Short Communication

Reservoir Performance Assessment Based on Intelligent Well Technology

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Abstract

The main challenge facing the oil industry is to reduce development costs while accelerating recovery with maximizing reserves. One of the key enabling technologies in this area is intelligent well completions. Intelligent well technology (IWT) is a relatively new technology that has been adopted by many operators in recent years to improve oil and gas recovery. Intelligent well completions employ Annular Flow Control Valves (AFCVs) to balance the production profile along the length of the well completion by splitting it into two (or more) sections. The aim of intelligent wells is to optimize the production (Delaying the gas and water breakthrough and decreasing water production).

The energy that moves crude oil and natural gas from the subsurface rock to the production well is called the reservoir drive [1]. These energies because of their different mechanisms, have different effects on reservoir production. In spite of advancement in Intelligent Well Technology, the effect of intelligent well on reservoir drive mechanisms under different reservoir characterization have not been well addressed. In this paper, six conceptual models of oil reservoir have been built and different production scenarios have been discussed. Based on the objective function, scenarios will be selected and will compare with a conventional scenario and decide whether to use smart well in these models or not.

Keywords

Annular flow control valves;
Drive mechanisms;
Intelligent Well Technology.

Introduction

With the developments in drilling technology, long horizontal, high angle and multilateral wells are providing a necessary platform to increase productivity per well and decrease the number of wells necessary to develop an asset. Intelligent well technology (IWT) provides the suitable platform for an engineer to achieve this objective. With this technology, the engineer can more effectively monitor the conditions by using downhole permanent sensors, and control the flow of fluids into and out of the wellbore using Annular flow Control Valves (AFCVs) on demand without physical intervention. AFCVs enable the controlling of each valve individually from the surface to maximize oil production and/or minimize formation water and/or gas production. There are three main types of AFCVs in terms of the style of control: two position valves (open or close), multiple

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step valves and infinitely variable valves. The two position AFCV is either fully open or fully closed. The multiple step AFCVs are constructed in various designs with typically 4 to >10 steps for the choke settings as it changes from the fully open to the fully closed position. The infinitely variable AFCV has the flexibility to provide optimum control (always assuming that it was placed to cover the most appropriate sections / length of the wellbore). Not surprisingly, variable AFCVs are more expensive and require more sophisticated control algorithms than the simpler types of AFCV [2]. The benefits of IWT are established in a number of previous researches based on reservoir simulation and case studies. These include control of multiple zone intelligent well to meet production optimization requirements [3], improved reservoir management [4,5], manual optimization of valve apertures with applications in water flooding [6], optimization of Intelligent Wells – A Field Case Study [7]. Elmsallati et al worked on a case study Value Generation with IWT in a High Productivity, Thin Oil Rim Reservoir and discussed the added values of IWT [8]. In spite of advancement in IWT, the effects of intelligent wells on unwanted fluid production reduction under different reservoir characterization and production mechanisms have not been well addressed.

Water production is one of the major technical, environmental, and economical problems associated with oil and gas production. Water production can limit the productive life of the oil and gas wells and can cause severe problems including corrosion of tubular, fines migration, and hydrostatic loading. Produced water represents the largest waste stream associated with oil and gas production. In the United States, it is estimated that on average 8 barrels of water are produced for each barrel of oil [9]. The environmental impact of handling, treating and disposing of the produced water can seriously affect the profitability of oil and gas production. The annual cost of disposing the produced water in the United States is estimated to be 5-10 billion dollars [10]. Numerous technologies are available for controlling unwanted water production so this problem has been resolved by appropriate reservoir management.

One approach for using intelligent well technology is to react to production problems (e.g., water coning) and then reset the instrumentation to mitigate them (reactive control strategy). A better approach is to use AFCVs in conjunction with a predictive reservoir model. This allows for the optimization of reservoir performance rather than just the correction of problems that have already occurred [11].

2. Methodology

In the first step, a conceptual oil reservoir model is built. The reservoir model contains 59x59x10 grid cells in X, Y and Z directions, respectively; i.e., a total of 34810 cells. That model has 100 ft thickness; in the other words, the dimensions of model are 2000 ft x 2000 ft x 100 ft and upper layer of reservoir was set at 8940 ft.

2.1 Problem statement

The purpose of implementation of Intelligent Well Technology is to improve the reservoir performance. In this paper, reservoirs under different production mechanisms are studied with IWT. In various case studies, the objective function is different. If the reservoir produced water from the aquifer, the objective function would be cumulative water production reduction. If the reservoir produced gas from gas cap, the objective function would be cumulative gas production reduction. If the reservoir produced water and gas, the objective function would be cumulative water production reduction.

2.2 Reservoir Static Modeling

In the second step, Static properties of the model are defined. Because of applying different reservoir characterizations, two types of reservoirs are defined: homogenous and heterogeneous.

In the homogenous model, the permeability in the X and Y directions are equal and between 27.7 and 65.4 mD and its average is 48.6 mD with $K_v/K_H = 0.1$ (Figure 1). The porosity range is between 0.07 and 0.22 and its average is 0.15. In the heterogeneous model, heterogeneity is applied by the channel that crosses the reservoir. The following amendments are made to introduce heterogeneity (Figure 2):

Grid cells:

For 1 - 9 x 59 x 10 (x, y, z), permeability is 48.6 mD and porosity 0.15

For 10 – 18 x 59 x 10 (x, y, z), permeability is 486 mD and porosity 0.25

For 19 – 59 x 59 x 10 (x, y, z), permeability is 48.6 mD and porosity 0.15

In the homogenous type, reservoir rock type is sandstone. In the heterogeneous type, main rock type is sandstone, and rock type of channel that crosses the reservoir, is unconsolidated sandstone.

2.3 Reservoir Dynamic Modeling

In this section, different production mechanisms are applied to reservoir models. So, according to

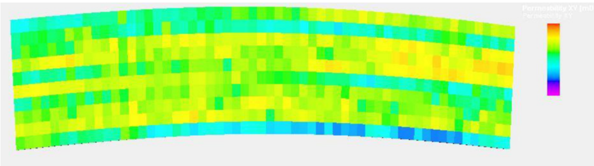

Figure 1. Permeability distribution in homogenous models.

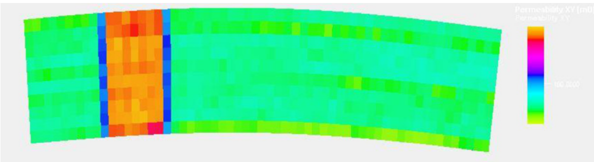

Figure 2. Permeability distribution in heterogeneous models.

production mechanisms [12], four different production mechanisms are applied to reservoir models. The used models are as below:

Model I: Homogenous, Water Drive
Model II: Homogenous, Gas Cap Drive
Model III: Homogenous, Solution Gas Drive
Model IV: Homogenous, Combination Drive
Model V: Heterogeneous, Water Drive
Model VI: Heterogeneous, Combination Drive

Dynamic properties of these models are shown in Table 1. The relative permeability curve of the homogenous models is plotted in Figure 3.

According to the production mechanism of conceptual models, dynamic properties are defined. In Models I, III, and V, initial reservoir pressure must be more than bubble point pressure, and GOR must be less than other cases. According to the production mechanism that was applied, oil formation volume factor is defined.

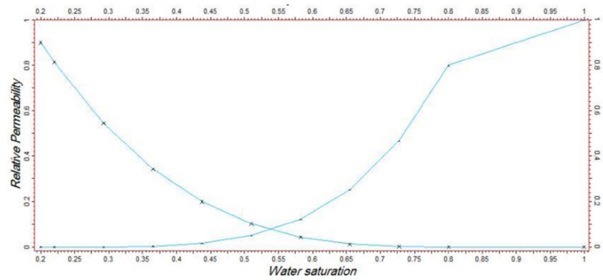

Figure 3. Relative permeability of homogenous models.

To investigate the effect of intelligent well technology, we defined two cases for each model, base and intelligent cases that are completed without and with IWT, respectively. The important note that must be expressed is all parameters of each model in Table 1 are the same for each case that is equipped with and without IWT during reservoir simulation.

2.4 Well Trajectory

All models are drilled with the same well trajectory. Well head coordinates are 64 and 1024 in X and Y directions respectively. So, well is drilled in the west part of the reservoir. Well enters the reservoir at 94, 1055 and 8950 coordinates in X, Y and Z directions, respectively. Well is drilled horizontal in the reservoir about 1300 ft. Well is completed in the reservoir with and without IWT. Each case is defined as base case and intelligent case. Base and intelligent cases are completed without and with

Table 1. Dynamic properties of models.

Properties	I	II	III	IV	V	VI
Reservoir thickness (ft)	100	100	100	100	100	100
Production rate (STBD)	900	350	400	600	900	600
Initial average oil saturation	0.72	0.72	0.72	0.72	0.72	0.72
Well depth (ft)	8970	8970	8970	8980	8970	8980
Initial reservoir pressure (psi)	3500	3500	3500	3500	3500	3500
Average reservoir temperature (°F)	200	200	200	200	200	200
Production period (years)	5	5	5	5	5	5
Bubble point pressure (psi)	2500	4000	2000	4000	2500	4000
GOR (MSCF/STB)	0.7	1.1	1.05	1.1	0.7	1.1
FVF_o (RB/STB)	1.38	1.5	1.28	1.5	1.38	1.5

IWT. We have two kinds of completion, the intelligent and basic completion. The first one with 6 5/8 inches casing and 5 inches tubing completed by IWT, and the second one which has 6 5/8 inches is not completed.

2.5 Strategy development

Simulation of all models is started on 01.06.2014 and will be finished 5 years later on 01.06.2019. Two types of limitations are defined. First one is based on oil production rate. Table 1 shows production rate limitations in each model. The other limitation is the bottom hole pressure that is set as 1500 psi for all models. According to the reservoir initial pressure and the bubble point pressure of the cases that were expressed in Table 1, bottom hole pressure limitation is set at 1500 psi. It must be less than the values of initial pressure. The first limitation stabilizes the oil production rate and does not permit an increase from that value at simulation time. By the second limitation, if the bottom hole pressure reduces from the set value, the well will be closed.

Results and Discussion

3.1 Model I: Homogenous, Water Drive

In this model, production mechanism is water drive. The aquifer is set at the bottom of the reservoir and sweeps oil to bore hole. The horizontal well drilled in the reservoir is completed in the intelligent case with three AFCVs (Figure 4). The "heel-toe" effect leads to a difference in the specific influx rate between the heel and the toe of the well [13]. According to this effect in horizontal wells, AFCVs are set in the heel and toe of the well. AFCV1 is set in the heel of the well and AFCV2 in the middle of well and AFCV3 at the end of the well in the reservoir.

As Figures 5 and 6 illustrate, at the heel of the well, water raises more than other parts of the well in the base case, and this cause water breakthrough. But in the intelligent case, by shutting the AFCV1 that is placed at the heel of the well, water breakthrough is delayed, and water is raised in other parts of the well. By controlling the AFCVs (Table 2), until the end of assumed production time, cumulative water production is decreased.

As shown in Table 2, number 1 is ascribed to fully opened position of AFCV, number 0 is ascribed to fully closed position and other positions are ascribed by numbers in the range of (0,1).

The cumulative water production and cumulative oil production in the base case (dashed line) and intelligent case (solid line) are plotted in Figures 7 and 8. As Figures 7 and 8 illustrate, while the cumulative oil production is fixed at a constant value in both base and intelligent cases, the cumulative water production is reduced. Reduction of cumulative water production significantly reduces the cost of field operations.

According to Table 2, during production time, AFCV1 that is set in the heel of the well is being closed. So, oil production increases in other parts of the reservoir. So breakthrough was delayed and this phenomenon causes cumulative water production in intelligent case to be less than the base case. By controlling AFCV1, the effect of breakthrough phenomenon and respectively water production, decreases.

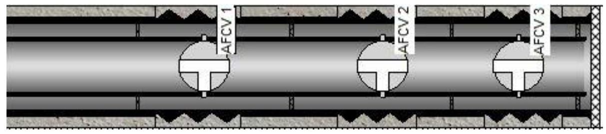

Figure 4. Well Schematic.

Table 2. AFCVs conditions during production time of model I.

Time	$AFCV_1$	$AFCV_2$	$AFCV_3$
2014-06-01	1	1	1
2017-09-01	0	1	0.5
2018-06-01	0	0.5	1
2018-12-01	1	1	1

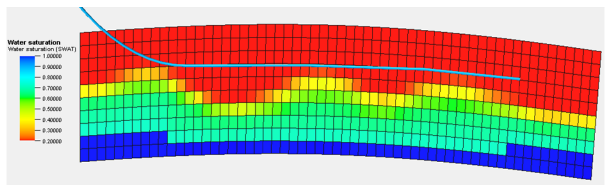

Figure 5. Water saturation in base case of Model I at three and a half years later.

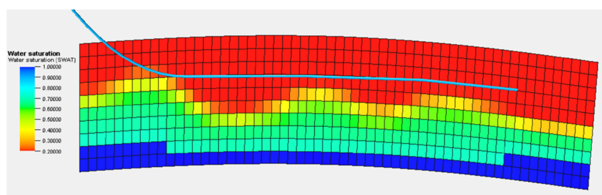

Figure 6. Water saturation in intelligent case of Model I at three and a half years later.

Table 3 shows the changes of water/oil cumulative production for Model I, with and without IWT. In Table 3, below equation is applied:

$$\%\,Difference = \frac{Intelligent - Base}{Base} \times 100$$

As seen in Table 3, cumulative water production is reduced by 6.37 % using IWT. The homogeneous water drive reservoir achieved this reduction, because of the active aquifer that exists at the bottom of the reservoir. This aquifer maintains the pressure of the reservoir and controls water production after breakthrough. By using IWT, high influx in the heel of the well does not occur. This creates a balanced inflow throughout the well and eliminates the heel-toe effect. In addition, by controlling water rising from the aquifer, breakthrough occurs later, so cumulative water production reduces and reservoir performance improves.

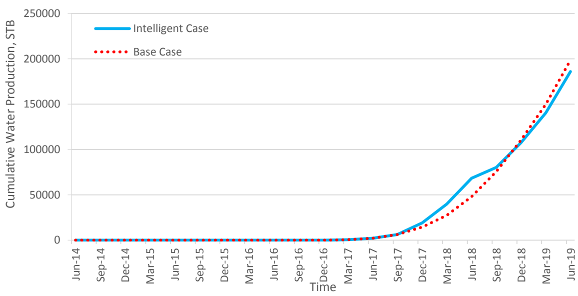

Figure 7. Cumulative water production in base and intelligent cases of Model I.

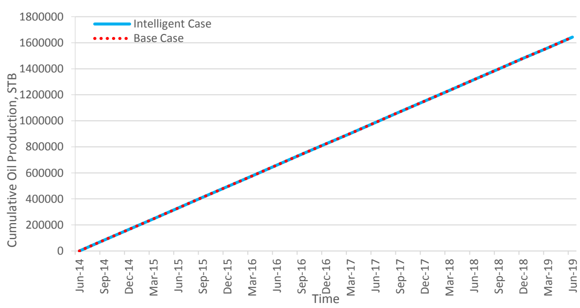

Figure 8. Cumulative oil production in base and intelligent cases of Model I.

3.2 Model II: Homogenous, Gas Cap Drive

In this model, production mechanism is Gas Cap drive. Gas-oil contact depth is 8955 ft. The schematic of horizontal well of this model is similar to Figure 4. Considering the mechanism of the reservoir, gas is the only unwanted fluid expected to be produced. According to Figure 9, gas production from the heel of the well is more than other parts of the well and in this section breakthrough occurs.

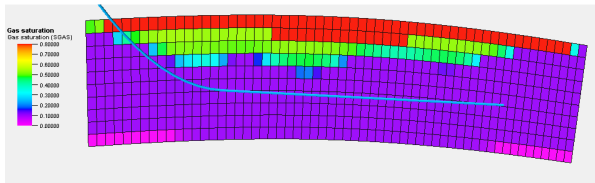

Figure 9. Gas saturation in base case of Model II at three years and three months later.

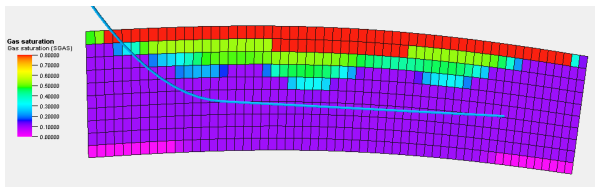

Figure 10. Gas saturation in intelligent case of Model II at three years and three months later.

Table 3. Base and intelligent cases comparing of model I.

	Cum. O (STB)	Cum. W (STB)
Base Case	198,601	1,643,400
Intelligent Case	185,940	1,643,400
% Difference	-6.37	0

Table 4. AFCVs conditions during production time of model II.

Time	$AFCV_1$	$AFCV_2$	$AFCV_3$
2014-06-01	1	1	1
2017-06-01	0	0.5	1
2017-12-01	1	1	1

As seen in Figure 10, by using IWT, uniform distribution of gas frontier is the cause of delay in gas breakthrough.

Table 4 shows AFCVs configuration of Model II in intelligent case, during production time.

Figures 11 and 12 show IWT can control cumulative gas production by making cumulative oil production stable.

Table 5 shows the changes of oil/gas cumulative production for Model II with and without IWT.

As Table 5 shows, IWT could reduce cumulative gas production about 1.31%. This value is negligible. Homogeneity and lack of active aquifer are reasons behind this minor difference. Because of the homogeneity of the reservoir, gas falls uniformly in to the well, but at the heel of the well high influx occurs and by using IWT reservoir`s performance improves.

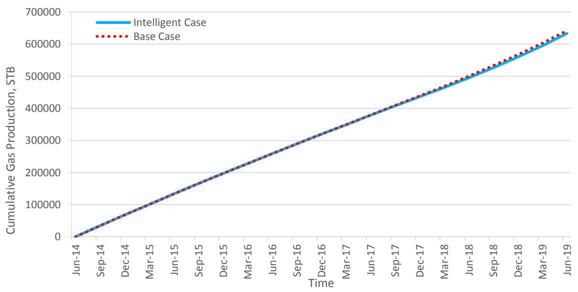

Figure 11. Cumulative gas production in base and intelligent cases of Model II.

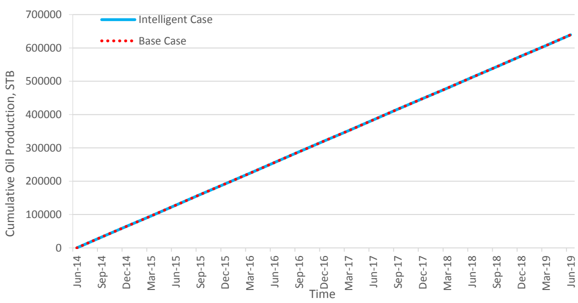

Figure 12. Cumulative oil production in base and intelligent cases of Model II.

Table 5. Base and intelligent cases comparing of model II.

	Cum. W (STB)	Cum. O (STB)
Base Case	641,805	639,100
Intelligent Case	633,380	639,100
% Difference	-1.31	0

3.3 Model III: Homogenous, Solution Gas Drive

According to the reservoir production mechanism, the reservoir does not have an active aquifer and gas cap so unwanted fluid production is not expected. Figures 13 and 14 show the visual result of simulation of the Case III in the base case. As seen in these figures, Model III does not have any opportunity to use IWT. Figure 14 shows, at the end of production time (2019-06-01), water doesn`t rise. So cumulative water production doesn`t give any opportunity to use IWT.

Of course, if the simulation is continued, reservoir pressure gets less than bubble point pressure, so Model III transforms to Model II that has gas cap. With respect to this transformation, reservoir future planning must be planned.

3.4 Model IV: Homogenous, Combination Drive

In this model, production mechanism was Combination drive (Water Drive and Gas Cap Drive).

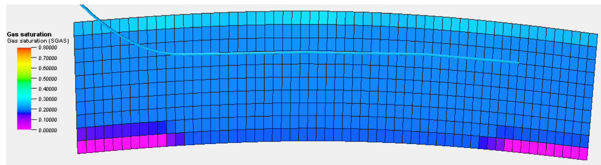

Figure 13. Gas saturation in base case of Model III at the end of production life.

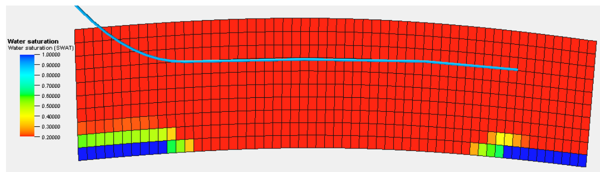

Figure 14. Water saturation in base case of Model III at production life.

The aquifer was set at the bottom of the reservoir and Gas-oil contact depth was 8955 ft and it swept oil to the bore hole. The horizontal well that was drilled in the reservoir, was completed in intelligent case with three AFCVs (Figure 3). Considering the horizontal well that was drilled in the reservoir, biggest pressure drop in the well, occurred at the heel of the well, so water of the aquifer rises more at the heel of well and breakthrough occurs (Figure 15). Because of breakthrough, water production from the reservoir increases. In the intelligent case, considering the breakthrough, AFCV1 that was set at the heel of well was shut and let other perforations to flow the oil to the surface (Figure 16).

By controlling the AFCVs (Table 6), until the end of assumed production time, water breakthrough is delayed and then water frontier has more uniform distribution in the length of the horizontal well.

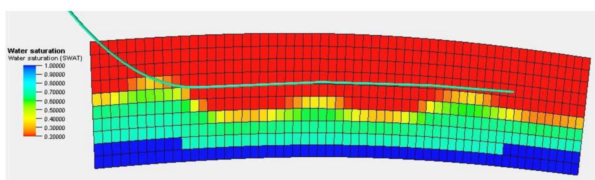

Figure 15. Water saturation in base case of Model IV at three years later.

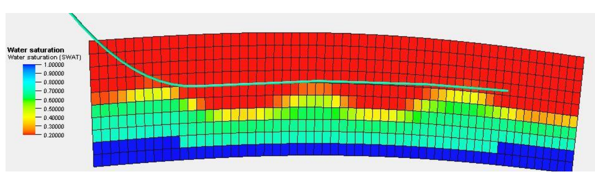

Figure 16. Water saturation in intelligent case of Model IV at three years later.

Figures 17 and 18 show IWT could delay water breakthrough and control cumulative water production by making cumulative oil production stable. Reduction of cumulative water production significantly reduces the cost of field operations.

Table 7 shows the changes of oil/water cumulative production for case IV with and without IWT.

As seen in Table 7, cumulative water production is reduced by 6.86 % using IWT. As expressed before, if the reservoir produces water and gas, the objective function is reduction of cumulative water production. By using IWT, high influx in heel does not occur. This creates a balanced inflow throughout the well and eliminates the heel-toe effects. Because of the existence of gas cap on top of the reservoir, pressure drop of reservoir during production time is expected to be less than reservoir without gas cap.

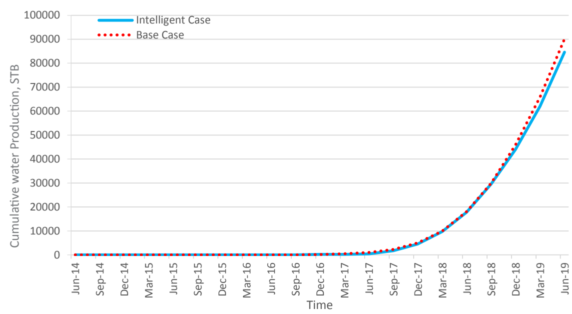

Figure 17. Cumulative water production in base and intelligent cases of Model IV.

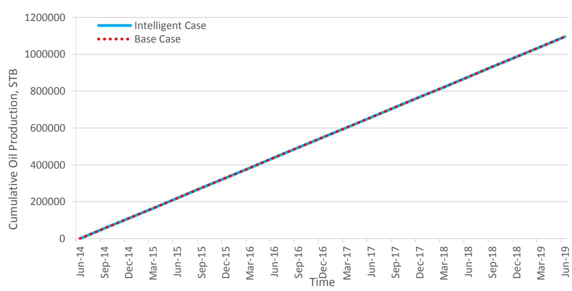

Figure 18. Cumulative oil production in base and intelligent cases of Model IV.

3.5 Model V: Heterogeneous, Water Drive

In this model, production mechanism is water drive. The properties of this model such as production rate, initial average pressure, bubble point pressure and initial oil and water saturation were similar to Model I, but this model had heterogeneity in porosity and permeability. The aquifer was set at the bottom of the reservoir at the depth of 9030 ft and swept oil to the bore hole. As seen in Figure 4, the horizontal well drilled in the reservoir was completed in the intelligent case with three AFCVs. Table 8 shows AFCVs conditions at production time of Model V in intelligent case.

Table 6. AFCVs conditions during production time of model IV.

Time	$AFCV_1$	$AFCV_2$	$AFCV_3$
2014-06-01	1	1	1
2016-12-01	0	1	1
2017-09-01	1	1	0
2017-12-01	1	1	1
2018-10-01	0	1	1

Table 7. Base and intelligent cases comparing of model IV.

	Cum. W (STB)	Cum. O (STB)
Base Case	90,242	1,095,600
Intelligent Case	84,050	1,095,600
% Difference	-6.86	0

Figures 19 and 20 show that IWT could delay water breakthrough and could control cumulative water production by making cumulative oil production stable. This obvious reduction in cumulative water production was because of heterogeneity of Model V. High porosity and permeability of heterogeneous zone raised water faster and breakthrough happened sooner. This was a great opportunity to use IWT for reservoir management.

Table 9 shows the changes of oil/water cumulative production for Model IV with and without IWT.

As seen in Table 9, IWT could control cumulative water production 16.96%. This high difference between Models I and V is because of heterogeneity that exists in Model V. As expressed before, all properties of Models I and V are similar and the

Table 8. AFCVs conditions during production time of model V.

Time	$AFCV_1$	$AFCV_2$	$AFCV_3$
2014-06-01	1	1	1
2017-12-01	0	1	0
2018-06-01	0	0	1
2018-12-01	0	1	1

only difference is heterogeneity. This heterogeneity causes the water that exists at the bottom of the reservoir to rise sooner than the homogeneous model and water breakthrough occurs in short time, but by using IWT, highly permeable zone is effectively choked and stimulates production from less permeable zones.

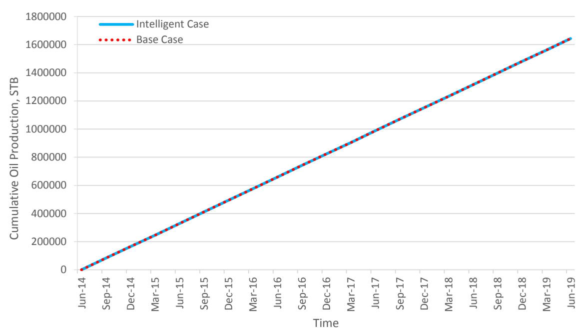

Figure 19. Cumulative oil production in base and intelligent cases of Model V.

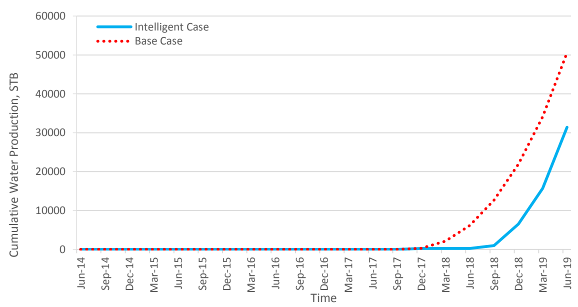

Figure 20. Cumulative water production in base and intelligent cases of Model V.

Table 9. Base and intelligent cases comparing of model V.

	Cum. W (STB)	Cum. O (STB)
Base Case	97,075	1,643,400
Intelligent Case	80,605	1,643,400
% Difference	-16.96	0

3.6 Model VI: Heterogeneous, Combi-nation Drive

In this model production mechanism is combination drive (Water Drive and Gas Cap Drive). The properties of this case such as production rate, initial average pressure, bubble point pressure and initial oil and water saturation are similar to Model IV, but this case has heterogeneity in porosity and permeability. The aquifer is set at the bottom of reservoir and Gas-oil contact depth is 8955 ft and it sweeps oil to the bore hole. The horizontal well that is drilled in reservoir is completed in intelligent case with three AFCVs (Figure 4).

Table 10 shows AFCVs conditions at production time of Model VI in intelligent case.

Figures 21 and 22 also show that IWT could delay water breakthrough and control cumulative water production by making cumulative oil production stable.

Table 10. AFCVs conditions during production time of model VI.

Time	$AFCV_1$	$AFCV_2$	$AFCV_3$
2014-06-01	1	1	1
2017-12-01	0	1	1
2018-06-01	0	1	0
2018-09-01	0	0	1
2018-12-01	0	1	1

Table 11 shows the changes of oil/water cumulative production for case IV with and without IWT.

In this model, the heterogenetic zone is also the cause of high water production in base case and using IWT by AFCVs placement could control water production and decrease cumulative water production. AFCV that was placed in heterogeneous zone was shut early during the production time because of this zone, responsible for water production in the base case.

Table 11. Base and intelligent cases comparing of model VI.

	Cum. W (STB)	Cum. O (STB)
Base Case	50,590	1,095,600
Intelligent Case	31,407	1,095,600
% Difference	-37.91	0

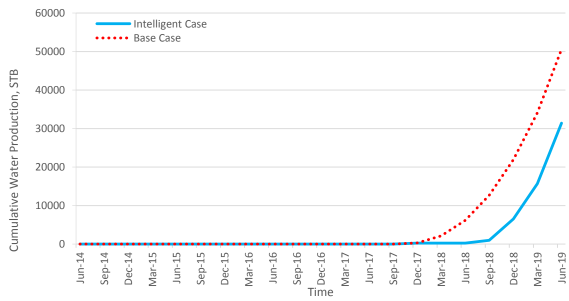

Figure 21. Cumulative water production in base and intelligent cases of Model VI.

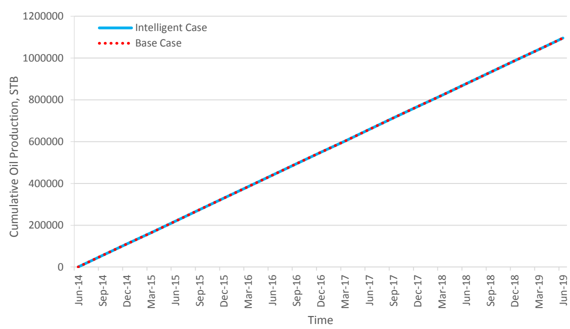

Figure 22. Cumulative oil production in base and intelligent cases of Model VI.

Conclusion

1. Active aquifer, because of the maintained pressure of the reservoir, provides a great opportunity to use IWT. According to the heel-toe effect, different influx rate occurs along the well, so water is raised in parts of the well with higher rate than other parts. By using IWT, production profile is balanced. (Models I & IV relative to models II & III)

2. Reservoirs with gas cap drive mechanisms in homogenous cases get little opportunity to control cumulative gas production. (Model II)

3. Reservoirs with solution gas drive mechanisms cannot get an opportunity to use IWT in well completion. (Model III)

4. Reservoirs with combination drive mechanism, because of the reservoir pressure maintained by aquifer and gas cap that help pressure drops later than other drive mechanism types, have better opportunity to use IWT. (Models I and V relative to models IV and VI, respectively)

5. Heterogeneity of the reservoir causes rising of water from the aquifer to well bore and provides a great opportunity to control cumulative water production by using IWT. (Models I and IV relative to models V and VI, respectively)

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