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A Novel Integrated Approach to Oil Production Optimization and Limiting the Water Cut Using Intelligent Well Concept: Using Case Studies

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Abstract

Intelligent well technology has provided facility for real time production control through use of subsurface instrumentation. Early detection of water production allows for a prompt remedial action. Effective water control requires the appropriate performance of individual devices in wells on maintaining the equilibrium between water and oil production over the entire field life. However, there is still an incomplete understanding of using intelligent well concept to control unwanted fluids and the way this leads to improving hydrocarbon recovery.

The present study proposes using intelligent well technology to develop a new integrated methodology for selecting/ranking the candidate wells/fields, interval control valve (ICV) size determination, and ICV setting optimization. Various technical and economical parameters weighted by expert opinions are used for candidate well/field ranking to implement the intelligent technology. A workflow is proposed for ICV size determination based on its effect on a predefined objective function. Inappropriate ICV size selection leads to suboptimum production scenarios. Furthermore, this study proposes an efficient ICV setting optimization in an intelligent well. The objective function can maximize cumulative oil, minimize water production, or conduct both. It was shown that for selecting the optimized cases, the balance between water and oil production under predefined criteria should be practiced. Real case studies were considered to demonstrate the effectiveness and robustness of the proposed methodology. A considerable improvement in the objective function was achieved using the developed methodology.

Keywords: Intelligent Well, Screening, Optimization, ICV Sizing, ICV Setting

1. Introduction

Field development decisions usually encounter high uncertainties because of large reservoir size and insufficient data. Therefore, an appropriate strategy and technology are needed to securely and efficiently handle the risky conditions. In this regard, proper designing and implementing intelligent wells and field technologies have been proven as efficient approaches in this context, if implemented properly. It is very important to have a priority schedule including all the related parameters for different wells/fields to effectively implement this specific or any other technology (Holmes et al., 1998; Aitokhuehi et al., 2004; Behrouz. et al., 2013). The next step after selecting/ranking the

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hydrocarbon wells/fields is to apply the technology correctly based on the specification of the host wells/fields in order to get the optimized performance of the technology. The main element of an intelligent well is interval control valve (ICV). ICVs are the heart of subsurface controlling systems. Their functionalities directly affect the well performance based on the ICVs configurations or settings.

Holmes et al. (1998) optimized the valve configuration. They studied the effects of geological uncertainty and showed that it directly impacts the benefits of subsurface control in terms of cumulative production as an objective function (Holmes et al., 1998; Aitokhuehi et al., 2004). Yeten (2003) and Yeten et al. (2002) investigated the reactive control method. This method needs the valve configurations as a prerequisite for which a predictive reservoir and well model is used (Yeten, 2002, Yeten et al., 2003).

Brouwer et al. (2001) used a static optimization in the defensive method in a water flooding plan. They used just *On*/*Off* valves in their study; these valves were closed as water breakthrough the well (Brouwer et al., 2001). In addition, Arenas and Dolle (2003) used a pressure cycling concept in a water flooding project within a fractured reservoir (Arenas et al., 2003).

Maximum reservoir contact (MRC) wells are more efficient by replacing several conventional wells, but they present new challenges in terms of completion such as unwanted fluid production due to long length and complexity of the wells contact to the reservoir (Salamy, 2005). To avoid these kinds of challenges, the intelligent well technology and MRC well have been discussed in different oil wells (Ibrahim et al., 2007).

Intelligent wells, equipped with specific downhole control devices, offer opportunity to improve recovery factor by managing the flow of undesired fluids (such as water) from heterogeneous reservoirs (Al-Ghareeb, 2009).

Mubarak et al. (2007) carried out a production test in a defensive approach to decrease water production from a multilateral intelligent well (Mubarak, 2008). Alhuthali et al. (2009) presented a water flooding optimization method in intelligent wells to achieve the optimum oil production rate (Alhuthali et al., 2009).

A key factor in the management of long horizontal wells is controlling the production profile along the horizontal leg. This is achievable through increasing the tubing size or shorter laterals although such solutions are not always affordable or practical (Salamy, 2005). However, by an intelligent well approach and by using controlling devices, the aforementioned production problems can be resolved.

In this study, a methodology is presented to select best well/field for implementing the intelligent well technology. Moreover, comprehensive workflows are generated for ICV size optimization to be used in an intelligent well. Furthermore, an optimization procedure is presented to improve the performance of ICVs. It should be noted that, to the best the authors’ knowledge, all these activities have not been reported yet.

2. Methodology

2.1. Screening criteria for smart wells/fields

A unified approach to candidate wells or fields selection is introduced in this study to implement an intelligent well technology. Hydrocarbon wells/fields should be prioritized and ranked according to both technical and economic considerations. For this purpose, a Gate-Step procedure is developed. It consists of three main steps, including documentation, assessment, and selection. These steps should be performed consecutively as each phase provides the required input data for the next phase. In the first two steps, the intelligence opportunities are identified and assessed. These opportunities can be increasing recovery factor, improving net present value of the project, minimizing uncertainty effects, and so on. Project feasibility is investigated in the documentation phase. Upon the approval of the first phase, we start the assessment phase. In this step, all the killer or vetoing parameters should be extracted. These parameters should be checked in the target wells/fields. Selection phase is started only when such a parameter is found relevant to the project in the second phase (Behrouz et al., 2013).

In the selection phase, a novel method is presented based on important parameters integrated from related disciplines to choose the best case. These parameters are organized in a decision tree, a structured technique for dealing with complex judgments. Based on their importance level, all the related parameters for making a decision are organized in the tree. In the current study, the first level or main branches of this tree are technical, economical, geographical, and environmental issues. Other parameters are placed on the next levels in the decision tree as shown in Figure 1.

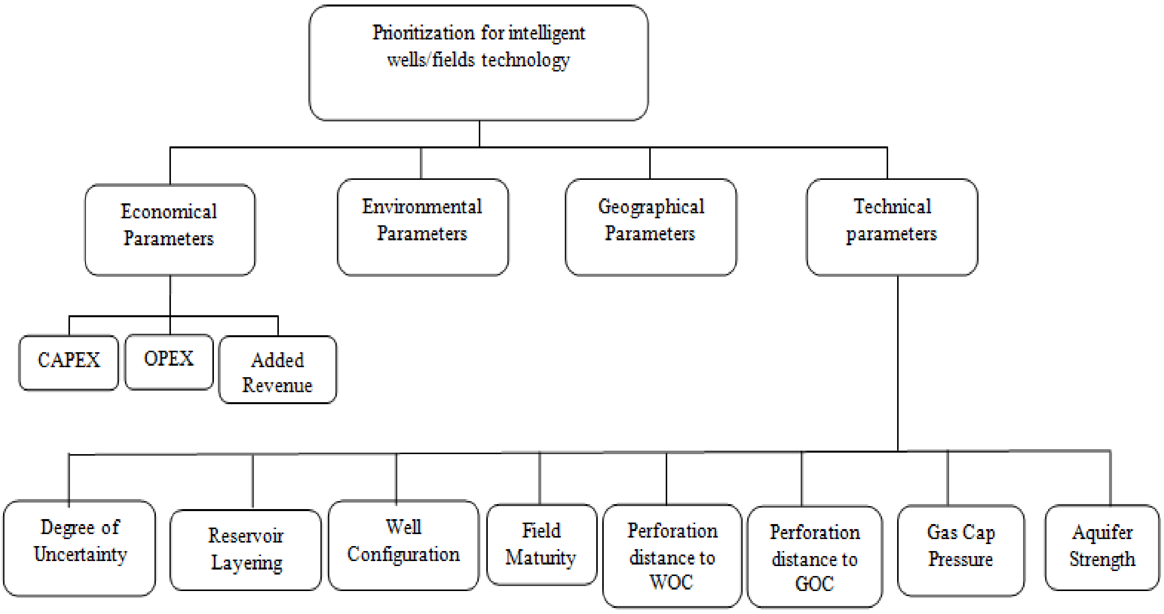

Figure1
The decision tree for intelligent well prioritization.

Using software in analytical hierarchy process (AHP) which is a subsidiary of the multi criteria decision making (MCDM) problems, all the parameters are evaluated and weighted. Parameters weighting is performed according to Experts Opinions. The results are therefore highly experts-oriented. The output of this step is finalized weight factors for the parameters not biased to any specific field or well. Table 1 shows typical weight factors, which are obtained with the cooperation of some multidisciplinary experts in a real oil field as a case study. From these screening criteria, it is possible to select or rank the wells or fields with the highest score to which apply the smart well technology. Having selected the candidate well or field for smart well technology, the optimization should be made on the performance of ICVs to get the most benefit from the technology (Behrouz et al., 2013).

Table 1

Typical weight factors for branches of designed decision tree based on AHP.

Purpose	Parameters (level 1)	Weight	Parameters (level 2)	Weight
Prioritization	Economical parameters	55	OPEX	6
			CAPEX	13.3
			Revenue	35.9
	Technical parameters	28	Heterogeneity	10
			Well Type	5.9
			Field life cycle	4.1
			Layering	3.2
			Distance to WOC	1.3
			Aquifer strength	1.2
			Distance to GOC	1.1
			Gas cap pressure	1
	Geographical parameters	10	-	-
	Environmental parameters	7	-	-
Summation	-	100	-	100

3. ICV size determination

Finding ICV flow area at fully open positions (ICV size) is a concern in each intelligent well design. It is completely case sensitive and depends on reservoir capability. When the installed ICV size is more than the appropriate size, different settings of ICVs will not considerably affect the objective function (O.F.). This occurs especially in higher settings; ICV settings are fractions of ICV area in a fully open position. With big ICV sizes, some area fractions (settings) are too large to be able to effectively optimize the production. When adjusted in their upper ranges of openness, the big ICVs act nearly as they are in a fully open position.

On the other hand, with too small ICV sizes, the oil well capability for production is more than the ICVs capacity in their fully open position and the production cannot be optimized. Considering the importance of ICV size, a method was proposed to design the optimum ICV size in this section.

As the first step, the static and dynamic model of the candidate field should be prepared a priori. A base case with a predefined objective function should be built. The objective function can be increasing oil production, decreasing water and/or gas production, improving NPV, etc. The proposed procedure for ICV size determination is schematically presented in Figure 2. Starting with a predefined ICV area at a fully open position, the objective function is calculated by running the dynamic model. Then, the ICV size is reduced to re-run the dynamic model and update the objective function as before. If there is (no) considerable difference between the two objective functions, the cross section area of the ICVs is successively (decreased) increased. In any case, the ICV size at which the objective function starts to change is considered as the suitable size to be implemented in the candidate well.

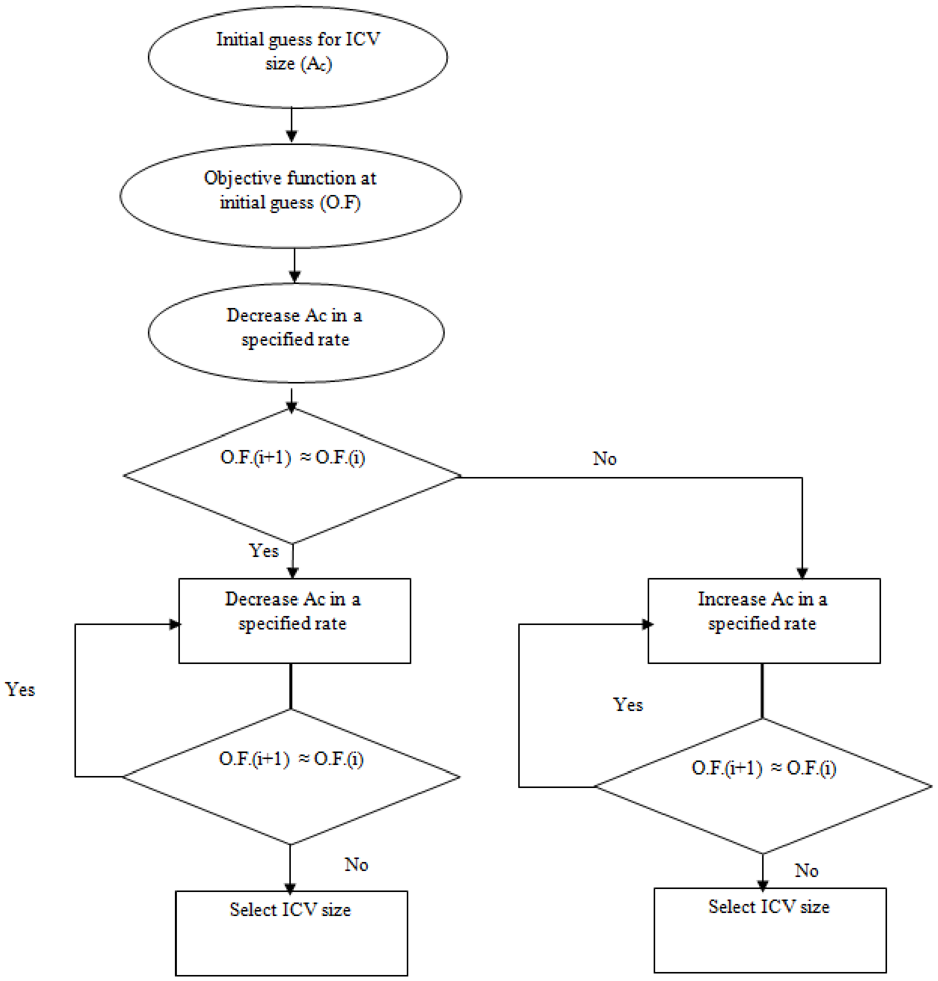

Figure 2
The ICV sizing workflow.

4. ICV setting optimization

Having selected appropriate wells/fields for intelligent implementation and obtained the ICVs correct size and placement, the well performance should be optimized in the next step by adjusting the ICVs settings. This is because of the inherent uncertainties existed in the studied geological zones and reservoirs. To find the optimum ICV configuration which optimizes an objective function, namely increasing hydrocarbon production, improving NPV, or minimizing unwanted fluid production, ICVs should be operated so that each setting has a significant effect on improving the objective function.

The ICVs performance optimization is realized by adjusting the ICVs settings in the best position between the fully open and fully closed situations. The degree of valve openness is varied as different scenarios from fully closed to fully open in the process of objective function optimization. This procedure is described in Figure 3. For ICV setting optimization, all the possible ICV configurations should be investigated. According to the degree of ICV openness, different cross area sections (A_c) will be assigned based on the manufacturer regulation. In reservoir life cycle, it is obvious that ICVs cannot operate just in one configuration for the whole duration. ICV configurations, therefore, should be optimized in several time periods. This process started with optimizing the objective function in the first time step. For the next time period, the ICVs settings will be optimized based on the re-evaluation of the objective function. This process continues until the end of the reservoir development period. Shorter time steps add flexibility to better optimize the objective function with the cost of heavier calculations and, of course, more operational complexity; thus it is not feasible to change ICVs setting in short time intervals. This duration is usually between 6 months to 2 years.

In the next sections, the results of the proposed optimization methodology in two field case studies are presented and discussed in details.

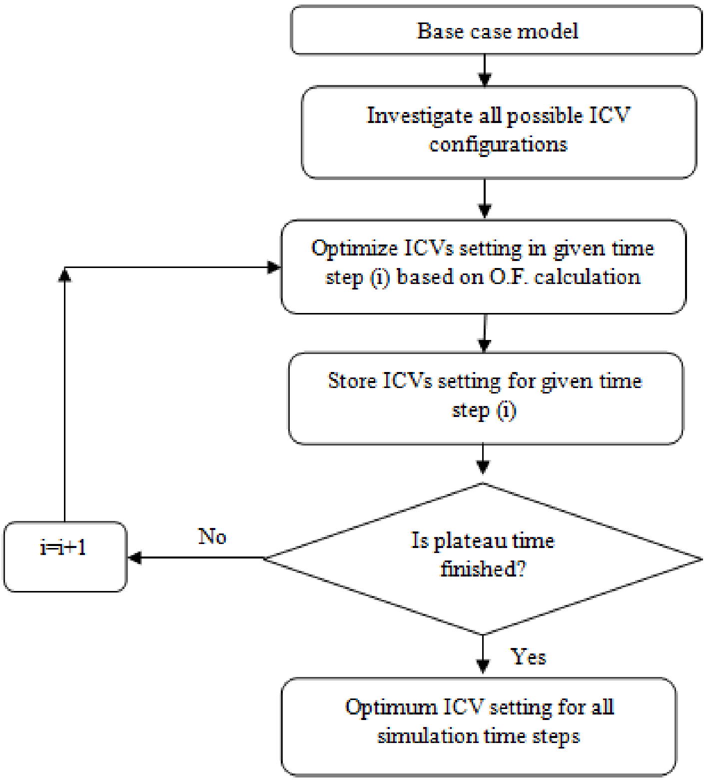

Figure 3
The optimization procedure.

5. Case study 1

An Iranian oil field is considered to investigate the proposed ICV performance optimization in detail. Ilam formation is the producing oil layer in this field, which is characterized by a complex sequence of shale and limestone intervals. The average reservoir porosity and permeability are 20% and 80 mD respectively. The areal grid is 100×100 meters square shaped with a vertical grid size varies from 3 to 12 meters according to the quality of the reservoir layers. The up-scaled model is gridded into 138 cells in *x* direction, 106 cells in *y* direction, and 19 cells in *z* direction, making a total number of 277932 grid cells.

This field is supported with a strong aquifer, which makes water coning very likely in the production wells. The properties of the aquifer including permeability, porosity, total compressibility, external radius, thickness, and angle of influence are presented in Table 2. Figure 4 shows the schematic of the reservoir. 4 wells, all of which are located in the crestal area of the reservoir, are considered in the optimization study. Each well is equipped with 2 ICVs the sizes and settings of which should be optimized during 20 years of the field production life. The initial conditions of this case study, including pressure, datum depth, gas-oil contact, and water-oil contact are listed in Table 3.

Table 2
Aquifer properties for case study 1.

Property	Value for case study 1	Value for case study 2
Permeability (mD)	5	5
Porosity	0.07	0.25
Total Compressibility (1/bar)	0.0000345	0.00001
External Radius (m)	7000	5000
Thickness (m)	50	100
Angle of influence (deg)	180	360

Table 3
Initial condition for case study 1.

Property	Value for case study 1	Value for case study 2
Pressure (bar)	389	98.8000
Datum depth (m)	-3350	-889.00
Gas-oil contact (m)	0.00	0.00
Water-oil contact (m)	3435	-945.00

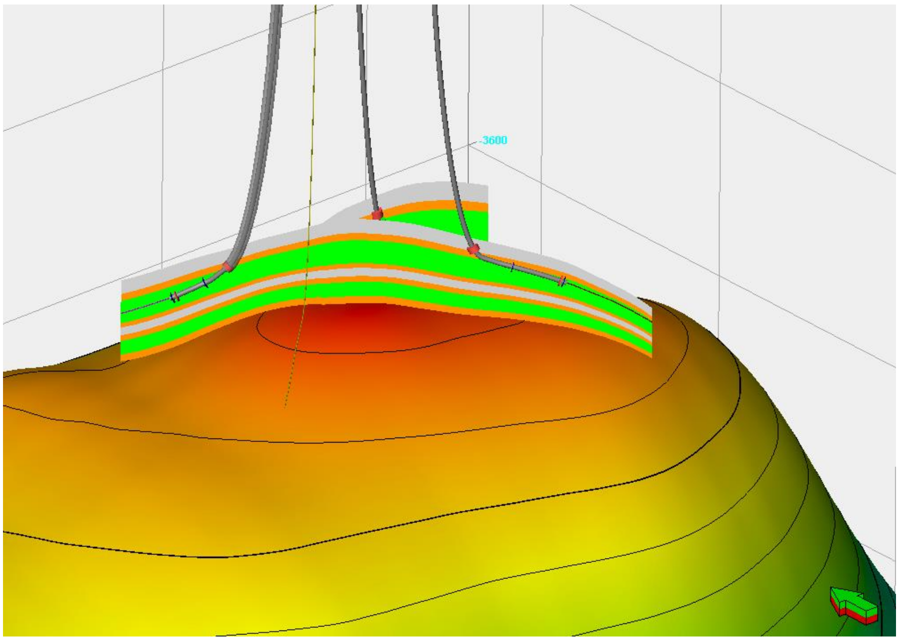

Figure 4
A schematic of the selected wells and ICVs.

The objective function is maximizing cumulative oil production subjected to the total plateau production of 10000 bbl./day.

The optimization routines are performed on sizes and settings of the 8 ICVs of the oil wells. The oil and water flow rates from each ICV are shown respectively in Figures 5 and 6. According to the reservoir characteristic and production strategy, ICVs can be opened or closed during some specific duration. Because of work-over expenses to change the well completion, all the ICVs, which might be required in the future, were installed. For example, ICV42(2) remained closed for some 17 years and then became a major oil producer valve as shown in Figure 5.

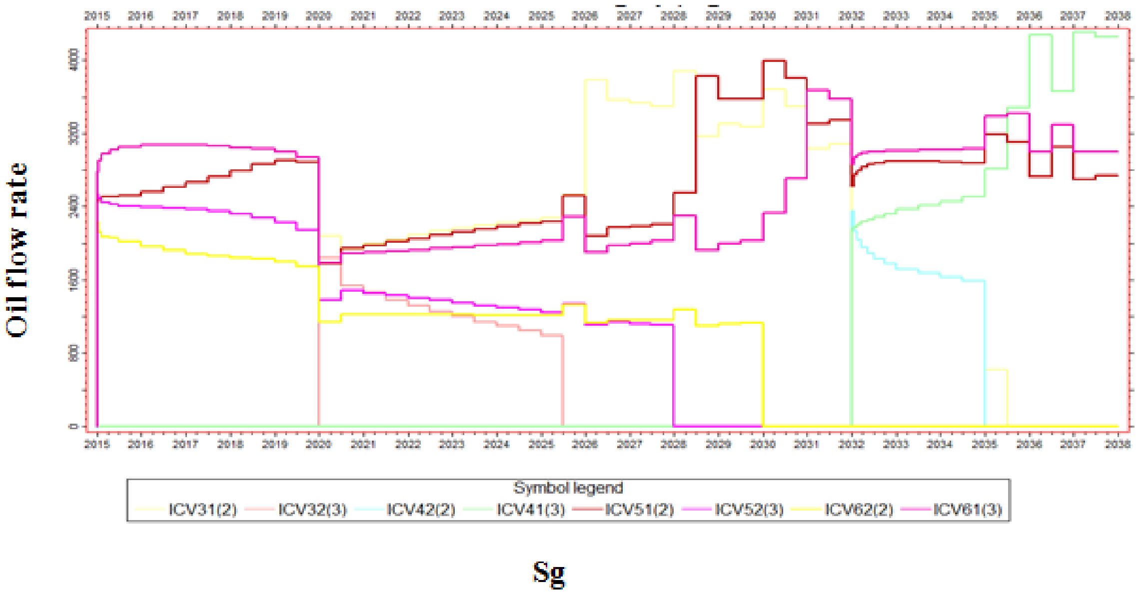

Figure 5
ICVs oil flow rates.

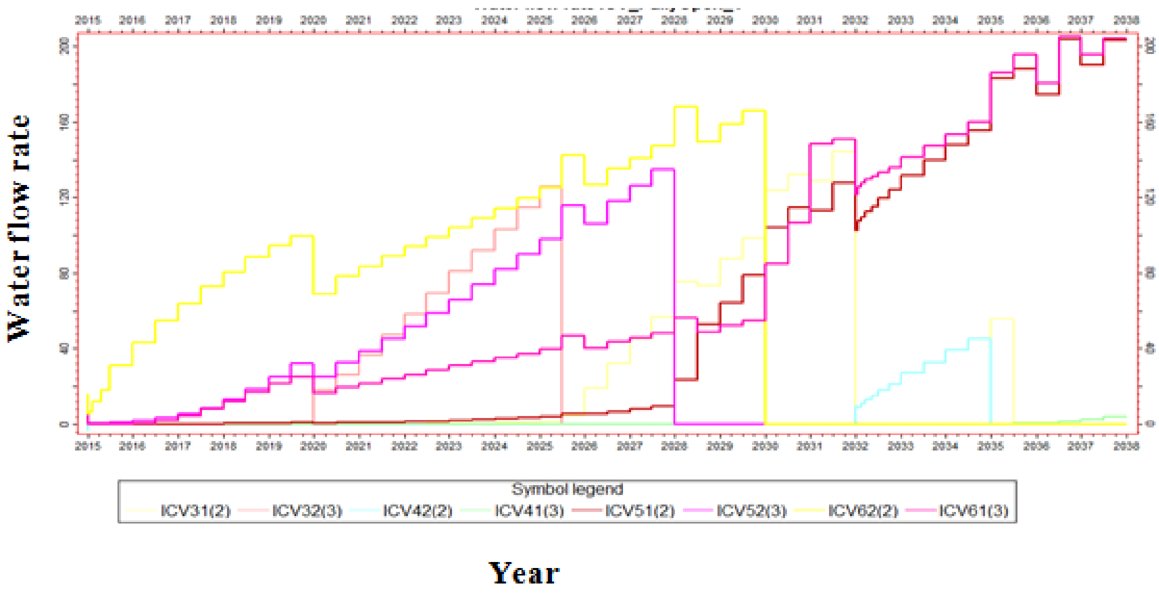

Figure 6
ICVs water flow rates.

The impact of the optimized smart well technology on the field oil production rate and cumulative productions, compared to the conventional wells, are shown in Figures 7 and 8 respectively. As can be seen, considerable improvements in sustaining the plateau period, cumulative oil production, and water production control were obtained with these optimized ICVs. During the optimization process, a water cut criterion of 30% was applied due to surface facility limitations.

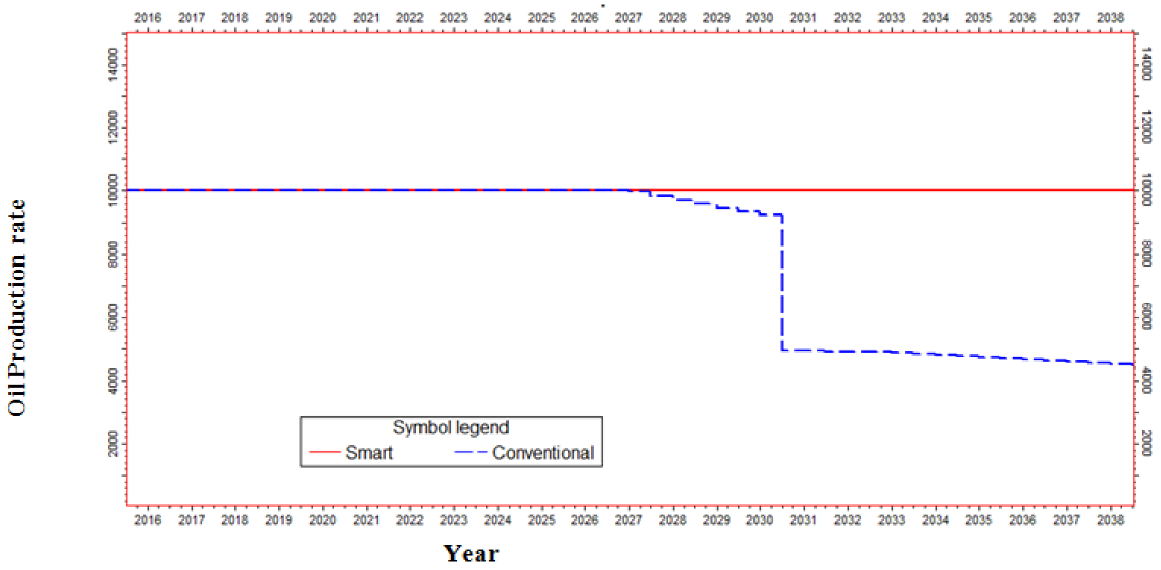

Figure 7
Field oil production in conventional and optimized completions.

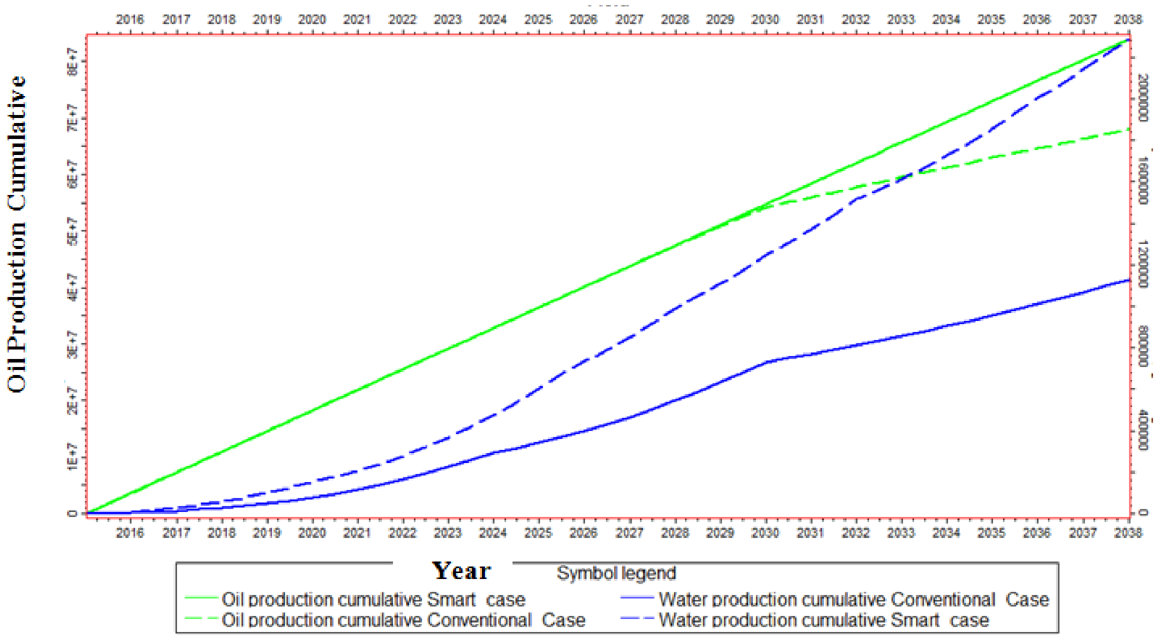

Figure 8
Field cumulative oil and water production in conventional and optimized completions.

6. Case study 2

In this case study, a sector model of an Iranian oil field was selected. This field has 3 different reservoir oil zones separated by non-reservoir flow barriers. The main production mechanism of the reservoir is a water drive from an aquifer. The general characteristic of these oil layers are tabulated in Table 4.

Table 4

Characteristics of 3 oil zones for case study 2.

Zone number	Porosity	Permeability (mD)	Initial pressure (bar)
Madaud	0.17	5	98.8
Upper Dariyan	0.23	4.7	112
Lower Dariyan	0.27	4.8	120

Areal grid is 100×100 meters square shaped with a vertical grid size varies from 3 to 12 meters according to the quality of the reservoir layers. The up-scaled model is gridded into 138 cells in *x* direction, 106 cells in *y* direction, and 19 cells in *z* direction, making a total number of 277932 grid cells.

This field is supported with a strong aquifer which makes water coning very likely in the production wells. The properties of the aquifer, including permeability, porosity, total compressibility, external radius, thickness, and angle of influence are presented in Table 2.

The initial conditions of this case study, including pressure, datum depth, gas-oil contact, and water-oil contact are listed in Table 3. Furthermore, a typical sample of the relative permeability curve is shown in Figure 9.

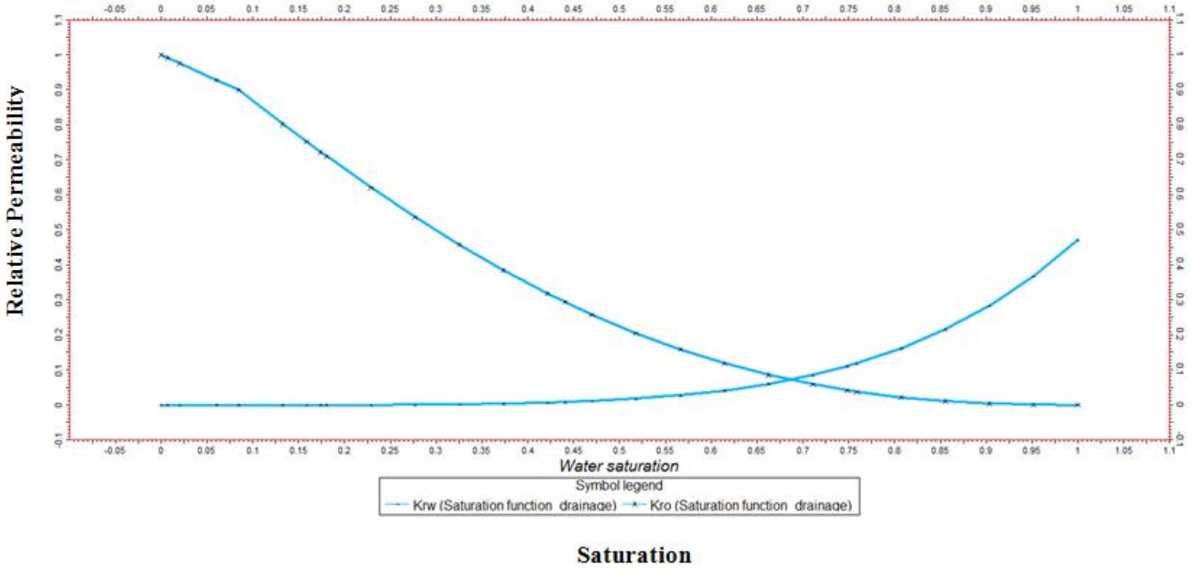

Figure 9

Water-oil relative permeability curve.

In this case, a multilateral well with three legs is considered (Figure 10) and each leg is about 2100 meter long. The average reservoir porosity, water saturation, and reservoir thickness are 0.22 m, 0.65 m, and 53 m respectively. 3 ICVs are placed in the main hole to control the production of the well legs. Eleven settings are considered for each ICV from its fully open to fully closed positions. Using ICV size determination workflow (Figure 2), the value of 0.01 ft^2 was obtained for the ICV size.

Two different strategies of conventional and intelligent completion were employed and compared. In the conventional strategy, it was assumed that all the ICVs can only take their fully open positions. This scenario resulted to excess water production more than the tolerable range. Mitigating the situation, the ICVs setting was optimized to improve oil production within an acceptable water production range. Herein, the difference between oil production and water production was considered as an objective function. Monitoring the objective function during ICVs setting optimization, defined different ICV configurations were defined in different time periods. The optimized ICVs configurations after applying the proposed workflow are listed in Table 5.

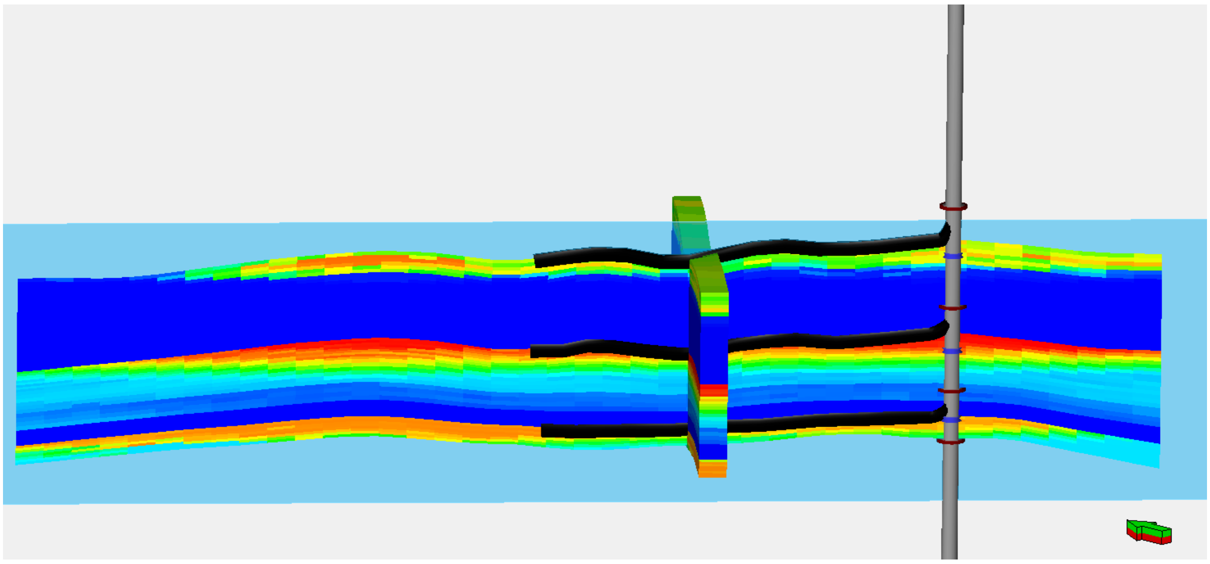

Figure 10
A schematic diagram of the selected well and ICVs.

Table 5
ICVs settings in the optimized scenario.

Duration	ICV1	ICV2	ICV3
2011-2014	1	1	1
2014-2015	0.433	1	0.121
2015-2017	0.025	1	0.121
2017-2019	0.069	0.433	0.069
2019-2021	0.018	1	0.018
2021-2022	0.069	1	0
2022-2023	0	1	0.121
2023-2025	0	1	0.069

As can be seen in Figure 11, the oil production in the conventional completion case is marginally more than that of the optimized case; however, considerably less water is produced with the optimized ICVs as shown in Figure 12. Water cut is therefore decreased from 80% in the conventional wells to 30% in the optimized ICVs case (Figure 13). Table 6 presents the improvement in the objective function after the optimized intelligent well completion was employed in this case.

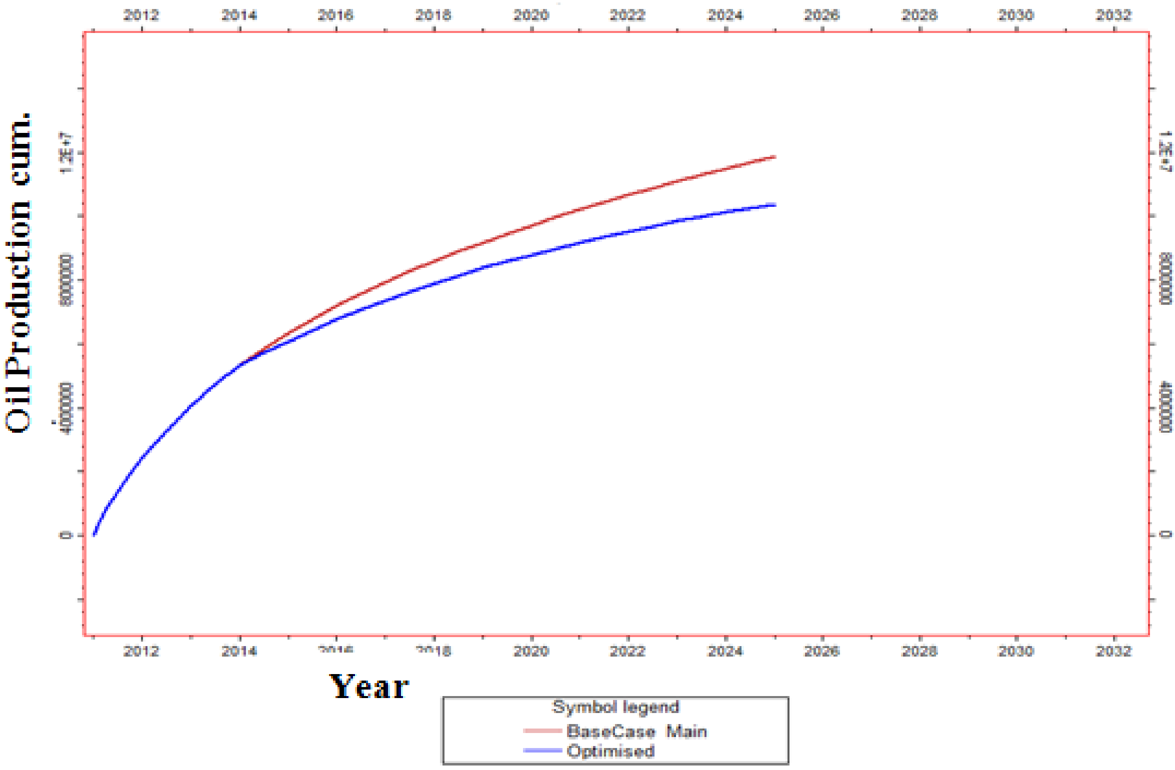

Figure 11
A cumulative comparison of the oil production.

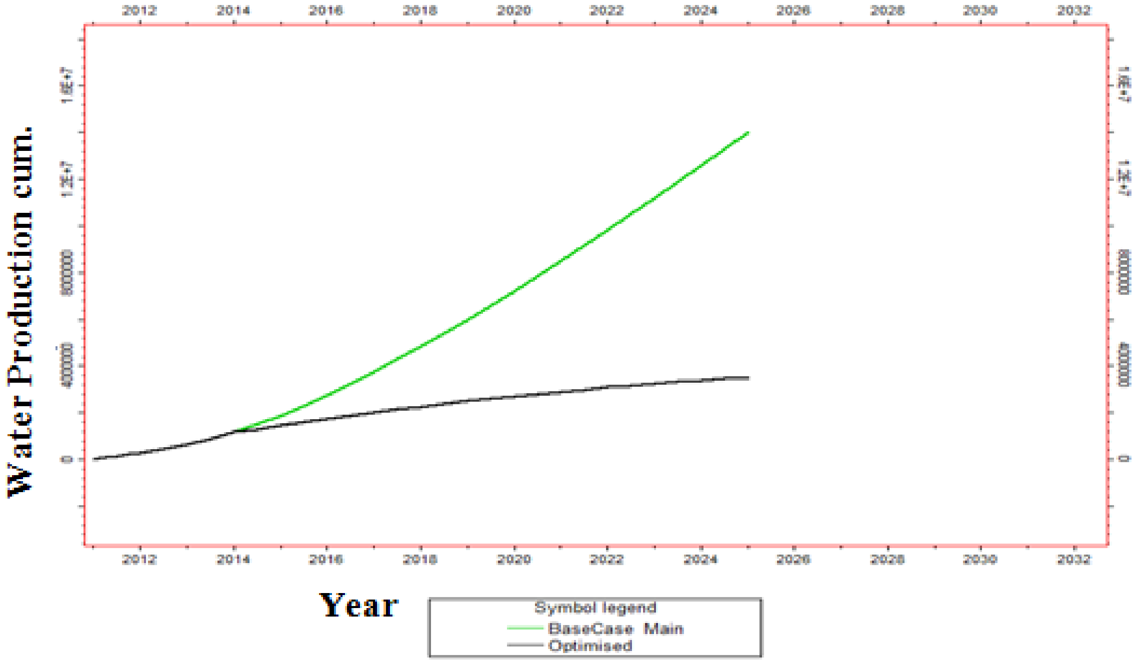

Figure 12
A cumulative comparison of the water production.

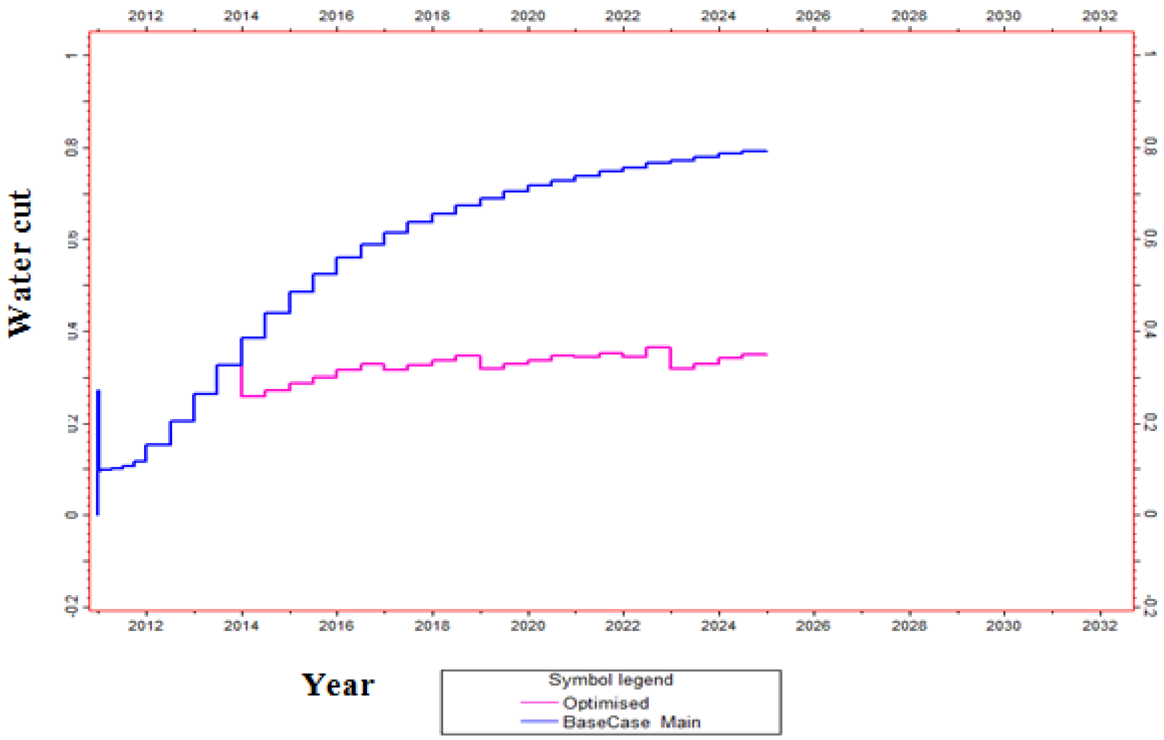

Figure 13
A comparison of water cut.

Table 6
Summary production of the conventional and optimized cases.

	Conventional Case	Optimized Case
Cumulative oil production (bbl.)	11874756	10368415
Cumulative water production (bbl.)	14021017	3526102
Objective function (O-W)	-2146261	6842313

7. Conclusions

- A methodology which combines intelligent well/field screening workflow and their performance optimizations was developed. In this methodology, all the technical and economical parameters are extracted and ranked. The selected wells/fields can be used for a further study in terms of production optimization.
- ICV size is one of the main concerns for the production optimization. A methodology to determine the appropriate ICV size is presented, in which the objective functions starts to change in the candidate well.
- Having obtaining the ICVs correct size and placement, the well performance should then be optimized by adjusting the ICVs settings. This is realized by adjusting the ICVs settings in the best position between the fully open and fully closed situations.
- ICVs cannot operate just in one configuration for the whole reservoir life cycle. ICVs configurations are therefore optimized in several time periods based on the objective function re-evaluation.

- Optimization can be performed with different objective functions in the proposed methodology. The optimization process was investigated in two real reservoirs as case studies each of which had its own objective function. Although the selection of the objective function can change the optimization results, this subject was not studied herein; it is another fascinating area which should extensively be covered in a separate study.

Nomenclature

AHP	: Analytical hierarchy process
GOC	: Gas oil contact
ICD	: Interval control device
ICV	: Interval control valve
IWT	: Intelligent well technology
MCDM	: Multi criteria decision making
MRC	: Maximum reservoir contact
O.F.	: Objective function
WOC	: Water oil contact

References

Aitokhuehi, I, Real Time Optimization of Smart Wells, Master of Science Dissertation, Stanford University, 2004.

Al-Ghareeb, M., Monitoring and Control of Smart Wells, Master of Science Dissertation, Stanford University, 2009.

Alhuthali, A. H., Datta-Gupta, A., Bevan, Y., and Fontanilla, J. P., Field Applications of Waterflood Optimization via Optimal Rate Control with Smart Wells, Woodland, Texas, 2009.

Arenas, E. and Dolle, N. Smart Waterflooding Tight Fractured Reservoirs Using Inflow Control Valves, Denver, Colorado, 2003.

Behrouz, T., Motahhari, M., Nadripari, M. and Hendi, S., Presenting a Method for Determining Coefficient of Geological, Environmental and Economic Factors to Implement Intelligent Well Technology, Iranian Journal of Petroleum Geology, Vol. 3 , No. 3, p. 77-99, 2013.

Brouwer, D. R., Jansen, J. D., Van Der Starre, S., Van Kruijsdijk, C. P. J. W., and Berentsen, C. W. J., Recovery Increase through Water Flooding with Smart Well Technology, The Hague, The Netherlands, 2001.

Glandt, A. C., Reservoir Aspect of Smart Wells, Paper Presented at the SPE Latin American and Caribbean Petroleum Engineering Conference held in Port-of-Spain, Trinidad, West Indies, 27-30 April 2003.

Going, W. S., Thigpen, P. M., and Anderson, A. B., Intelligent-well Technology: Are We Ready for Closed Loop Control, Paper Presented at SPE Intelligent Energy Conference and Exhibition held in Amsterdam, The Netherlands, 11-13 April 2006.

Holmes, J. A., Barkve, T., and Lund, Ø., Application of a Multi-segment Well Model to Simulate Flow in Advanced Wells, Paper SPE 50646 Presented at the SPE European Petroleum Conference, The Hague, Netherlands, 20-22 October, 1998.

Ibrahim, H., Smart Wells Experiences and Best Practices at Haradh-III, Ghawar Field, Paper SPE 105618 Presented at the 15th SPE Middle East Oil & Gas Show, Bahrain International Exhibition Centre, Bahrain, 11-14 March, 2007.

Leo de Best, Frans van den Berg. Smart fields-Making the Most of Our Assets, Paper Presented at the SPE Russian Oil and Gas Technical Conference and Exhibition held in Moscow, Russia, 3-6 October, 2006.

Mochizuki, M., Saputelli, S., L. A., Kabir, C. S., Cramer, R., Lochmann, M.J., Topsail Ventures, Reese, R. D., Harms, L. K., Sisk, C. D., Hite, J. R., Real Time Optimization: Classification and Assessment, Paper Presented at Annual Technical Conference and Exhibition held in Houston, Texas, U.S.A., 26-29 September, 2004.

Mubarak, M., Real Time Reservoir Management from Data Acquisition through Implementation: Close-loop Approach, Amsterdam, The Netherlands, 2008.

Salamy, S. P., Maximum Reservoir Contact (MRC) Wells: A New Generation of Wells for Developing Tight Reservoir Facies, In: SPE Distinguish Lecturer Series, URL http://dx.doi.org/10.2118/108806-DL, 2005.

Vasily, M., Analytical Modeling of Wells with inflow Control Devices, Ph.D. Dissertation , Heriot-Watt University, 2010.

Yeten, B., Durlofsky, L. J., and Aziz, K., Optimization of Smart Well Control, Paper SPE 79031 Presented at the SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference, Calgary, Canada, 4-7 November, 2002.

Yeten, B., Durlofsky, L. J., and Aziz, K., Optimization of Nonconventional Well Type, Location and Trajectory, SPE Journal, Vo. 8, No. 3, p. 200-210, 2003.