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An Intelligent Well Approach to Controlling Water Coning Problems in Horizontal Production Wells

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***Abstract*—This work explores the use of intelligent completions to attenuate the problem of water coning during the production phase of a horizontal well. In this work, the horizontal section of a well was transformed into a multi-segment well with downhole sensors and inflow control valves (ICV) fitted in these segments which allowed for the independent monitoring and control of fluid flow into each segment of the wellbore. The intelligent well (IW) was modelled to control water coning using a reservoir simulating software. A reactive strategy for operating the ICV's was developed which involved setting the valves to respond dynamically by shutting in a segment when water production exceeds a trigger value. After simulating the production performance of the well with a conventional completion (without ICV's), an optimized control strategy was developed for the intelligent well (with ICV's). A comparison of the economic performance of the intelligent well to the conventional well proved its viability. As against the conventional well, the intelligent well recorded a 41.9% reduction in water production, and 21.1% increment in oil recovery. The applicability of intelligent wells under different reservoir conditions was also investigated in this work. The performance of IWT was seen to vary significantly under various reservoir conditions, and therefore may not be applicable for all reservoir types. It was observed that compared to the conventional well, IWT proved significant in yielding optimum benefits of oil productivity and profitability in fields with high porosity and permeability, oil-wet reservoirs, thin pay zones and heterogeneous reservoirs.**

Keywords— Water coning, Intelligent wells, Inflow control valves, Horizontal well, Reactive control strategy.

I. INTRODUCTION

Controlling the flow of formation fluids into the wellbore of an oil well is imperative throughout the well's productive life. Since Oil, which often coexists with water and/or gas is usually the target fluid of reservoir development operations, efficient well control mechanisms need to be employed to gain control over the potential flow of other fluids through the well to be produced in combination with the oil at the surface.

One major technical, environmental, and economic problem that is faced during the production life of a well producing from a reservoir overlying an aquifer is water encroachment. The mechanism underlying the upward movement of water into the perforations of a producing well is usually termed as coning. Water coning is enhanced by the existence of a pressure gradient that exists near a well during production [1, 2]. The water preferentially proceeds in the form of a cone, as such its name. It yields associated problems of reduced efficiency of depletion mechanism, early abandonment of affected wells, reduced field recovery, reduced field profitability and an extra cost for handling produced water. In the United States (US) for instance, it is estimated that on an average, eight (8) barrels of water are produced for each barrel of oil. The world average is 3 barrels of water per day [3]. Also the cost of treatment of produced water in the US ranges between 0.2 to 8.5 USD per barrel whiles the cost of disposal falls between 0.07-1.6 USD per barrel [4]. This highlights the significant negative impact that water coning may have on the profitability of a well.

Preventing coning requires producing oil wells below the critical oil flow rate (q_{oc}) of the reservoir, which yields very small oil volumes that are economically unviable [2, 5]. Since economical oil production is achieved at flow rates higher than the q_{oc}, water coning is labelled as an inevitable leveled phenomenon during reservoir engineering considerations. The available option thus is to control the problem of coning and possibly delay its occurrence. Some techniques have been developed to control unwanted water production. Among these is the application of Geo-steering techniques to place a horizontal well further up away from the Oil Water Contact (OWC), and Intelligent well technology; which is the focus of this research document in relation to its application in horizontal wells.

Intelligent wells, sometimes referred to as 'smart wells' are basically wells fitted with special downhole completion equipment that measure and monitor well conditions and reservoir parameters such as flow rate, fluid composition, bottomhole temperature and pressure. Intelligent wells also have downhole control valves to regulate, seal portions of the wellbore and optimize the movement of hydrocarbons into the well to enhance oil recovery [6, 7]. IWT can also provide an effective way to deal with water coning by deploying special downhole instrumentation which can be operated remotely [8].

In horizontal wells, there is uneven inflow along the axis of the well (Figure 1). Due to the typically extensive length of the production tubing, there is also a considerable pressure drop in the tubing itself. This causes a higher drawdown at the heel of the well than at the toe. The oil closer to the heel is produced faster than that at the toe and eventually coned water will break through cutting off considerable amounts of oil at the toe (Figure 2). With the segmentation of the horizontal sections and using ICV's in these segments as shown in figure 3, the inflow profile is evened along the entire length of the horizontal section [9, 10].

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The main objective of this project is to study the application of IWT with a reactive control strategy to deal with water coning in a horizontal well to optimize productivity and eventually increase profitability.

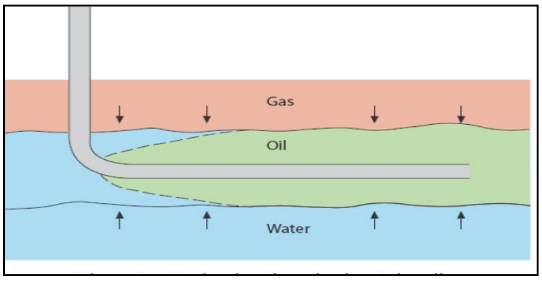

Fig. 1. Coning in a long horizontal well [11]

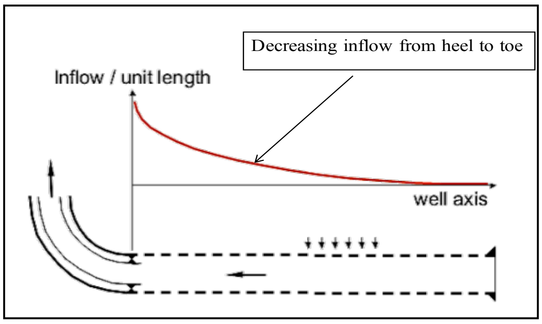

Fig. 2. Inflow profile from heel to toe without ICV [12]

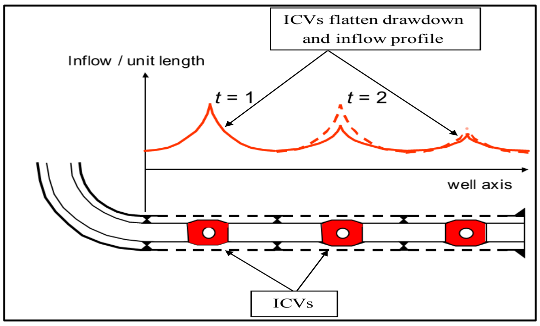

Fig. 3. Inflow profile with ICV [12]

II. Methodology

In trying to validate the suitability of intelligent wells for controlling water coning, we focused on obtaining an optimized reactive control strategy for a producing reservoir with an underlying aquifer and overlying gas cap. To accomplish this, fluid flow in a reservoir was simulated using both conventional and intelligent completion cases for the horizontal well. The same was done under varying reservoir conditions for sensitivity analysis purposes. For an intelligent well to prove viable for mitigating water coning problems, it must readily provide the means to greatly reduce water production to yield increased oil margins, as opposed to the conventional well.

A. Reservoir Modelling and Well Configuration

A reservoir simulating software used for the reservoir modelling and simulation process. We used a simple conceptual block model with one producer in this study (Figure 4). The model has dimensions 4500ft x 4500ft x 100ft and is sub-divided into ten layers of equal thickness. There are 30 cells in both the x and y directions, and 10 cells in the z direction. The model contained 9000 active grid blocks. The top of the reservoir is located at depth of 6000ft with an initial reservoir pressure of 4800 psi. The OWC is at a depth of 6175ft whiles the gas-oil contact depth is at 6000ft. Other relevant reservoir data are attached in Table A1 in the appendix

A single horizontal producer completed in the fourth layer was used (Figure 5). We considered two different downhole well completion cases. The first being a conventional completion which we called our base-case. The second is the intelligent completion which is designated as the production case and achieved by fixing an ICV close to the heel and another to the toe of the horizontal well.

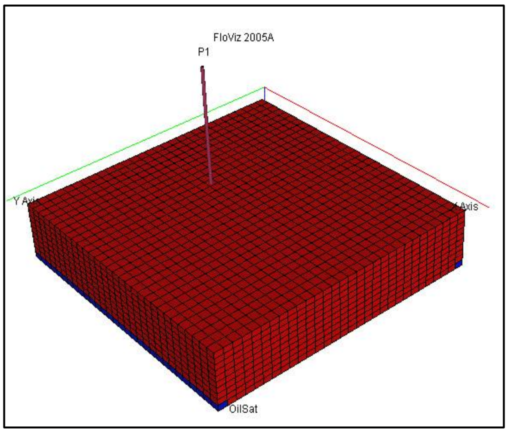

Figure 4. Reservoir Model

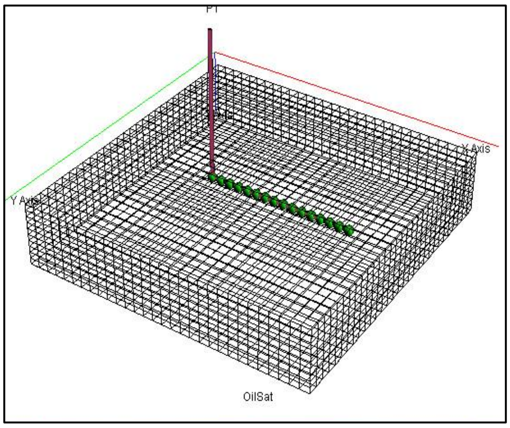

Fig. 5. Horizontal Well Configuration

B. Production strategy

The production was simulated under a fixed surface liquid rate control (LRAT) of 2500STB/day. The critical flow rate of the reservoir was calculated using the Joshi equations [13] to be 74.33 STB/day. This gave the maximum oil rate that would prevent water breakthrough. The control value for the LRAT was chosen to allow for a reasonably economic flow rate without excessive energy loss, hence the 2500 STB/day limit. For our base case, there was no zonal segregation along the length of the well and water production was left uncontrolled.

For the intelligent well production, the placement of the ICVs was based on simulation results from the base case used to identify segments with high water cuts. In all, the horizontal was divided into 14 segments; with the ICVs placed in segments 6 and 14. Their placement was also partly to even out the inflow profile to prevent heel-to-toe effect (Figure 3). The strategy used was for the ICVs in segments with high water cut to be shut when their specified water cuts (trigger values) were reached and reopened when they fall below these values. The trigger value for segment 6 was 0.6 whiles that of segment 14 was 0.5.

C. Sensitivity Analysis

Simulations were run to observe the effect of varying both static reservoir parameters (permeability, porosity) and dynamic reservoir parameters (fluid contacts, relative permeability and skin). In both cases, the optimistic and pessimistic values were set relative to the initial optimized values from the reactive control strategy. Table A2 and A3 in the appendix shows the static and dynamic reservoir parameters with the values as used. Sensitivity analysis is performed to account for uncertainties in a reservoir due to changes in reservoir and fluid properties. Figures 6 and 7 show schematics of the work flow diagram and the reactive control strategy respectively

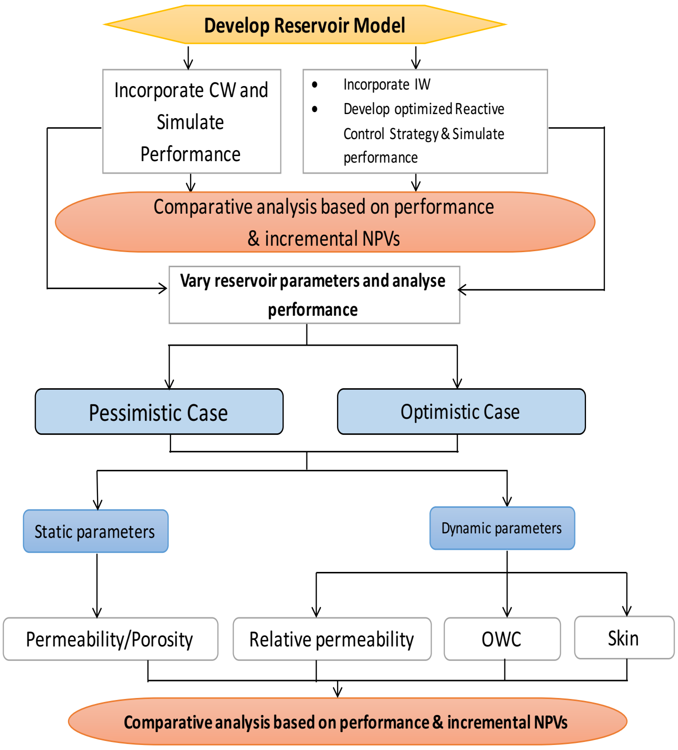

Fig. 6. Work flow Diagram

D. Economic Model

The general idea for an economic model is to scrutinize the effective value of a project prior to its approval and subsequent development. We used the standard petroleum engineering Net Present Value (NPV) analysis to determine the economic values of both the IW and CW. The following relations were used in computing the NPV for both the conventional and IWT cases. Assumptions considered in the evaluation are presented in Table A4.

$$\text{Cost}_{\text{IW}} = [\$_{\text{IW equipment}}] + \left[\left(\$/\text{day}\right)_{\text{rig}} * \text{Drilling time (days)}\right] + [\text{Well equipment cost}] \quad (1)$$

$$Cost_{CW} = \left[\left(\$/day\right)_{rig} * Drilling\ time\ (days)\right] + [Well\ equipment\ cost] \quad (2)$$

$$Yearly\ NPV = \frac{NCF}{(1+D.R)^n} \quad (3)$$

$$= \frac{(N_p * O_{price} + G_p * G_{price}) - (W_P * W_{cost} + OPEX + CAPEX)}{(1+D.R)^n}$$

$$Total\ NPV = \sum_{i=0}^{n=20} \frac{NCF_i}{(1+D.R)^n} \quad (4)$$

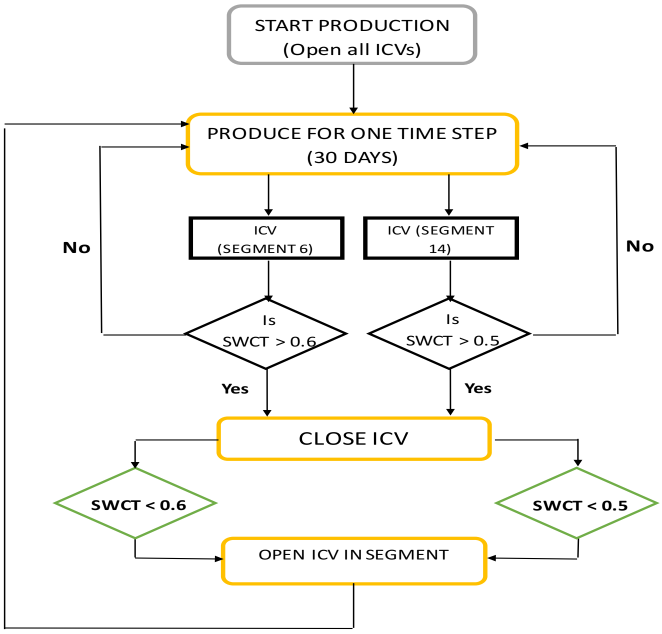

Fig. 7. Flow Chat of reactive Control Strategy

III. RESULTS AND DISCUSSIONS

A. Performance Comparison of CW and IW

In the early life of the reservoir, before the trigger values for the ICVs were reached, the field water cut had risen steadily from 0.2 to 0.47 (Figure 8). After ten (10) years, the water cut had exceeded 0.5 reaching a maximum value of 0.69 at a water rate of over 1700STB/day. This was as a result of the very high permeability in segments 6 and 14 in the reservoir. High pressure drops in these zones led to increased fluid influx, thereby increasing the water production in the CW case. As water saturation increased in the reservoir, the relative permeability, and hence the mobility of oil decreased. This accounts for the reduction in oil production rate with rising water cut as shown (figures 9 and 10). In the IW case, once the ICVs were activated, there was a sharp increase in oil flow rate (Figure 10) corresponding to drops in the water cut. This trend translated into an increased total oil production for the IW compared to the CW. The cumulative oil production for the IW was at 10.5 MMSTB representing 65.86% of the total field

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liquid production. The oil production for the conventional well stood at 8.7MM STB representing 48.13% (Figure 11)

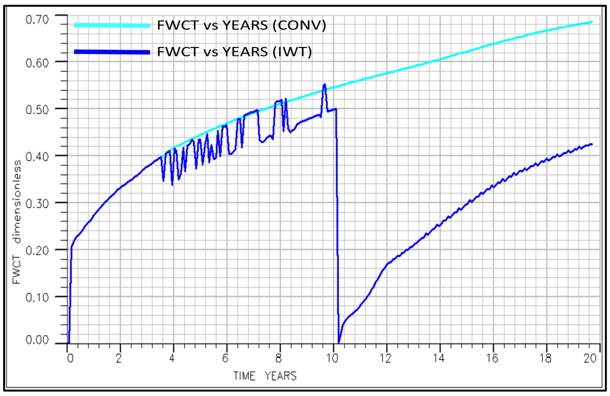

Fig. 8. Field Water Cut with Time for CW and IW

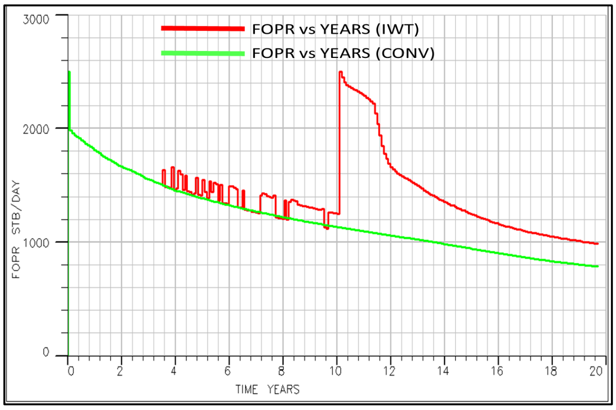

Fig. 9. Field Oil Production Rates with for CW and IW

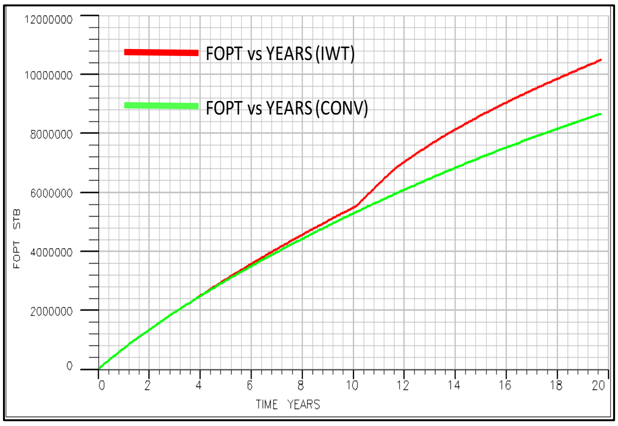

Fig. 10. Total Oil Production with Time for CW and IW

B. Dynamic Parameters- Relative Permeability

A water wet system was used to depict an optimistic case, and an oil wet system depicted a pessimistic case

A generally improved performance is observed in a water wet system compared to an oil wet system due to reduced water mobility.

$$Mobility\ ratio,\ M = \frac{k_{rw}/\mu_w}{k_{ro}/\mu_o} \qquad (5)$$

The mobility ratio of the water-wet system was 1.103 compared to 4.27 for the oil wet system. Maintaining the IW control strategy under a water wet system, not much improvement in performance was observed in both conventional and intelligent wells (Figure 11). In this case, the need for intelligent completions is not paramount. However, to realize a significant improvement in performance, it might be expedient to adjust the trigger values for the ICVs to ensure earlier water control.

For the oil wet system, increased water production led to early breakthrough. Hence the ICVs were engaged in the early production stages. (Figure 12). Based on the control strategy, the ICVs were shut from year eight (8) due to excessively high water production. Here again, the control strategy trigger values would have to be adjusted to prevent the shutdown.

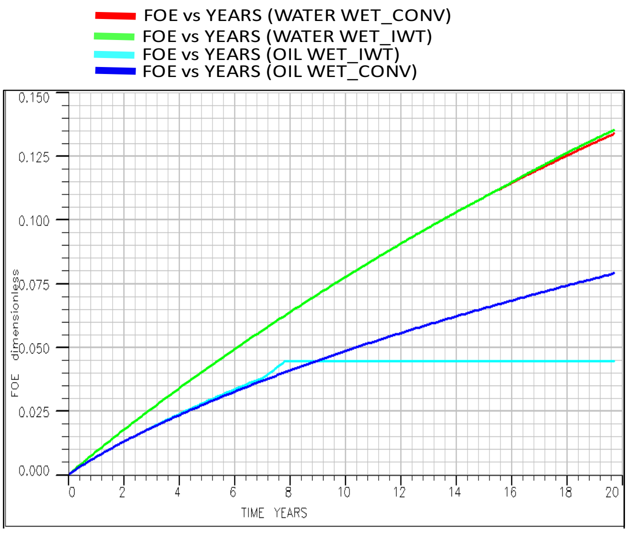

Figure 11. FOE for Oil-Wet and Water-Wet System (CW & IW)

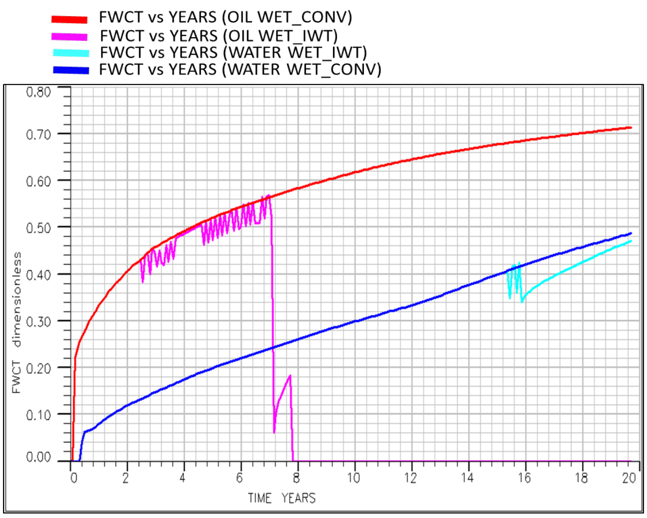

Fig. 12. FWCT for an Oil-Wet and Water-Wet System (CW &. IW)

C. Dynamic Parameters- Skin

Positive skin and negative skin were used to depict pessimistic and optimistic well conditions respectively. Introduction of skin generates additional pressure drop in the wellbore. The productivity index of conventional and intelligent wells due to varied skin conditions were compared.

$$P_e - P_{wf} = 141.2\frac{q\mu B_o}{kh}\left(ln\frac{re}{rw} + s\right) \qquad (6)$$

$$PI = \frac{q}{P_e - P_{wf}} \qquad (7)$$

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Vol. 6 Issue 01, January-2017

TABLE I. PRODUCTIVITY INDEX FOR YEAR FIVE (5)

	Optimistic Value		Pessimistic Value	
	CW	IW	IW	CW
Q_o, stb/day	1358.4	1354.9	1454.9	1307.4
P_e, psia	4491.0	4490.8	4491	4491.3
P_{wf}, psia	4404.8	4405.6	4220.9	4324.8
PI	15.87	15.9	5.4	7.8

TABLE II. PRODUCTIVITY INDEX FOR YEAR TEN (10)

	Optimistic Value		Pessimistic Value	
	CW	IW	IW	CW
Q_o, stb/day	1358.4	1354.8	1908.5	1082
P_e, psia	4471.8	4469.6	4471.2	4472
P_{wf}, psia	4366.7	392.1	14.7	4309
PI	12.9	0.33	0.42	6.67

TABLE III. PRODUCTIVITY INDEX FOR YEAR FIFTEEN (15)

	Optimistic Value		Pessimistic Value	
	CW	IW	IW	CW
Qo, stb/day	917.9	1490.2	843.7	906.8
Pe, psia	4453.5	4449.38	4463	4453.9
Pwf, psia	4366.7	392.16	14.7	4292.9
PI	10.57	0.36	0.18	5.6

D. Dynamic Parameters- Oil-Water Contact

Maintaining a well completion depth of 6060ft from the top of the reservoir, an optimistic OWC of 6300ft and a pessimistic value of 6100ft were set, and the well performance monitored. Values of total field water production (FWPT) and field water cut (FWCT) were significantly higher in the reservoir with 6100ft OWC than in the reservoir with 6300ft OWC. In the first scenario, the OWC is closer to the well, thereby recording an earlier water breakthrough and hence, increased water rate with time.

Water control by the ICVs in the 6300ft OWC reservoir proved insignificant. Since very little water is produced in this reservoir, the ICVs do not have a significant effect on the well performance (Figure 13).

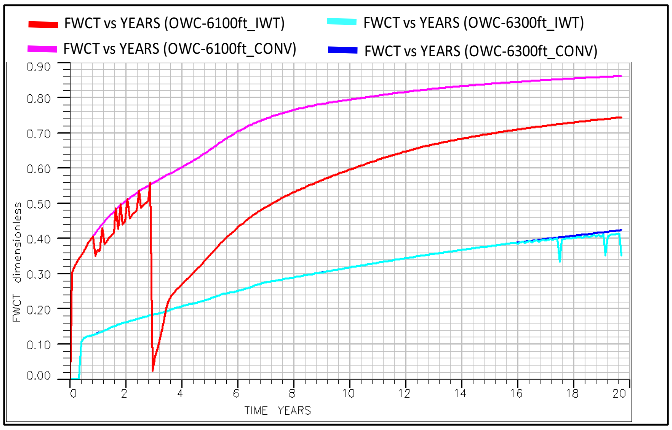

Fig. 13. Water cut for different oil-water contact (CW & IW)

E. Static Parameters- Porosity-Permeability

The porosity and permeability values were altered. For the optimistic case, porosity and permeability were multiplied by factors of 1.5 and 2.0 respectively. In the pessimistic case, porosity and permeability values were multiplied by factors of 0.5 and 0.75 respectively. It was assumed that a direct relationship exists between porosity and permeability of our reservoir.

$$q = \frac{kA(p_1 - p_2)}{\mu L} \qquad (8)$$

According to Darcy's Flow equation, the flow rate is directly proportional to reservoir permeability. Thus it is expected that increase in permeability will give a corresponding rise in flow rate (with a constant reservoir pressure). Figure 14 shows the graphs of performance of both conventional and intelligent wells under varied porosity and permeability conditions.

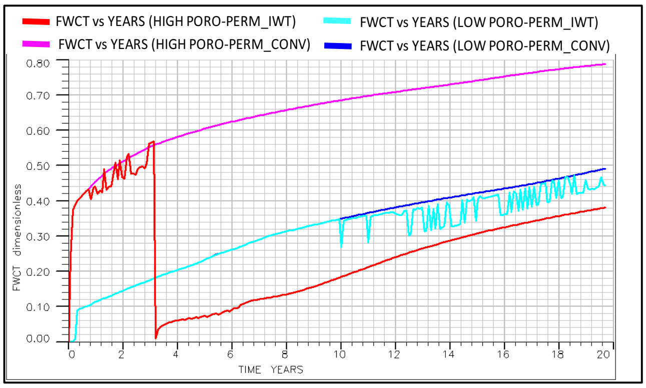

Fig. 14. Water cut for different porosity-permeability conditions (CW & IW)

F. Economic Analysis

Through the application of an optimized reactive control strategy the IW had an increased NPV of **12.45%** (Table 1). From figure 18, it can be seen that until the fourth year of production, the CW and IW both had equal NPV. After, the IW outperformed the CW for the subsequent years. This is so because the ICV in segment 14 was triggered from the fourth year, which meant that water production was being controlled. A further increase in NPV is also seen from year 10. This corresponds with the time the second ICV in segment 6 was activated.

Thus it can be seen that the IW outperforms the CW in all aspects of the analysis (Figure 15). Table 4.0 below presents the economic performance of our optimized intelligent well case.

Figure 16 shows the economic performance of CW and IW for varying reservoir conditions.

TABLE IV. ECONOMIC PERFORMANCE OF OPTIMIZED BASE

	FOE	NPV [$MM]	% Increase in NPV [(NPV_{IW} – NPV_{CW})/ NPV_{CW}]*100%
CW	0.091	8,243	
IW	0.110	9,269	**12.45**

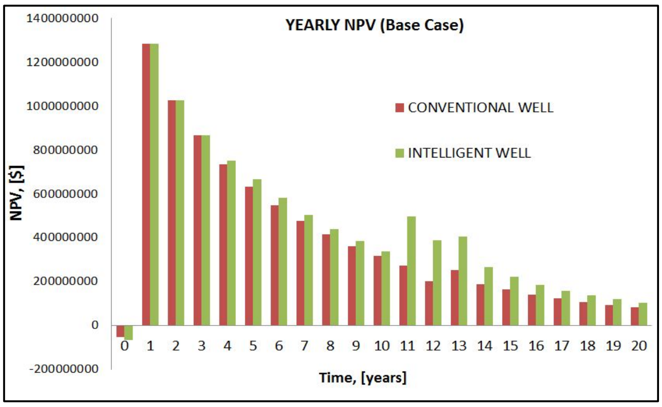

Figure 15. Yearly NPV for CW and IW

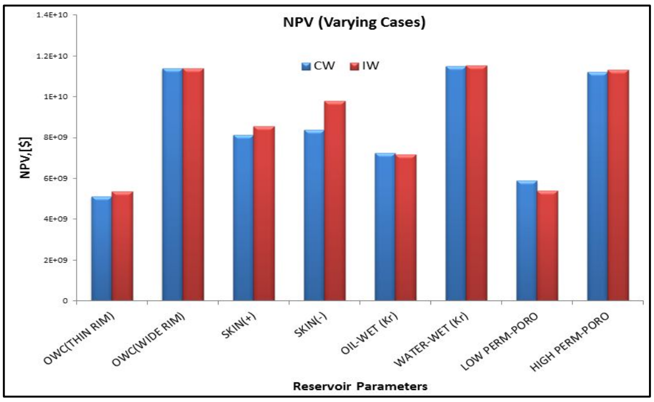

Fig. 16. NPV comparison of CW & IW for various reservoir conditions

IV. CONCLUSION

The results presented show that IWT can be used to control water and increase oil production in a well, by choking production from high permeability zones. The IW reduced the field water produced by 41.9% (from 9.3 MMSTB in the conventional well to 5.4 MMSTB) after 20 years of production. Consequently, field oil production was vamped from 8.66 MMSTB in the conventional well to 10.49 MMSTB. This translates into a 21.1% increment in total oil production. IWT eliminated the need for workovers, which reduced operational costs and the risk of damage to the wellbore. The combined effect of this was a 12.45% increase in NPV for the IW.

It was observed that intelligent well efficiency varied under different reservoir conditions and thus, may not be applicable in reservoirs with certain characteristic properties.

- In low porosity-permeability reservoirs, IWT yielded poor benefits, and thus may not be justified for water control under such conditions.
- The relative mobility of the oil and water affects the benefit of employing IWT. IWT yields optimum benefit in fields with adverse mobility ratio. This is typical in oil-wet reservoirs, where water has a higher mobility. The control strategy reflected this in the first eight years of production. However, in subsequent years, excessive water cut beyond our trigger values changed the trend.
- IWT yields optimum results in water drive reservoirs with thin pay zones or oil rim as compared to those with thicker oil rim where water breakthrough occurs later during production.

For further work, the reservoir model should be expanded to incorporate a greater number and variety of wells (both producers and injectors). Additional investigation on the performance of the control strategy under more varied parameters needs to be carried out to further develop an effective and robust control strategy. The application of IWT in heterogeneous reservoirs is also to be explored.

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NOMENCLATURE

CW - Conventional Well	STB - Stock Tank Barrel
D.R. - Discount Rate	SWCT - Segment Water Cut
FOE - Field Oil Efficiency	D_b - Distance from the bottom of the perforations to the oil-water contact, ft
FOPR - Field Oil Production Rate	
FOPT - Field Oil Production Total	
FWCT - Field Water Cut	G_p - Total gas production, MMSCF
ICV -Interval Control Valve	G_{price} - Gas price, $
IW - Intelligent Well	h - Oil column thickness, ft
IWT - Intelligent Well Technology	N_p - Total Oil Production
LRAT - Liquid Rate	O_{price} - Oil price
NCF - Net Cash Flow	s - Skin factor
NPV - Net Present Value	W_{cost} - Cost of water treatment
OWC - Oil Water Contact	W_p - Total water production

APPENDIX

TABLE A.1 RESERVOIR MODEL DESCRIPTION

	Parameter	Amount	Field Unit
Reservoir Dimensions	Length	150	ft.
	Width	150	ft.
	Height	17.5	ft.
Reservoir Properties	Datum Depth	6000	ft.
	Datum Pressure	4800	Psia
	OWC	6175	ft.
	GOC	6000	ft.
Rock Properties	Horizontal Permeability	50	mD
	Vertical Permeability	5	mD
	Rock compressibility	4.0×10^{-5}	
	porosity	0.25 (all grids)	Psi^{-1}
Fluid Properties	Oil Density	45.000	$lb./ft^3$
	Water density	62.4000	$lb./ft^3$
	Gas density	0.0001	$lb./ft^3$

TABLE A.2. STATIC PARAMETERS

Parameter		Pessimistic Value	Base Case Value	Optimistic Value
Permeability, md	$X_{direction}$	10	50	100
	$Y_{direction}$	10	50	100
	$Z_{direction}$	1	5	10
Porosity (x,y,z-directions)		0.19	0.25	0.38

TABLE A.3. DYNAMIC PARAMETERS

	Pessimistic Value	Base Case Value	Optimistic Value
OWC, ft.	6100	6175	6300
Skin	5	0	-2
Relative Permeability	Oil-wet Case	Base	Water-wet case

TABLE A.4. PARAMETERS FOR NPV COMPUTATION

Parameters	Conventional Well	Intelligent Well
Rig Rate, $/Day [14]	150 000	150 000
Drilling time, Days [15]	80	90
Workover Time, Days	20	-
Well Equipment Cost, $	3 000 000	3 000 000
Intelligent Completion Cost, $	-	2 200 000
Water treatment Cost, $/BBL	5	5
OPEX, % of Revenue	5%	5%
Discount Rate (DR)	10%	10%

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