IJST (2014) 38A4: 481-487
Iranian Journal of Science & Technology

http://ijsts.shirazu.ac.ir

Effective workflow for optimization of intelligent well completions

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Abstract

Intelligent wells provide the ability for monitoring and control of downhole environment of the wells. Downhole monitoring is achieved through sensors while control is realized with downhole valves. Recovery from intelligent wells can be improved by proper selection of candidate wells/fields and optimizing the number, location and performance of the installed Interval Control Valves. Design criteria, however, suffer from incomplete understanding of the precise determination of these parameters, their interaction and combined effects.
Having known the candidate well, we presented a new workflow to optimize the number, location and performance of Interval Control Valves as the main element of intelligent wells. This is a very computationally demanding and time consuming task; therefore a proxy model is developed and applied to speed up the process. Primary evaluations show that optimization of each parameter independently is not the best practice because of their interrelation and combined effects on objective function. An integrated optimization approach is therefore developed in which all the Interval Control Valves' parameters are optimized together during the process. Considerable improvement in cumulative oil production and control of produced water is achieved by applying this method on real field data.

***Keywords**:* Intelligent well; optimization; proxy model; workflow; interval control valve (ICV)

1. Introduction

Intelligent wells, equipped with special downhole control devices, provide opportunity to improve recovery factor by controlling the flow of undesired fluids from heterogeneous/layered reservoirs. (Al-Ghareeb, 2009)

Flow monitoring, flow control and well/field optimization are the main elements of intelligent wells. Flow monitoring involves sophisticated sensors and Flow control needs complex ICVs, packers, cables, etc. Optimization process consists of data processing and decision tools for reservoir management.

Different monitoring sensors can be used according to the wellbore static and dynamic conditions. Pressure and temperature sensors are usually used in every intelligent well, while water cut, gas oil ratio, and composition sensors may be applied in special wells with specific purposes.

Packers are used to isolate different reservoir zones which need to be controlled individually by ICVs. ICVs are classified as on/off, discrete and infinite variables that will be used according to their specific application in each interval or reservoir zone. Using intelligent well technology, the objective can be improved with balanced rate allocation from each individual zone (Al-Ghareeb, 2009) or limiting undesired fluid flow from some well segments. It should be emphasized that installation of all the intelligent devices does not mean that we have intelligent well-it should have added value in reservoir management chain (Ebadi and Davies, 2006).

Due to different uncertainties in subsurface rock and fluid data, risk of device failure and their operational reliability, it is difficult in practice to optimize production from intelligent wells. Contrary to traditional wells where surface control is applied to manage the production flow, optimization of intelligent wells requires to evaluate the combination of the number and locate ICVs and their functionality (ICV setting) to reach the maximum efficiency.

Generally there are two different attitudes in intelligent well/field operations: 1-Defensive/reactive approach in which intelligent well reacts after problem detection to reduce production of undesired fluid; 2-Proactive approach where intelligent well technology is used before any problem occurrence (Ebadi and Davies, 2006). Various reactive and proactive techniques are presented to optimize production from intelligent wells (Bieker et al., 2006). Jalali et al. (1998) successfully improved the recovery of an intelligent

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Received: 14 December 2013 / Accepted: 24 November 2014

gas well with two different layers. They produced from the top layer without any intervention while the bottom layer was being controlled. Brouwer et al. (2001) used static optimization in the defensive manner in a waterflooding project. They used just On/Off valves in their study. These valves were closed as water broke through the well. Arenas and Dolle (2003) used a pressure cycling concept in a waterflooding project within a fractured reservoir. Their evaluation was based on 2D model with horizontal production and injection wells. Naus, Dolle, and Jansen (2006) presented a methodology whereby a well flow rate was closely related to the ICV setting. Mubarak et al. (2007) did a production test in defensive mode to minimize water production from a multilateral intelligent well. Alhuthali et al. (2009) presented a waterflooding optimization method in intelligent wells to achieve the optimum oil production rate.

Intelligent well elements should be carefully designed, applied and operated and performance of intelligent wells should be continuously tuned with time to add the most value in reservoir management process. ICVs are the main element of intelligent wells. As mentioned before, three main important parameters related to ICVs are their numbers, location and functionalities. Implementing too many ICVs obviously increase the complexity and cost of the wells and potentially decrease the reliability. Too few ICVs will not provide adequate flexibility to react against subsurface problems (Ebadi, 2006). ICVs can improve well efficiency if they are located and set properly. However optimizing all the ICVs parameters is a challenge we deal with in this paper.

2. Methodology

Three important ICV parameters i.e., the number of ICVs, their location and their performance, are considered in our methodology. Performance optimization of intelligent wells is only possible through optimization of all these parameters. In the following, we describe the workflow in which the optimization of these parameters is achieved.

a) Optimizing the number of ICVs

Heterogeneities in porosity, permeability, fluid saturation, pressure and other rock and fluid properties are commonly encountered in real hydrocarbon reservoirs. Intelligent well technology should effectively control downhole flow behavior driven by all these heterogeneities. To this end, main dynamic flow zones in each intelligent well should be correctly identified and controlled by ICVs.

Considering the type of the well and related geological, petrophysical, well test and core data, a workflow was developed to identify prevailing dynamic rock types and hence the number of ICVs which are needed for effective application of intelligent well technology. Fig.1 schematically shows the proposed workflow (workflow #1).

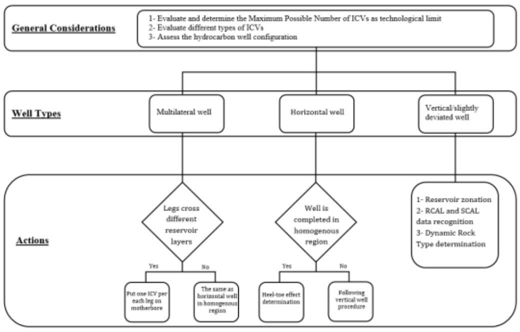

Fig. 1. ICVs number determination work flow

In addition to the rock types, the number of ICVs in this workflow is restricted to some general operating considerations. For instance, the maximum number of ICVs used in multilateral well according to operational difficulties is six ICVs per well (Birchenko, V.M. et al., 2008). In vertical or slightly deviated wells, intervals with different dynamic rock types should be identified. These intervals can be considered as the maximum number of ICVs which should be optimized based on techno-economical analysis in the next steps. Dynamic rock typing is a multidisciplinary task of incorporating all the geological, petrophysical, RCAL, SCAL, and PLT data. The same procedure is also applied for horizontal wells, with consideration of minimizing the so-called the heel-to-toe effect. Ratio of toe productivity index relative to heel productivity index (J_t/J_h) is used to locate the intervals in which ICVs are needed. Multilateral wells are most suitable to be equipped with one ICV for each leg on the mainbore to control every lateral independently. Therefore, the problems of water or gas conning in each leg can be treated without interfering in the production of other legs.

b) ICV location optimization

Deep geological insight of the target reservoir is the foundation for proper placement of ICVs. Correct knowledge of drive mechanisms also improves our forecast of fluid front movement, allowing optimum placement of ICVs along the well. Considering these technical points, we propose an integrated procedure to determine appropriate locations of ICVs based on objective function that will be discussed later. Some reservoir parameters such as permeability (K), distance from Water Oil Contact (WOC), distance from Gas Oil Contact (GOC), well production rate and some other static and dynamic properties are the main players in our proposed procedure.

Placement of ICVs is straightforward in vertical or slightly deviated wells with simple expansion, gas cap drive, or bottom water drive mechanisms. This is because the reservoir heterogeneity/layering does not dictate the displacement process within the reservoir (and undesired fluid production). Hence ICVs should be located at the bottom or the top of the oil zone respectively in a reservoir producing under gas cap or water drive mechanism. The same procedure can be followed when solution gas drive is the main production mechanism of the reservoir.

In multilateral wells, current technology limits ICV placement in main laterals rather than different sections within a lateral.

The situation becomes more complex in heterogeneous layered reservoirs with dominant displacement mechanisms such as edge-drive aquifers and/or fluid injection in the oil zone. Multiple simulation runs are required in these cases to optimize ICVs locations based on a predefined objective function such as oil production, water production, and/or recovery factor. The accuracy in these situations is chiefly controlled by the number of simulation runs which makes the process very computationally expensive and time consuming.

To speed up the process, a proxy model was used as a fast approximation of the massive real model to optimize the ICVs' locations. Proxies are most suited in situations where a large number of time-demanding model evaluations have to be carried out, similar to what we are dealing with here. When real model is replaced by a proxy algorithm, every assessment is just an analytical function with identified coefficients. In order to set up these coefficients, the proxy must closely follow the real model using several carefully chosen sampling points in a well-known training process. The real model must be assessed at these sample points in order to build the training data. Proxy model is generated based on response surface method with quadratic model type and Monte-Carlo sampling approach. Fig.2 shows the designed workflow for ICV placement optimization (workflow #2).

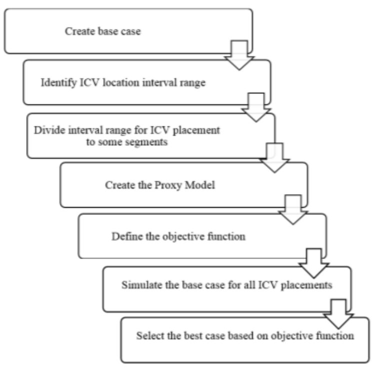

Fig. 2. ICV placement Work flow

c) ICV performance optimization

In order to obtain the right ICV setting to optimize the objective function (whether it is improving oil recovery, maximizing NPV or minimizing unwanted fluid production), ICVs should be designed in such a methodology that each setting has meaningful effect on the objective function. ICVs should be designed according to the existing subsurface operational conditions. The condition experienced by an ICV in high productive reservoir is different from that of a low productive one, resulting in different requirements for ICV design.

Determining ICV flow area at fully open positions is a concern in each intelligent reservoir application. It is completely case sensitive and depends on reservoir characteristics. Fig.3 illustrates the design procedure for ICV size that was developed in this paper. Before starting workflow encoding, the base case of the reservoir model from static to dynamic reservoir model should be prepared (if not existed) as priori.

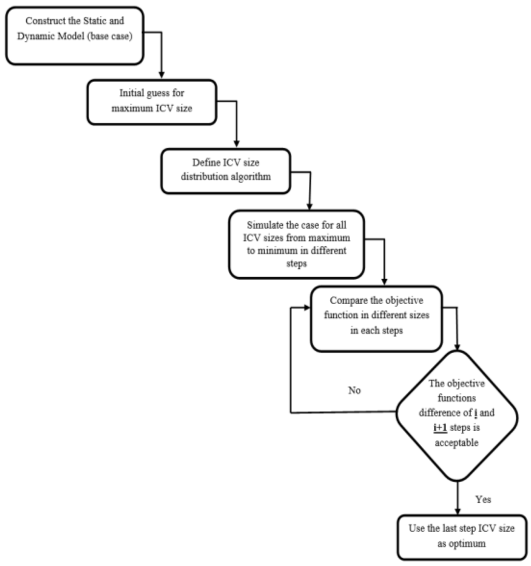

Fig. 3. ICV Design procedure

We run the base case in different ICV cross sectional areas (Ac) that ranges from 0 to an assumed maximum possible value. Our purpose here is to determine the proper Ac of ICV that has a reasonable effect on the objective function. We take 10% change in objective function as reasonable and the corresponding Ac as the proper cross sectional area for ICV in the target well/reservoir. However this criterion depends on the accuracy expected from ICV size design algorithm.

After designing ICV size, the ICV setting, i.e. its openness degree, should be optimized based on the objective function evaluation in the current time step; this evaluation procedure should be repeated during plateau time period or any time of interest of reservoir life. The proposed optimization procedure described above is shown in detail in Fig.4 (workflow #3).

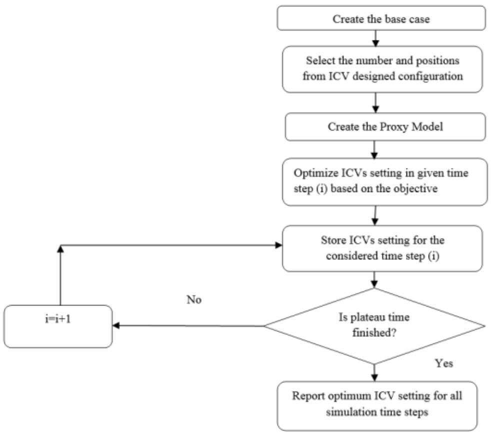

Fig. 4. ICV performance optimization work flow

d) Integrated Optimization:

The above mentioned optimization process is a single parameter optimization approach in which only one of the number, location or configuration parameters of ICVs is optimized while the others are fixed. This is obviously a simple and fast procedure, but not necessarily returns the best results as the ICV parameters are not independent. In order to consider the interrelation of the parameters, an integrated optimization approach is practiced in which all the three parameters are changed during the process. The proxy model is used to calculate the objective function in each combination of ICVs parameters. Optimization workflow is applied to guide the parameters toward their optimum values. Fig.5 shows the flowchart of integrated optimization process as described above. This flowchart integrates all three mentioned independent optimization workflows and uses them simultaneously to optimize all the key intelligent well parameters together.

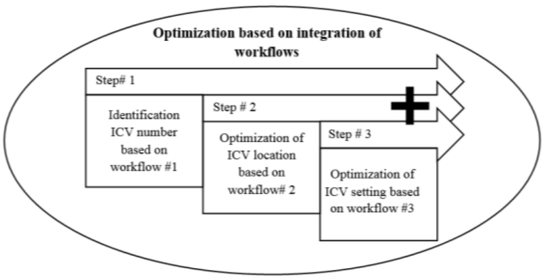

Fig. 5. Workflow of ICV parameter integration for production optimization

3. Application and Results

As an example, a sector model of a real oil field is considered for detailed description of the proposed workflows. The field has three different oil zones separated by shaly barriers based on reservoir characterization and geological evaluations. The general characteristics of these three oil zones are listed in Table 1.

Table 1. Reservoir properties of three different zones

Zone name	Porosity	Water saturation	Thickness (m)	Initial pressure (bar)
Madaud	0.17	0.78	55	98.8
Upper Dariyan	0.23	0.65	75	112
Lower Dariyan	0.27	0.51	30	120

A multilateral well with three legs is used to produce oil from all zones. Fig.6 shows a cross section of the reservoir and this multilateral well. In this case, the number of reservoir zones which actually dictate the different behavior, is a good suggestion for the number of required ICVs.

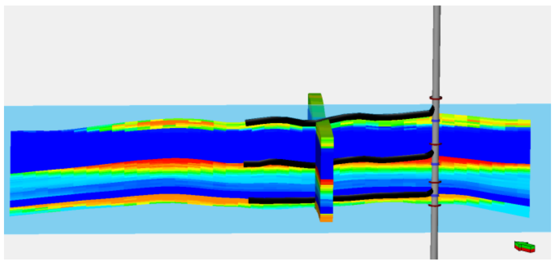

Fig. 6. Sector view of selected well and ICVs

Then, the locations of ICVs are optimized based on the objective function. The mentioned multilateral well is drilled in the oil field with nine different geological zones, three of which are oil bearing (Madaud 2, upper Daryian and lower Dariyan). These oil zones are located at 880-980, 990-1070 and 1080-1130 m respectively as shown in Fig. 7. In this step, the optimization workflow was used to vary the ICVs positions in the mentioned intervals such that the best value of a predefined objective function is obtained. Difference between cumulative oil and water production is considered as the objective function (O.F.) in this case:

Objective Function (O.F.) = Cumulative Oil Production - Cumulative Water Production

Therefore, the objective function as defined above should be maximized in the optimization process of ICVs parameters.

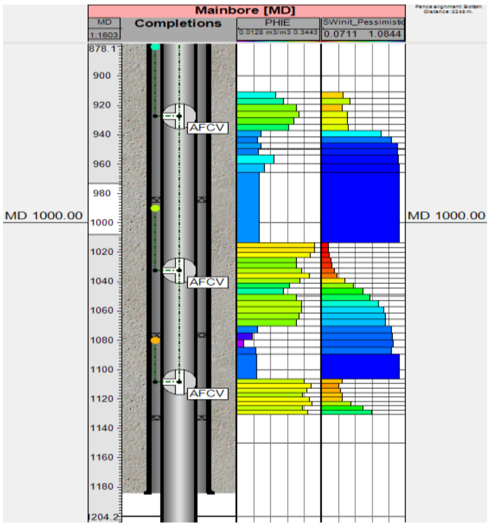

Fig. 7. ICV placement in intelligent well

The position of each ICV is varied between the lower and upper packers that isolate the corresponding oil zone. For each ICV location during the selected interval, objective function is calculated from the proxy model. A total numbers of 200 proxy runs is performed to investigate the ICVs locations (scenarios). The best locations of the three ICVs which maximized the objective function are obtained. The independent optimized ICV locations are shown in Table 2. Note that the number and performance of ICVs are known and fixed when investigating the effect of ICV locations as a single parameter.

Table 2. Optimized results for ICV placement optimization (single parameter)

ICV1 location (m)	ICV2 location (m)	ICV3 location (m)
930	1070	1087

In the next step, the performances of ICVs are optimized. Eleven positions including on and off situations are considered for each ICV. The degree of valve openness is varied as different scenarios from fully closed to fully open positions in the process of optimizing the objective function. Totally, 1331 different cases are investigated.

Considering reservoir characteristics summarized in Table 1, Maudud and Lower-Dariyan formations show the highest and lowest water saturation values, respectively. The ICVs' configuration optimization algorithm as described above, correctly adjusts the ICVs' openness from fully open to fully close situation as shown in Table 3 to maximize (minimize) production of oil (water) formulated in the objective function. ICVs are set less opened as water saturation increased in the layers to reduce produced water-cut in this example model. Note that the number and location of ICVs are known and fixed when investigating the effect of ICV performance as single parameter.

Table 3. Optimized results for ICV performance optimization (single parameter)

ICV1 size setting (fraction)	ICV2 size setting (fraction)	ICV3 size setting (fraction)
0.5	0.8	0.9

In the final step, field example data are used again to evaluate the performance of integrated optimization procedure. Considering geological zonation and reservoir properties, three ICVs are proposed and their optimized locations and settings (openness) are obtained as given in Table 4 based on maximizing the objective function.

Table 4. Optimized results from integrated ICV optimization

ICV1 size setting (fraction)	ICV2 size setting (fraction)	ICV3 size setting (fraction)	ICV1 location (m)	ICV2 location (m)	ICV3 location (m)
0.5	0.6	1.0	966	1070	1080

The calculated objective function by this integrated approach is clearly better than previous single-parameter optimization approach with the cost of more computational effort and time. As mentioned before, the proxy model is developed and applied to speed up the process. The integrated scenario without using the proxy model takes about 260 minutes to obtain the optimum parameters, while it takes only two minutes when using the proxy model.

Figure 8 shows the improvement in the objective function (cumulative oil production minus cumulative water production) of the integrated approach in comparison to the single-parameter optimization method. Comparison of cumulative oil and water production of the best single-parameter optimization approach and the integrated optimization method are shown in Figs. 9 to 11.

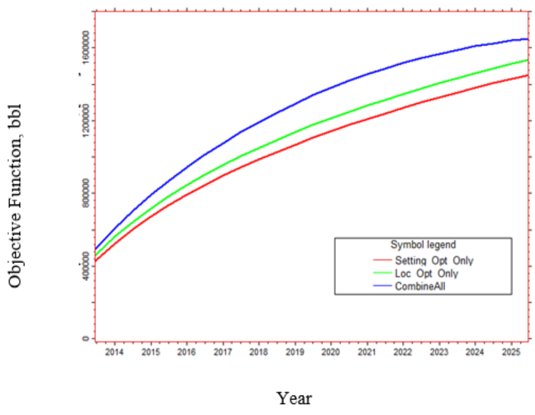

Fig. 8. Comparison of objective function of single parameter vs. integrated optimization approaches

Cumulative oil production is increased by 2.35 MMSTB while that of the water is increased by 692 MSTB in the integrated optimization approach.

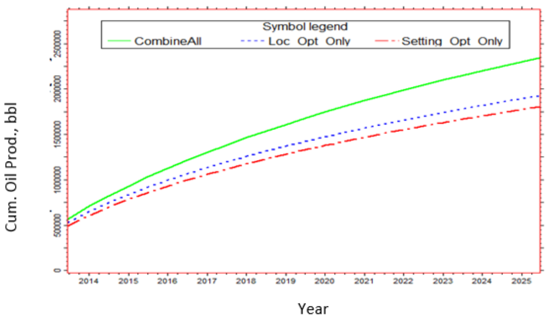

Fig. 9. Cumulative oil production of location optimization, setting optimization and integrated optimization cases

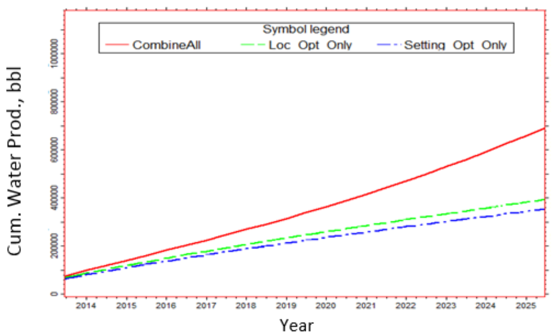

Fig. 10. Cumulative water production of location optimization, setting optimization and integrated optimization cases

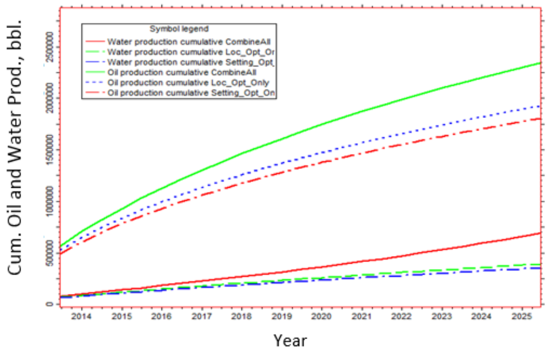

Fig. 11. Cumulative oil and water production of location optimization, setting optimization and integrated optimized cases

4. Conclusion

-Intelligent well technology is becoming more popular as a way to improve reservoir management concepts. Possible applications that could be realized by using intelligent wells mainly depend on appropriate selection of candidate wells/reservoirs and on the optimized implementation of ICVs in this technology.

-Optimization of intelligent wells requires determining the best combination of ICV settings (ICV configuration), number and their locations. A good insight of the geological condition of the reservoir is very important for determining ICVs number and placements. Correct knowledge of drive mechanisms also improves our forecast of fluid front movement, allowing optimum placement of ICVs along the well.

-Determination of ICVs positions and their degree of openness is possible in an integration phase based on maximizing objective function which was considered as the difference between cumulative oil and water production in this study.

-Optimization accuracy of ICVs parameters is chiefly controlled by the number of simulation runs which is the limiting factor in these problems; therefore, a proxy model was used as a fast approximation of massive real reservoir model to speed up the process. The proxy model is generated based on the response surface method with quadratic model type and Monte-Carlo sampling approach.

-Both single-parameter and integrated optimization approaches were examined. In the first method, only one of the number, location and setting of ICVs is optimized while keeping the others fixed; though all parameters are optimized together in the integrated approach. Implementing these optimization approaches in a real oil field data revealed the superior performance of integrated approach in comparison to single-parameter optimization as the ICV parameters are not independent. The presented workflow and ICVs optimization procedures can effectively exploit the benefits of intelligent well technology and associated time and money.

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