 - WC_j) \quad (A.1) \]

where \(0 < a_i < 1\) – reducing coefficients which correspond to certain valve positions and provide maximum oil rate, \(Ch\) – is a set of operating zones, \(WC_i\) – zonal water cut.

3 Zones

First of all let's show that the statement is correct for 3 zones with zones 1 and 2 partially choked.

The equation A.1 in this case can be written as

\[ Q_{\text{max}} = a_1 \cdot Q_{1,\text{Liquid}} (1 - WC_1) + a_2 \cdot Q_{2,\text{Liquid}} (1 - WC_2) + Q_{3,\text{Liquid}} (1 - WC_3) + \Delta P_{\text{BHP}} \cdot J_3 (1 - WC_3) \]

(A.2)

If \(a_1 = a_2\) then zones 1 and 2 can be replaced with one zone:

\[ Q_{\text{max}} = a_1 \cdot (J_1 \cdot dP_1 (1 - WC_1) + J_2 \cdot dP_2 (1 - WC_2)) + Q_{3,\text{Liquid}} (1 - WC_3) + \Delta P_{\text{BHP}} \cdot J_3 (1 - WC_3) = \]

\[ = a_1 \cdot J^* \cdot dP^* (1 - WC^*) + Q_{3,\text{Liquid}} (1 - WC_3) + \Delta P_{\text{BHP}} \cdot J_3 (1 - WC_3) \]

(A.3)

Where

\[ J^* = J_1 + J_2 \quad (A.4) \]

\[ dP^* = \frac{J_1 \cdot dP_1 + J_2 \cdot dP_2}{J_1 + J_2} \quad (A.5) \]

\[ WC^* = \frac{J_1 \cdot dP_1 \cdot WC_1 + J_2 \cdot dP_2 \cdot WC_2}{J_1 \cdot dP_1 + J_2 \cdot dP_2} \quad (A.6) \]

\[ GOR^* = \frac{J_1 \cdot dP_1 \cdot GOR_1 + J_2 \cdot dP_2 \cdot GOR_2}{J_1 \cdot dP_1 + J_2 \cdot dP_2} \quad (A.7) \]

Suggest that \(a_1 < a_2\), then from the equation A.1:
\[ Q_{\text{max}}^{\text{Old}} = a_1 \cdot (J_1 \cdot dP_1 \cdot (1 - WC_1) + J_2 \cdot dP_2 \cdot (1 - WC_2)) + (a_2 - a_1) \cdot J_2 \cdot dP_2 \cdot (1 - WC_2) + Q_3^{\text{Liquid}} \cdot (1 - WC_3) + \Delta P_{\text{BHP}} \cdot J_3 \cdot (1 - WC_3) \]

(A.8)

The first term of the equation A.8 can be described by fully open zone with

\[ J^* = a_1 (J_1 + J_2) \quad \text{(A.9)} \]

and the other parameters defined by equations A.5, A.6 and A.7.

Zone 2 is operated with reducing coefficient \( b \) which changes from 0 to \( 1 - a_1 \cdot \Delta \). The value of term \( \Delta \) will be explained further.

The oil rate therefore is

\[ Q_b^{\text{Old}} = J^* \cdot dP^* \cdot (1 - WC^*) + \Delta P_{\text{BHP}}^b \cdot J^* \cdot (1 - WC^*) + b \cdot J_2 \cdot dP_2^b \cdot (1 - WC_2) + Q_3^{\text{Liquid}} \cdot (1 - WC_3) + (\Delta P_{\text{BHP}}^b + \Delta P_{\text{BHP}}^{b,3}) \cdot J_3 \cdot (1 - WC_3) \quad \text{(A.10)} \]

If \( b = a_2 - a_1 \) then \( Q_b^{\text{Old}} = Q_{\text{max}}^{\text{Old}} \)

We need to show that this intermediate position of \( 0 < b = a_2 - a_1 < 1 - a_1 \cdot \Delta \) is still optimal for this case.

From Equations A.5, A.6 and A.9:

\[ J^* \cdot (1 - WC^*) \cdot \Delta P_{\text{BHP}}^b = a_1 \cdot (J_1 + J_2) \cdot \frac{J_1 \cdot dP_1 \cdot (1 - WC_1) + J_2 \cdot dP_2 \cdot (1 - WC_2)}{J_1 \cdot dP_1 + J_2 \cdot dP_2} \cdot \Delta P_{\text{BHP}}^b = \]

\[ = a_1 \cdot (J_1 \cdot dP_1 \cdot (1 - WC_1) + J_2 \cdot dP_2 \cdot (1 - WC_2)) \cdot \frac{\Delta P_{\text{BHP}}^b}{dP^*} \quad \text{(A.11)} \]

Therefore Equation A.10 becomes
\[ Q^{Old} = a_i \cdot J_i \cdot (1 + \frac{\Delta P_{BHP}^b}{dP'}) \cdot dP_i \cdot (1 - WC_i) + J_2 \cdot (a_1 \cdot \frac{\Delta P_{BHP}^b}{dP'} + b) \cdot dP_2 \cdot (1 - WC_2) + \\
+ Q_{3^{Liquid}} (1 - WC_3) + \Delta P_{BHP}^b \cdot J_3 (1 - WC_3) \quad \text{(A.12)} \]

In the original case the coefficient \( b \) varies from 0 to \( 1-a_1 \). However, if we choose this upper boundary for our modified case the reducing coefficient for zone 2 becomes

\[ 1 - a_1 + a_i \cdot \frac{\Delta P_{BHP}^b}{dP'} \]

Therefore, we need to reduce the upper boundary for a value \( \Delta = a_i \cdot \frac{\Delta P_{BHP}^b}{dP'} \) if we want to stay in the boundaries of the original case.

Equation A.12 describes original case with the optimal position at \( b = a_2 - a_1 \). Therefore original case is replaced with the one operating zone case with the same optimal choke position.

**N Zones**

In case of any number of zones, they can be reordered that \( a_1 < a_2 < ... < a_{N-1} \).

The equation A.8 for this situation can be written as:

\[ Q_{\text{max}}^{Old} = a_i \cdot \sum_{i=1}^{N-1} J_i \cdot dP_i \cdot (1 - WC_i) + a_2 \cdot \sum_{i=2}^{N-1} J_i \cdot dP_i \cdot (1 - WC_i) + ... + a_{N-2} \cdot \sum_{i=N-2}^{N-1} J_i \cdot dP_i \cdot (1 - WC_i) + \\
+ (a_{N-1} - a_{N-2}) \cdot J_{N-1} \cdot dP_{N-1} \cdot (1 - WC_{N-1}) + Q_{N^{Liquid}} (1 - WC_N) + \Delta P_{BHP}^b \cdot J_N (1 - WC_N) \quad \text{(A.13)} \]

The first \( N-2 \) terms can be modelled with fully open zones. Similar to the previous case can be shown that \( N-1^{\text{th}} \) choke has the optimal position at intermediate point with reducing coefficient \( b = a_{N-1} - a_{N-2} \).
Appendix B. Converting from any number of zones into three zones

Problem formulation

The liquid rate of an intelligent well producing from \( N \) zones with Zone1 ICV choked can be described by equation 5:

\[
Q_{\text{new}}^{\text{Liquid}} = a Q_i^{\text{Liquid}} + \sum_{i=2}^{N} dP_i \cdot J_i + \sum_{i=2}^{N} J_i \cdot \Delta P_{\text{BHP}}
\]

Assume that \( dP_i \geq 0 \).

Find \( J_2^*, J_3^*, dP_2^*, dP_3^*, WC_2^*, WC_3^*, GOR_2^*, GOR_3^*, \rho_2^* \) and \( \rho_3^* \) that the following system of equations is satisfied at a fixed BHP value:

\[
\begin{align*}
J_2^* + J_3^* &= \sum_{i=2}^{N} J_i \quad \text{(B.1)} \\
J_2^* \cdot dP_2^* + J_3^* \cdot dP_3^* &= \sum_{i=2}^{N} J_i \cdot dP_i \quad \text{(B.2)} \\
J_2^* \cdot WC_2^* + J_3^* \cdot WC_3^* &= \sum_{i=2}^{N} J_i \cdot WC_i \quad \text{(B.3)} \\
J_2^* \cdot dP_2^* \cdot WC_2^* + J_3^* \cdot dP_3^* \cdot WC_3^* &= \sum_{i=2}^{N} J_i \cdot dP_i \cdot WC_i \quad \text{(B.4)} \\
J_2^* \cdot GOR_2^* + J_3^* \cdot GOR_3^* &= \sum_{i=2}^{N} J_i \cdot GOR_i \quad \text{(B.5)} \\
J_2^* \cdot dP_2^* \cdot GOR_2^* + J_3^* \cdot dP_3^* \cdot GOR_3^* &= \sum_{i=2}^{N} J_i \cdot dP_i \cdot GOR_i \quad \text{(B.6)} \\
J_2^* \cdot \rho_2^* + J_3^* \cdot \rho_3^* &= \sum_{i=2}^{N} J_i \cdot \rho_i \quad \text{(B.7)} \\
J_2^* \cdot dP_2^* \cdot \rho_2^* + J_3^* \cdot dP_3^* \cdot \rho_3^* &= \sum_{i=2}^{N} J_i \cdot dP_i \cdot \rho_i \quad \text{(B.8)}
\end{align*}
\]

Solution
There are 10 parameters and 8 equations in total. Therefore 2 parameters are free and can have any values. Suggest that \( J_3^* \) and \( dP_3^* \) are free parameters. All the other parameters can be expressed from these 2.

From Equation B.1: \( J_2^* = \sum_{i=2}^{N} J_i - J_3^* \) (B.9)

From Equation B.2: \( dP_2^* = \frac{\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*}{\sum_{i=2}^{N} J_i - J_3^*} \) (B.10)

From Equation B.3: \( WC_2^* = \frac{\sum_{i=2}^{N} J_i \cdot WC_i - J_3^* \cdot WC_3^*}{J_2^*} = \frac{\sum_{i=2}^{N} J_i \cdot WC_i - J_3^* \cdot WC_3^*}{\sum_{i=2}^{N} J_i - J_3^*} \) (B.11)

Placing the values B.9 and B.11 in equation B.4 we have

\[
\frac{\left( \sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^* \right) \cdot \left( \sum_{i=2}^{N} J_i \cdot WC_i - J_3^* \cdot WC_3^* \right)}{\sum_{i=2}^{N} J_i - J_3^*} + J_3^* \cdot dP_3^* \cdot WC_3^* = \sum_{i=2}^{N} J_i \cdot dP_i \cdot WC_i
\]

(B.12)

After multiplying the equation on \( \sum_{i=2}^{N} J_i - J_3^* \) an assembling coefficient before \( WC_3^* \)

\[
(J_3^* \cdot dP_3^* \cdot \left( \sum_{i=2}^{N} J_i - J_3^* \right) \cdot J_3^* \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*)) \cdot WC_3^* = \\
\sum_{i=2}^{N} J_i \cdot dP_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i - J_3^*) \cdot \sum_{i=2}^{N} J_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*)
\]

(B.13)

After simplifying the left part of the equation:
\[ J_3^* \cdot (dP_3^* \cdot \sum_{i=2}^{N} J_i \cdot \sum_{i=2}^{N} J_i \cdot dP_i) \cdot WC_3^* = \]
\[ = \sum_{i=2}^{N} J_i \cdot dP_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i - J_3^*) \cdot \sum_{i=2}^{N} J_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*) \quad (B.14) \]

And finally
\[ WC_3^* = \frac{\sum_{i=2}^{N} J_i \cdot dP_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i - J_3^*) \cdot \sum_{i=2}^{N} J_i \cdot WC_i \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*)}{J_3^* \cdot (dP_3^* \cdot \sum_{i=2}^{N} J_i \cdot \sum_{i=2}^{N} J_i \cdot dP_i)} \quad (B.15) \]

Using the same technique from equations B.6 and B.8 can be found that
\[ GOR_3^* = \frac{\sum_{i=2}^{N} J_i \cdot dP_i \cdot GOR_i \cdot (\sum_{i=2}^{N} J_i - J_3^*) \cdot \sum_{i=2}^{N} J_i \cdot GOR_i \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*)}{J_3^* \cdot (dP_3^* \cdot \sum_{i=2}^{N} J_i \cdot \sum_{i=2}^{N} J_i \cdot dP_i)} \quad (B.16) \]
\[ \rho_3^* = \frac{\sum_{i=2}^{N} J_i \cdot dP_i \cdot \rho_i \cdot (\sum_{i=2}^{N} J_i - J_3^*) \cdot \sum_{i=2}^{N} J_i \cdot \rho_i \cdot (\sum_{i=2}^{N} J_i \cdot dP_i - J_3^* \cdot dP_3^*)}{J_3^* \cdot (dP_3^* \cdot \sum_{i=2}^{N} J_i \cdot \sum_{i=2}^{N} J_i \cdot dP_i)} \quad (B.17) \]

And finally \( GOR_2^* \) and \( \rho_2^* \) can be calculated from the equations B.5 and B.7:
\[ GOR_2^* = \frac{\sum_{i=2}^{N} J_i \cdot GOR_i - J_3^* \cdot GOR_3^*}{\sum_{i=2}^{N} J_i - J_3^*} \quad (B.18) \]
\[ \rho_2^* = \frac{\sum_{i=2}^{N} J_i \cdot \rho_i - J_3^* \cdot \rho_3^*}{\sum_{i=2}^{N} J_i - J_3^*} \quad (B.19) \]

Therefore all required parameters were found.
Appendix C. Calculation of stochastic error

Define

\[
V_{\text{NoOnOff}} = 1/N, \quad \text{if maximum oil production at the intermediate choke position}
\]

\[
V_{\text{NoOnOff}} = 0, \quad \text{if the maximum oil production at fully open or closed valve position}
\]

\(N\) is a number of cases.

Therefore, \([\text{No On/Off}]\) value equals

\[
[\text{No On/Off}] = \sum_{i=1}^{N} (V_{\text{NoOnOff}})^i \cdot 100\%
\] (C.1)

All cases are assumed to be independent and uniformly distributed. If we define \([\text{NoOn/Off}]_{\text{Total}}\) as a percentage of cases where On/Off strategy does not provide the maximum oil production for all possible scenarios, then \(V_{\text{NoOnOff}}\) value has a Bernoulli distribution with probability:

\[
p = P[V_{\text{NoOnOff}} = 1/N] = [\text{NoOn/Off}]_{\text{Total}} / 100\%
\]

\[
q = P[V_{\text{NoOnOff}} = 0] = 1-p
\] (C.2)

The Moivre-Laplace Theorem indicates that the sum of these values is asymptotically normally distributed, i.e. has a normal distribution at \(N \to \infty\).

The following formula estimates the number of required cases for the normal distribution:

\[
N = \frac{t^2 s^2}{\Delta^2}
\] (C.3)

Where, \(t\) – Student’s number (\(t=2\) for 95% certainty);

\(s\) – sample coefficient of variance;
\( \Delta_x \) – maximum error between entire assembly and our population.

References


Figures

Figure 1 Downhole completion schematic

Figure 2 Algorithm to describe a well inflow performance with more than 3 zones as a 3-zone well with an equivalent inflow performance
Figure 3 Difference of liquid rates, oil rates and GOR as a function of the choke position

Figure 4 Technical Maximum Oil Production as a function of Injected Gas Rate
Figure 5 ESP performance and liquid rate interval as a function of the choke position

Figure 6 Well Schematic
Figure 7 Workflow to investigate the application area for On/Off valves

Figure 8 Difference between the maximum oil production rate for an infinitely variable and an On/Off ICV
Figure 9 [No On/Off] values depending on the number of cases

Figure 10 Statistical error for [No On/Off] and [Diff] values depends on the number of cases

Figure 11 Distribution of the difference from the maximum oil production rate for a 2 zone, naturally flowing well
Figure 12 Ten parameters with the highest correlation coefficients

Figure 13 Difference from Optimum Oil Production rate depends on $\Delta$GOR
Tables

Table 1 Reservoir and fluid parameters for a 5 layer completion

<table>
<thead>
<tr>
<th>Zones/Units</th>
<th>J (m³/day/bar)</th>
<th>BHP (bar)</th>
<th>Pres (bar)</th>
<th>dP (bar)</th>
<th>WC (fraction)</th>
<th>GOR (sm³/sm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>104</td>
<td>175</td>
<td>193</td>
<td>18</td>
<td>0.7</td>
<td>97</td>
</tr>
<tr>
<td>Zone2</td>
<td>9</td>
<td>175</td>
<td>186</td>
<td>11</td>
<td>0.1</td>
<td>80</td>
</tr>
<tr>
<td>Zone3</td>
<td>16</td>
<td>175</td>
<td>190</td>
<td>15</td>
<td>0.15</td>
<td>106</td>
</tr>
<tr>
<td>Zone4</td>
<td>46</td>
<td>175</td>
<td>207</td>
<td>32</td>
<td>0.2</td>
<td>89</td>
</tr>
<tr>
<td>Zone5</td>
<td>2</td>
<td>175</td>
<td>200</td>
<td>25</td>
<td>0</td>
<td>97</td>
</tr>
</tbody>
</table>

Table 2 Reservoir and fluid parameters for 3 layers from the converting algorithm

<table>
<thead>
<tr>
<th>New Design</th>
<th>J (m³/day/bar)</th>
<th>BHP (bar)</th>
<th>Pres (bar)</th>
<th>dP (bar)</th>
<th>WC (fraction)</th>
<th>GOR (sm³/sm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone1</td>
<td>104</td>
<td>175</td>
<td>193</td>
<td>18</td>
<td>0.70</td>
<td>97</td>
</tr>
<tr>
<td>Zone2</td>
<td>15</td>
<td>175</td>
<td>215</td>
<td>40</td>
<td>0.25</td>
<td>84</td>
</tr>
<tr>
<td>Zone3</td>
<td>59</td>
<td>175</td>
<td>197</td>
<td>22</td>
<td>0.15</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 3 Maximum difference between the 5- and 3-zone cases

<table>
<thead>
<tr>
<th>Parameter/CASE</th>
<th>Natural Flow</th>
<th>Gas Lift</th>
<th>ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Rate</td>
<td>0.07%</td>
<td>0.05%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Oil Rate</td>
<td>-0.03%</td>
<td>-0.10%</td>
<td>-0.10%</td>
</tr>
<tr>
<td>Produced GOR</td>
<td>0.09%</td>
<td>0.09%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

Table 4 Minimum and maximum parameters of the uniform distributions used in Monte Carlo simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PI, sm³/day/bar</th>
<th>WC, %</th>
<th>P&lt;sub&gt;res&lt;/sub&gt;, bar</th>
<th>GOR, scm/scm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>2</td>
<td>0</td>
<td>150</td>
<td>9</td>
</tr>
<tr>
<td>Max</td>
<td>231</td>
<td>100</td>
<td>250</td>
<td>585</td>
</tr>
</tbody>
</table>
Table 5 Example of input parameters for the 3 zone case

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$J_2$</th>
<th>$J_3$</th>
<th>$P_{res1}$</th>
<th>$P_{res2}$</th>
<th>$P_{res3}$</th>
<th>WC$_1$</th>
<th>WC$_2$</th>
<th>WC$_3$</th>
<th>GOR$_1$</th>
<th>GOR$_2$</th>
<th>GOR$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>sm$^3$/day/bar</td>
<td>bar</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>163</td>
<td>11</td>
<td>177</td>
<td>178</td>
<td>223</td>
<td>70</td>
<td>37</td>
<td>40</td>
<td>17</td>
<td>447</td>
<td>478</td>
</tr>
</tbody>
</table>

Table 6 Statistical error between 10,000 realisation and all possible scenarios

<table>
<thead>
<tr>
<th>Number of Zones</th>
<th>Lift Type</th>
<th>$\Delta_x$ (NoOn/Off)</th>
<th>$\Delta_x$ (Diff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Zones</td>
<td>Natural Flow</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>2-Zones</td>
<td>Gas Lift</td>
<td>7%</td>
<td>14%</td>
</tr>
<tr>
<td>3-Zones</td>
<td>Natural Flow</td>
<td>5%</td>
<td>12%</td>
</tr>
<tr>
<td>3-Zones</td>
<td>Gas Lift</td>
<td>6%</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 7 Percentage of cases where On/Off is sufficient and the median of the error if On/Off is not sufficient

<table>
<thead>
<tr>
<th>Number of Zones</th>
<th>Lift Type</th>
<th>On/Off</th>
<th>Median of the Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Zones</td>
<td>Natural Flow</td>
<td>89%</td>
<td>0.98%</td>
</tr>
<tr>
<td>2 Zones</td>
<td>Gas Lift</td>
<td>92%</td>
<td>0.33%</td>
</tr>
<tr>
<td>3 Zones</td>
<td>Natural Flow</td>
<td>87%</td>
<td>0.79%</td>
</tr>
<tr>
<td>3 Zones</td>
<td>Gas Lift</td>
<td>92%</td>
<td>0.24%</td>
</tr>
</tbody>
</table>

Table 8 |ΔGOR| and (Pres1-Pres2) boundaries for first and last 25% of all cases

| Number of cases | $|\Delta\text{GOR}|$ | Pres1-Pres2 |
|-----------------|-----------------|-------------|
| First 25% of cases (2500) | less than 70 sm$^3$/sm$^3$ | less than -25 bar |
| Last 25% of cases (2500) | more than 300 sm$^3$/sm$^3$ | more than +25 bar |
Table 9 Number of cases with a certain mismatch from the maximum oil rate

| Difference from Maximum Oil Rate, % | Total Number of Cases | |ΔGOR| | Pres1-Pres2 |
|-----------------------------------|-----------------------|----------|----------|----------|
|                                   |                       | <70 sm³/sm³ | >300 sm³/sm³ | <-25 bar | >25 bar |
|                                   | Number of Cases | % from total | Number of Cases | % from total | Number of Cases | % from total | Number of Cases | % from total |
| >0.50%                            | 691                   | 17        | 2.5%       | 424       | 61%       | 13       | 1.9%       | 240       | 35%       |
| >1%                               | 554                   | 4         | 0.7%       | 377       | 68%       | 5        | 0.9%       | 204       | 37%       |
| >2%                               | 410                   | 2         | 0.5%       | 291       | 71%       | 1        | 0.2%       | 168       | 41%       |
| >5%                               | 231                   | 0         | 0%         | 183       | 79%       | 0        | 0%         | 119       | 52%       |
| >10%                              | 108                   | 0         | 0%         | 94        | 87%       | 0        | 0%         | 63        | 58%       |