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Optimizing the ultimate recovery by infill drilling using streamline simulation

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Abstract:

Even though numerical simulators that use the finite difference approach to model the oil and gas fields and to forecast the field performance are popular in the petroleum industry, they suffer from a very long central processing unit (CPU) time in the complex reservoirs with large number of grids. This issue could be resolved by streamline simulation and it could significantly decrease the runtime. This work explains the the streamline simulation concept and then a real oil field is studied using this technique, the streamline simulation is conducted by a commercial simulator, i.e., FrontSim streamline simulator and then the model was analyzed to find the optimum location of infill wells. In this work, 34 different cases were studied using Streamline simulation method and FrontSim software by considering different arrangement of infill wells. It was concluded that a significant enhancement in the ultimate recovery factor of the oil reservoir could be attained by considering different arrangement of the infill horizontal and vertical wells. It was highlighted that the ultimate recovery factor could be increased significantly, i.e., 13%. Additionally the water cut of the field could be reduced significantly. The novelty of this work is to capture the impact of both vertical and horizontal wells on the ultimate recovery enhancement simultaneously using the concept of streamline simulation and optimization of the field performance using streamline simulation concept.

Keywords: ultimate recovery, recovery factor, streamline simulation, infill well, infill drilling, horizontal well, vertical well, water flooding.

Introduction

Recently, reservoir models are becoming more complex to further demonstrate the geological and fluid dynamic characteristic of the oil and gas reservoirs, consequently these complex reservoir models take a significantly long CPU time (central processing unit time). This issue lead the researches toward the

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application of the streamline method for the complex reservoirs compared to finite difference approach could result in significantly faster CPU time, a reduced amount of computer memory is required and better convergence is achieved (Jian, Zhang, Du, & Yu, 2008; Samier, Quettier, & Thiele, 2002) . In addition to these, this simulation approach which is based on the streamline simulation could provide further information in terms of the conductivity of the well, the drainage volume of the reservoir for each well and finally the well allocation factor, these additional flow information could not be attained by finite difference simulation approach (Thiele & Batycky 2003). Consequently, the streamline simulation approach is much more efficient in the simulation of heterogeneous, large and complex reservoirs compared to the conventional finite difference method. The streamlined based simulation technique decouple the three dimensional problems into a set of several one-dimensional problems in conjunction with a streamline. Several authors have used the streamline concept to model the fluid flow dynamic. The particle tracking concept is used in streamline simulation to express the pathline in three dimensional systems (Datta-Gupta & King, 2007; Dehdari, Aminshahidy, & Tabatabaei-nejad, 2008; Sayyafzadeh, Pourafshari, & Rashidi, 2010). Production from hydrocarbon fields entails accurate determination of properties of the reservoir fluid in conjunction with their positive impact on evaluation of the field behavior and fluid in place volume evaluations (Dowlatabad, Nasriani, Rashidi, & Movahedi, 2017; Nasriani et al., 2017a; Nasriani et al., 2017b; Nasriani, Asadi, Khajenoori, & Masihi, 2015a; Nasriani, Borazjani, Iraji, & Dowlatabad, 2015b). In order to mitigate the destructive impact of reservoir depletion on oil and gas recovery, pressure maintenance and different injection strategies of several fluid are commonly implemented in the petroleum industry (Kalantari Asl, Farhadi, & Nasriani, 2013; Nasiri Ghiri et al., 2015; Nasriani, Borazjani, Sinaei, & Hashemi, 2014; Zareenejad, Kalantariasl, Nasriani, & Zargar, 2015). In addition to infill drilling, hydraulic fracturing and an optimised post fracturing cleanup procedure are usually conducted in unconventional fields to maximise the recovery from oil and gas fields (Jamiolahmady, Alajmi, Nasriani, Ghahri, & Pichestapong, 2014; Nasriani & Jamiolahmady 2018a; Nasriani, Jamiolahmady, & Alajmi, 2014a; Nasriani & Jamiolahmady, 2018a and b; Nasriani, Jamiolahmady, Saif, & Sánchez, 2018c; Nasriani, Jamiolahmady, Alajmi, & Ghahri, 2014b) .

In this work, initially the optimum location of infill wells are specified by streamline simulation technique and subsequently, 6 scenarios (5 Scenario with horizontal well + 1 Scenario with vertical well) were considered for each infill well. Based on the results of the previous 6 scenarios, in addition to those scenarios, 10 new scenarios were studied by investigating the impact of four infill wells in the model, these four wells are either horizontal or vertical. Considering the previous scenarios, 34 scenarios (in total) were studied to enhance the ultimate oil recovery from the field. In this work, the simultaneous impact of vertical and horizontal infill wells on the ultimate recovery enhancement was studied in a mature oil field.

Base case scenario and the initial model

An under-saturated Middle Eastern oil reservoir was considered for this study, in this reservoir the main drive mechanism is the aquifer drive. The current numerical model of the field was considered as the base case model of this study. There are two active aquifer in the reservoir in the southeast and north east of the field which these two aquifers provide a relatively strong drive mechanism in the reservoir. A commercial three-dimensional three phase streamline-based simulator, i.e., FrontSim, was used in this study. FrontSim module is the streamlined based module in the Eclipse software package of Schlumberger Company (Schlumberger, 2015). The numerical model of the field is built using the Corner Point gridding approach with the total number of 6125 grids in the model, the model consist of 35 grid blocks in X and Y direction and 5 grid blocks in the Z direction. The three dimensional model of the reservoir is represented in Figure 1. The field has been producing for a year (1 year production history) previously and the model is set to forecast the next 10 years. The reservoir has nine active production wells. In addition to these production wells, there are three active water injection wells in the reservoirs, these 12 production and injection wells have been

active during the one-year history. One of the key reasons that streamline based simulation was selected for investigation of this reservoir was that this technique is significantly efficient in the modelling of the water injection in the reservoirs as one of the most prevalent enhanced oil recovery techniques in the oil and gas industry. Some constraints and limitations are subjected to the model to make the production of the field economically viable, the constraints are as follow:

Maximum water-cut: 90%;

Maximum water injection-rate: 6,000 STB day-1;

Maximum oil-rate: 2,000 STB day-1.

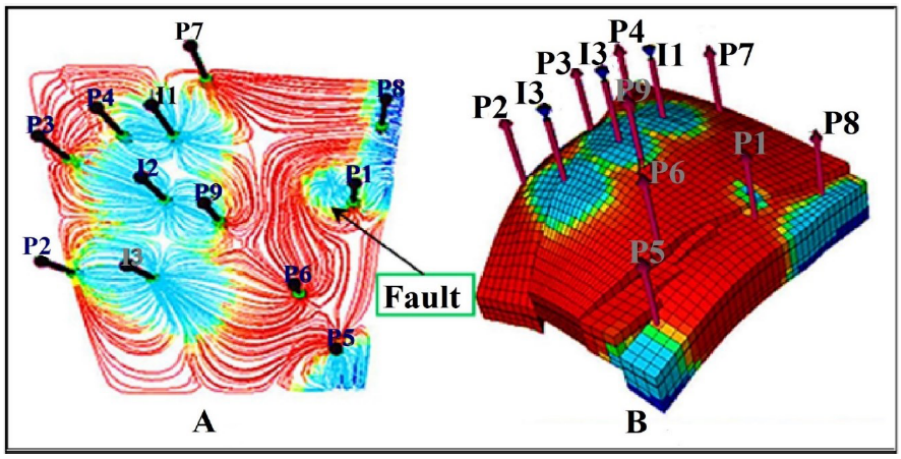

FIGURE 1.
The Model of the Base Case and Location of the Fault, A) Streamline-based Model, B) Finite difference-based three dimensional.

Procedure and the methodology

The purpose of this work find the optimum number of infill wells as well as their location in the reservoir to maximize the ultimate recovery of the field. The following steps are taken in this work:

Stage 1: First a reservoir model was built.

Stage 2: The methodology that was previously conducted by Sayyafzadeh et al (Sayyafzadeh et al., 2010) for attaining the best location for infill wells were replicated and the results were analyzed by using streamline simulation.

Stage 3: according to the experience and observations of stage 2, 4 additional infill wells were considered in the numerical model to capture the impact of the new infill drilling in maximizing the ultimate recovery of the oil.

Stage 4: six scenarios are studied for each infill well by considering the infill wells as either vertical or horizontal and the optimum layer for the horizontal well to be completed that results in the maximum recovery of oil.

Stage 5: thirty four scenarios were considered, they were investigated using streamline-based simulation approach and then the ultimate oil recovery factors were compared with each other and the base case model to attain the best case scenario.

Figure 2 represents a flowchart that is explaining the workflow.

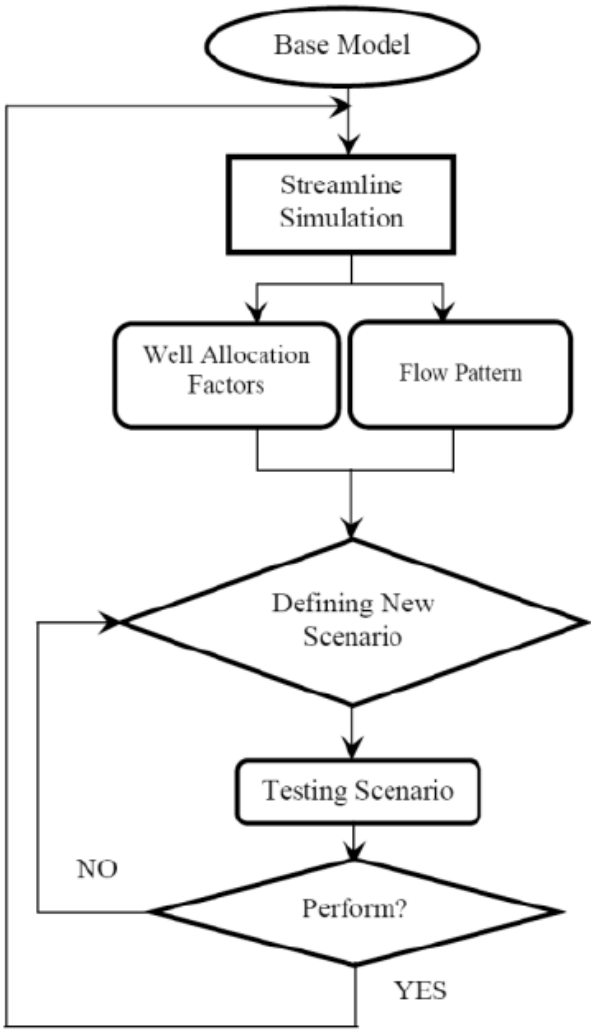

FIGURE 2.
Flowchart of the Simulation.

Building the numerical model and considering the well constraints like: oil flowrate, water production/ injection rates, water-cut, bottom hole flowing pressure and reservoir average pressure.

Finding the rates production wells and injection wells and understanding the relationship between the rate of water-injection and rate of oil-production for calculation of the impact of each injector on production wells and finally to enhance the oil production of the field.

According to the results of the streamlines simulation of the model, several scenarios were considered for example infill drilling and the location of infill wells.

When these changes were considered in the model, if the results are improved in any scenario, the scenario would be performed using streamline simulation if not another scenario will be considered.

Once a change in the model and the relevant scenario is accepted, a new streamline model will be constructed.

The process will continue until an economic constraint stops it.

Finding infill wells locations

Initially the model is built and the heterogeneity and faults are introduced to the model, then the model was history matched using a one-year production history. The model is then set to run for 3,683 days' production as the base case using FrontSim. The recovery factor of the base case model was 20.02% at the end of 3,683 days of production. Figure 1 is an illustration of the treamline model with its wells and their location in the model in the FloViz software. According to the flowchart that explained the workflow (Figure 2), infill wells are considered in the model and subsequently the optimum location of new infill well is attained. Subsequently, the optimum position for drilling of the new infill-well should be found. it was reported by (Sayyafzadeh et al., 2010) that in order to obtain a larger recovery factor in the streamline simulation technique, the new infill wells needs to be drilled in those regions of the reservoir which the density of the streamlines are low and the values of oil saturation are large. It should be noted that even though streamlines are likely to cluster in the areas with high flow and are lightly distributed in sections with low-permeability values (Datta-Gupta & King, 2007) , two new production wells were considered in high and low density of streamline and the resulting ultimate oil recovery factor were 23.98% and 24.06% correspondingly, hence similar observations are observed as those that were previously reported by Sayyafzadeh et al. (2010) for the well location using streamline approach. Consequently, besides the quality of rock properties, i.e., porosity, permeability and NTG that are really important in decision making regarding the well location, it is highly recommended to consider those regions in the field where the density of the streamlines is low and the oil-saturation is relatively high. Considering the streamline density and the well drainage areas that were represented in Figure 1, four new production wells (P10, P11, P12, and P13) were considered in the model, similar production constraints that were previously introduced to the current wells are introduced to the new wells in the model. In this study, 34 different scenarios are investigated to enhance the ultimate oil recovery of the reservoir. Initially, the four new infill wells were considered vertically and they were completed (perforated) in all 5 layers, consequently, the oil recovery factor increased to 32.63% in this scenario.

Infill wells

In next step, the impact of infill horizontal wells was studied. In order to investigate the infill horizontal wells comprehensively and to find that what layer is the most suitable for completion of the infill horizontal well to be most effective, each horizontal well was investigated under five different completion schemes. i.e., each infill horizontal well is considered in five different layers one after another in each scenario. Then the recovery factor was calculated for the well for 5 different completion case to understand that what layer has a greater impact on the field oil recovery for each infill well. In addition to the investigating different layers, different leg directions for the horizontal wells were studied to find the optimal leg orientation. Consequently, the optimal layer for the completion of the horizontal well and the optimum leg orientation to maximize the ultimate oil recover of the filed were selected. A full summary of the results of this stage is listed in Table 1. Table 1 shows the 4 new infill wells, i.e., P10, P11, P12, and P13 and their relevant recovery factor in different layers (layer 1 to 5). From Table 1, the best layer for each horizontal well that can enhance the recovery could be chosen. Additionally, the four infill wells are considered vertically and their relevant recovery factor is listed. Figure 3 demonstrates the streamlines in the vicinity of well P10 in different directions, i.e., horizontal or vertical. By means of streamline modeling approach, the numbers of scenarios for the investigation of the infill wells could be reduced since it clearly shows which parts of the field are un-swept, dissimilar to finite difference approach.

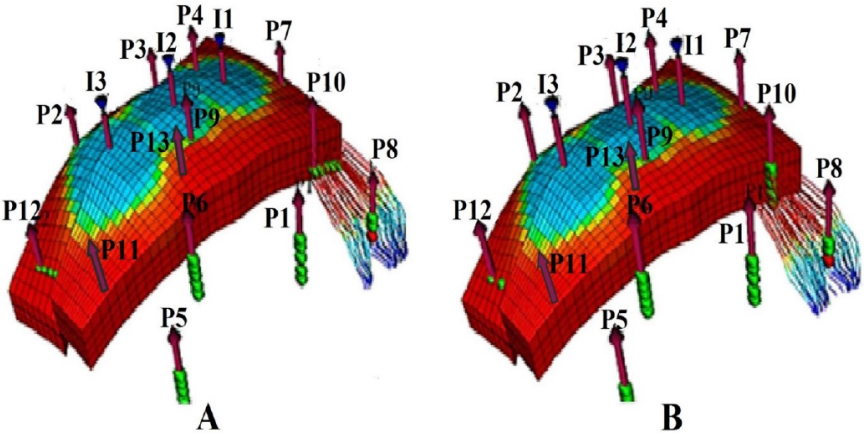

FIGURE 3.
Streamlines of Well P10 in the model. A) Horizontal, B) Vertical.

TABLE 1.
Infill wells' Scenarios (Horizontal/Vertical wells).

Horizontal Wells				Vertical Wells		Remark	
Infill well	Horizontal	Recovery factor (%)	Remark	Infill well	Recovery factor (%)	Infill drilling date	Number of perforation
P10	Layer-1	24.14		P10	23.72	After 1,461 days	5 Perforation in either Horizontal or Vertical Wells
	Layer-2	20.67					
	Layer-3	23.72					
	Layer-4	24.18	Max				
	Layer-5	23.66					
P11	Layer-1	21.93		P11	22	After 2,099 days	5 Perforation in either Horizontal or Vertical Wells
	Layer-2	20.37					
	Layer-3	20.2					
	Layer-4	22.02					
	Layer-5	22.12	Max				
P12	Layer-1	23.46	Max	P12	23.56	After 1,247 days	5 Perforation in either Horizontal or Vertical Wells
	Layer-2	23.3					
	Layer-3	23.4					
	Layer-4	23.36					
	Layer-5	23.37					
P13	Layer-1	22.91		P13	22.93	After 1,826 days	5 Perforation in either Horizontal or Vertical Wells
	Layer-2	20.59					
	Layer-3	22.93	Max				
	Layer-4	22.84					
	Layer-5	22.86					

Infill wells

In the previous section, the type of infill wells (either horizontal or vertical), their location, their corresponding oil recovery factor and the best layer to complete the wells in have been attained. In the previous section, the impact of the infill wells was studied individually, however in this section, ten additional scenarios were conducted by considering 4 new production wells altogether in the model. It should be noted that in each scenario, some of the new infill wells are considered vertically and some others are considered horizontally.

The considered infill horizontal wells were completed in the layer that ended up in the maximum oil recovery in the previous section and after simulation. In these 10 new scenarios, the ultimate oil recovery

factor of each scenario with its own specific arrangement of infill wells was found to maximise the ultimate oil production from the reservoir. The final results and the ten scenarios are listed in Table 2. The streamline model and full field 3D model grid for the best scenario (Scenario 10) is shown in Figure 4.

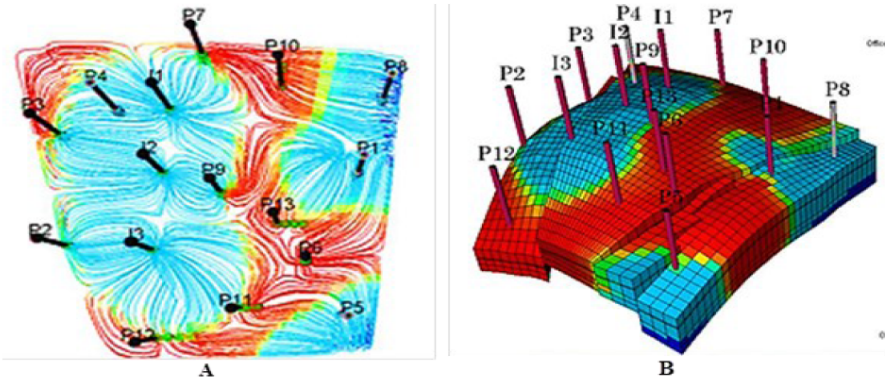

FIGURE 4.
The model of the best case scenario (Scenario 10), A) Streamline based Model, B) Finite difference 3D Model.

TABLE 2.
The results of 10 additional scenarios with 4 infill wells.

Rating	Recovery Factor (%)	Wells Model	Scenario	Row
**	20.02	P1-P2-P3-P4-P5-P6-P7-P8-P9	Base Model	0
*	32.56	P10-Vertical P11-Vertical P12–Horizontal Layer 1 P13-Vertical	Scenario 1	1
**	32.62	P10-Vertical P11-Horizontal Layer 5 P12-Vertical P13-Horizontal Layer 3	Scenario 2	2
	32.62	P10-Horizontal Layer 4 P11-Vertical P12-Vertical P13-Vertical	Scenario 3	3
**	32.62	P10-Horizontal Layer 4 P11-Horizontal Layer 5 P12-Vertical P13-Horizontal Layer 3	Scenario 4	4
**	32.64	P10-Vertical P11-Vertical P12-Vertical P13-Vertical	Scenario 5	5
***	32.68	P10-Vertical P11-Horizontal Layer 5 P12-Horizontal Layer 1 P13-Horizontal Layer 3	Scenario 6	6
***	32.69	P10-Horizontal Layer 4 P11-Vertical P12-Horizontal Layer 1 P13 Vertical	Scenario 7	7
****	32.73	P10-Horizontal Layer 4 P11-Horizontal Layer 5 P12-Horizontal Layer 1 P13-Vertical	Scenario 8	8
****	32.74	P10-Horizontal Layer 4 P11-Horizontal Layer 5 P12-Horizontal Layer 1 P13-Horizontal Layer 3	Scenario 9	9
*****	32.75	P10-Horizontal Layer 4 P11-Vertical P12-Horizontal Layer 1 P13-Horizontal Layer 3	Scenario 10	10

Results

The problem of associated water production in the surface facilities could be mitigated using the concept of streamline simulation by modifying the water injection rates in the injection wells to enhance/maximize the ultimate oil production rather than maximization of the water injection rates. To further understand the field performance during the water flooding and to achieve an improved water flooding management strategy, it is highly recommended to recognize the impact of each injection well's contribution on the oil production enhancement in the production wells. In order to better understand this contribution, a useful parameter is introduced by the streamline simulation technique called Well allocation factor (WAF). If WAF is considered for one of the producers (P13), it is noted that P13 is supported by two adjacent injection wells, i.e., I2 & I3, with 1.18% and 0.727% respectively, whilst 98.1% of the support is from the aquifer. Since the impact of the two injectors on P13 is minimal and almost all the support is from the aquifer, it is evident

that if the orientation of the leg of the horizontal section of P13 will be toward the aquifer it could end up in higher oil production.

According to such evidence, all production and injection wells could be optimized. Another solutions are to convert the inefficient production wells to the injection wells and increasing the injection rate in efficient injection wells and reducing the water injection rate in low-efficiency injection wells. There are some other benefits of WAF in water flooding management like: balancing the wells' pattern in the field, optimizing the production and injection rates of the wells, maximizing the sweep & injection performance.

It is also noted from Figure 1 that the streamlines' direction changes unexpectedly, this sudden change could be due to the existence of a fault or a fracture in the reservoir. Since it is known that there is no fracture in the reservoir, this sudden change in direction of the streamlines with a significant change in water saturation is due to a fault in that section of the reservoir. After investigating these 10 additional cases with four infill wells all together in the model, Scenario 10 was selected as the best scenario which is shown in Table 2. In scenario 10, P10-P12-P13 were considered as horizontal wells and P10 was a vertical well, this scenario was the best case scenario with the maximum ultimate oil recovery factor amongst other scenarios. It should be noted that the best case scenario was chosen based on the highest oil recovery for each infill well from Table 2. The oil production rate and cumulative oil production of the field for scenario 10 (best case scenario) compared to the base case scenario is shown in Figure 5. It is noted from Figure 5 that the field water cut decreased significantly and the field pressure with four new infill producers reduced.

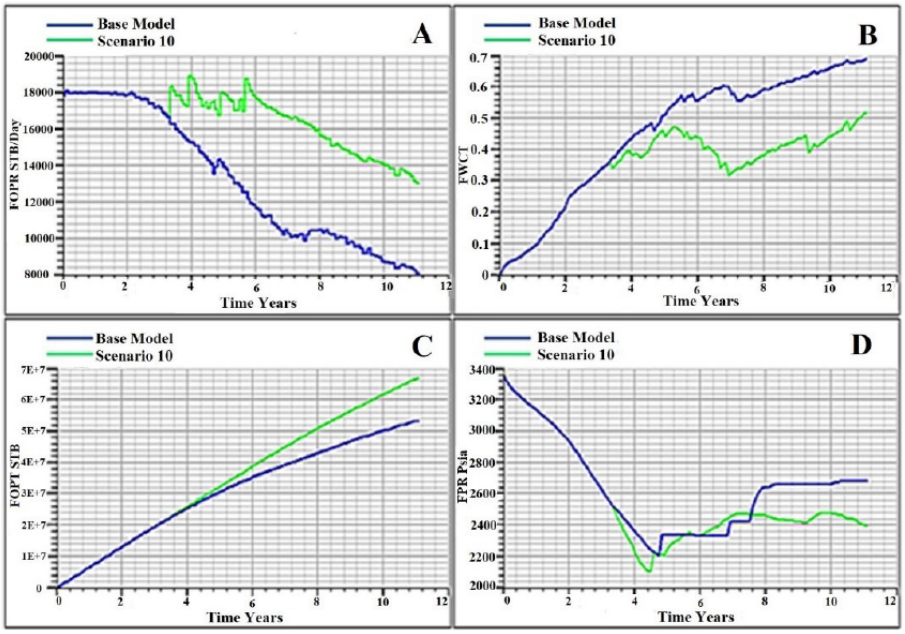

FIGURE 5.
A Comparison of the results of the base case and the best case (case 10) – A) Total Oil Production Rate of the Field, B) Field Water Cut, C) Field Cumulative Oil Production, D) Field Pressure.

Finally, in order to compare the central processing unit (CPU) time of the FrontSim for the Streamline-based modeling and finite difference approach, scenario 10 was considered and ran using the two simulators, i.e., streamline simulation and the finite difference simulation, with similar solver equations and conditions. The result showed a massive difference between the CPU time of the two simulator and indicated that FrontSim is roughly 36.42% faster than Eclipse 100 for this case study. This observation is because in Streamline simulation approach, all the equations are solved in one direction alongside streamlines but in the simulator that use infinite difference, saturation equations are solved in 3D simultaneously and consequently it employs much longer CPU time.

Conclusion

Due to significantly shorter CPU time of streamline simulation, it is highly recommended that streamline simulation is used for the complex reservoirs with heterogeneity and thousands of grid blocks. This shorter CPU time allow the petroleum engineers to analyze a scenario faster and allow them to consider more scenarios in a shorter period of time with a minimum runtime and consequently choosing the best case scenario with the highest oil recovery in a faster manner. In addition to shorter CPU time, there are more advantages associated with streamline simulation. In streamline simulation, un-swept sections of the reservoir could be simply recognized and the best location of the infill wells can be discovered. In this study, initially the best location for the vertical and horizontal infill wells as well as the best layer for the completion of the horizontal section were found through 24 different scenarios. Additionally, ten scenarios were considered to study the impact of all infill wells once they are considered all together simultaneously in the model. Therefore, in total 34 different scenarios were studied. Consequently, the oil recovery factor increased from 20.02% in the base case model to scenario to 32.75% in scenario 10 (the best case scenario).Furthermore, field water cut in scenario 10 (the best case scenario) decreased significantly compared to the base case scenario. It was also noted that once the leg of the horizontal well was toward the aquifer or water injection wells, the oil recovery factor increased.

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