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Design Of Wells In Case Of Water Coning

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Abstract-Wells drilled in the reservoirs with the bottom water drive are usually produced above the critical rate owing to economic reasons. This leads to water coning, or as called in case of horizontal wells a water crest, and breakthrough of water into the well. Water coning is described as a steady and usually sharp displacement of some or all the oil production by the bottom water when the critical withdrawal rate from the well is exceeded. Water coning may lead to several serious problems. A sample reservoir model is taken into consideration for optimization of oil production in the presence of water coning. Parameters to be optimized are well length and position of the well in the reservoir. Vertical and horizontal wells are both considered in this study. Two scenarios are considered: constant production rate and constant bottomhole flowing pressure. The optimum alternative is defined as the one which maximizes the economic profit. Moreover, the effects of some reservoir and fluid parameters on critical rate are analyzed.

Keywords: water coning, crest, stimulation, Ecrin, Rubis, optimization of horizontal wells, well length and its position.

INTRODUCTİON

Wells drilled in the reservoirs with the bottom water drive are usually produced above the critical rate owing to economic reasons. This leads to water coning, or as called in case of horizontal wells a water crest, and breakthrough of water into the well (Muscat, 1935). In this study we consider the optimal placement and optimal length of horizontal wells for maximizing economic profit. The costs related to the problem are drilling costs and water disposal costs. To find the optimal parameters, the simulator is run for various horizontal well lengths and various well placements. The scenario that gives the maximum profit is chosen as the optimal solution. Optimization process for the length and vertical position of the horizontal well and the completion interval of the vertical well will be discussed. Moreover, the differences between horizontal and vertical wells and advantages of the former over the latter are handled. In addition, one example problem is solved using RUBIS (Ecrin v4.20, 2013) and compared with the results from some correlations. Next the description of the reservoir model used in RUBIS is provided. Finally, simplified economic analysis for the optimization process and sensitivity analysis results, along with the effects of some parameters on the critical rate are given.

DESCRIPTION AND DESIGN OF THE MODEL

In the present simulation study the subprogram of ECRIN, RUBIS was used to study the water coning in horizontal and vertical wells. First, a single vertical well was considered in the study. Then a single horizontal well was completed in the reservoir. The reservoir is assumed to have a cylindrical shape with the dimensions shown in **Figure 1** and **Figure 2.**

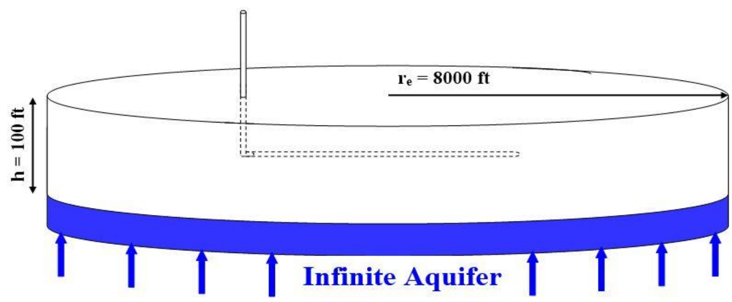

Figure 1 – A 3D shape of the oil reservoir with a horizontal well

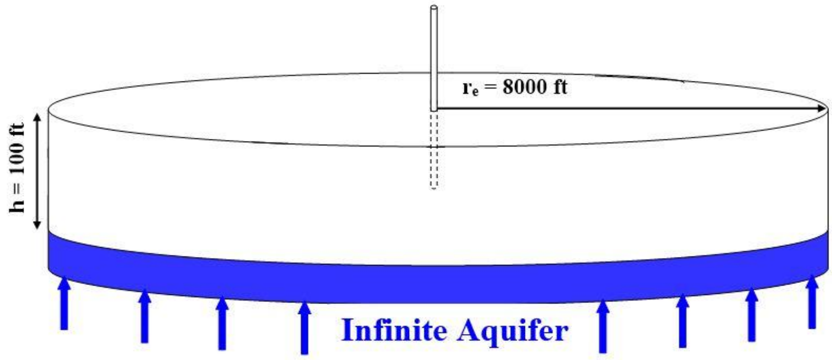

Figure 2 – A 3D shape of the oil reservoir with a vertical well

The reservoir has a bottom water drive with 200 bbl/psi-day, as recharge constant for the Schilthuis water influx model (Craft and Hawkins, 1991). The cases are run for 10000 days for different production rates. Correlations used by RUBIS (Ecrin v4.20, 2013) for the oil formation volume factor, compressibility of oil, and oil viscosity are Standing, Vasquez-Beggs and Beggs-Robinson correlations, respectively. As for water, Spivey and Van-Wingen and Frick correlations are used for water formation volume factor and water viscosity, respectively. Reservoir and fluid parameters used in the study are given in **Table 1**. Capillary pressure is assumed as negligible for more uniform and efficient oil displacement and for more precise water saturation profile. In order to observe coning and describe the pressure distribution and fluid flow more accurately, the model was layered into two sections. The upper layer is discretized into 4 and the lower layer into 30 grids in z-direction. The **Figure 3** shows water and oil relative permeability assumed in the simulation runs.

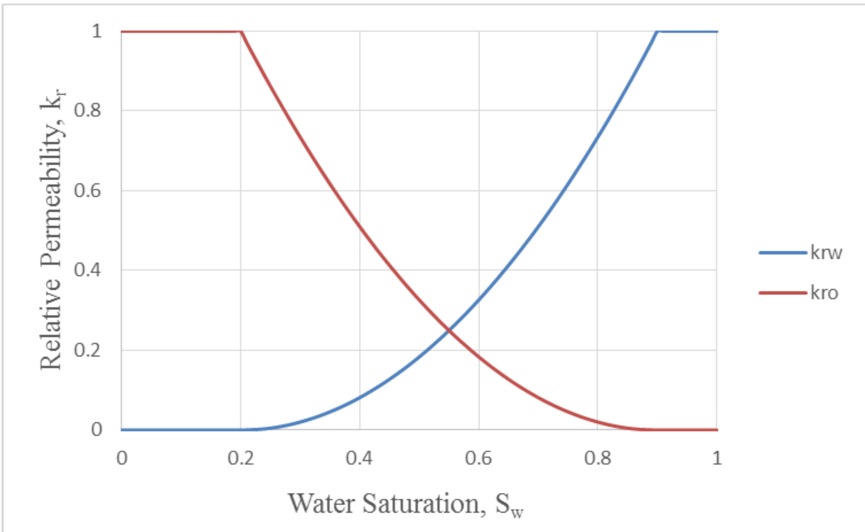

Figure 3 – Relative permeability curves

Table 1 – Reservoir and fluid parameters

Resevoir temperature, °F	212
Reservoir initial Pressure, psia	5000
°API gravity	26
Vertical depth, ft	6000
Reservoir oil thickness, ft	100
Reservoir drainage radius, ft	8000
Wellbore radius, ft	0.3
Vertical anisotropy ratio, fraction	0.1
Horizontal permeability, md	100
Vertical permeability, md	10
WOC, ft	6100
Oil viscosity, cp	8.58
Water density, lb/ ft	68.36
Oil density, lb/ ft	57.64
Porosity, fraction	0.164
Residual oil saturation, fraction	0.2
Connate water saturation, fraction	0.1
Water salinity, ppm	1.22E+05
Pore compressibility, psi	3.0E+06
Water compressibility, psi	2.5E-06
Oil compressibility, psi	3.43E-6
Initial oil formation volume factor, bbl/STB	0.9731
Initial water formation volume factor, bbl/STB	0.9985
Aquifer recharge index, bbl/psi-day	200

Several cases for two scenarios, a constant production rate and a constant bottomhole flowing pressure, are run for vertical and horizontal wells. The production rate and the bottomhole flowing pressure are chosen as 300 STB/day and 4800 psia, respectively for both types of wells. The effects of completion interval of vertical wells, and the length and vertical position of the horizontal well in those scenarios are studied. The simulation is run for 10000 days and all the data in the tables in this chapter are taken at the end of 10000 days.

For economic analysis the oil price and water disposal cost were assumed as 100 $/STB and 1.5 $/STB, respectively. Costs for vertical and horizontal wells are considered differently. Cost per foot was taken as 300 $ for vertical wells and 750 $ for horizontal wells. The cost for the horizontal well accounts for the total measured depth, that is, vertical section plus horizontal section.

OPTIMIZATION PROCESS FOR CONSTANT PRODUCTION RATE SCENARIO

Both vertical and horizontal wells are considered for optimization process. First, the vertical well is assumed to be completed at different intervals in the reservoir (**Figure 4**). Then for the horizontal well the vertical position and the length of the well are considered. For the vertical position a horizontal well having a length of 4000 ft is placed at different interval in the reservoir (**Figure 5**). For length optimization, the horizontal well is placed at 40 ft from the top of the reservoir (**Figure 6**).

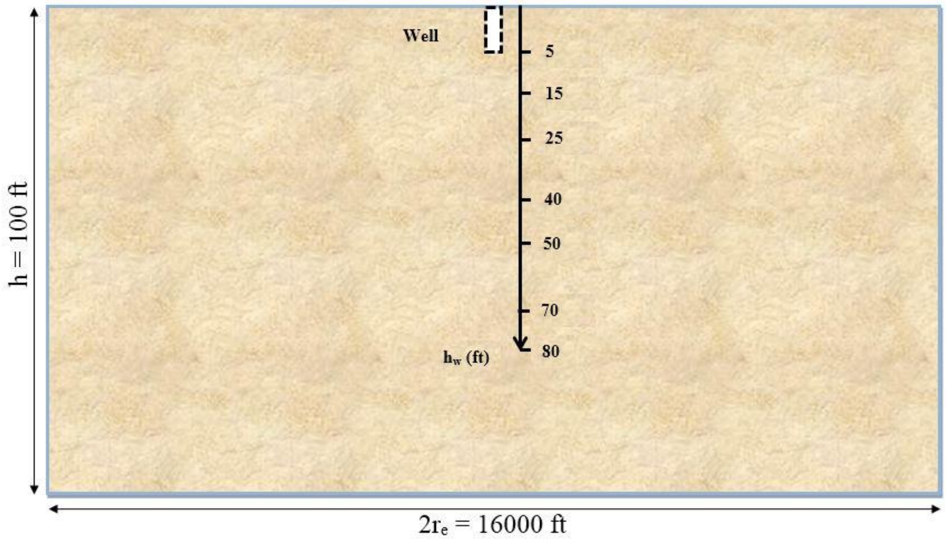

Figure 4 – Completion interval of the vertical well

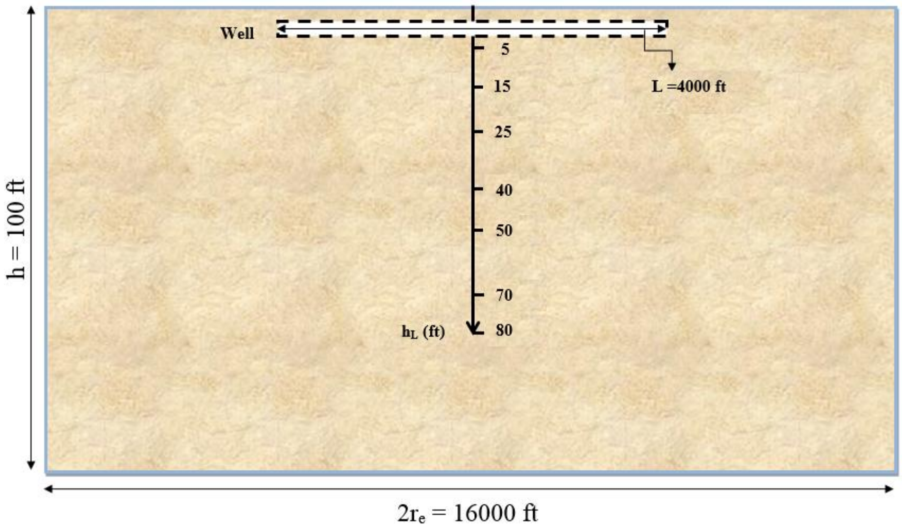

Figure 5 – Placement of the horizontal well at different vertical positions (L=4000 ft)

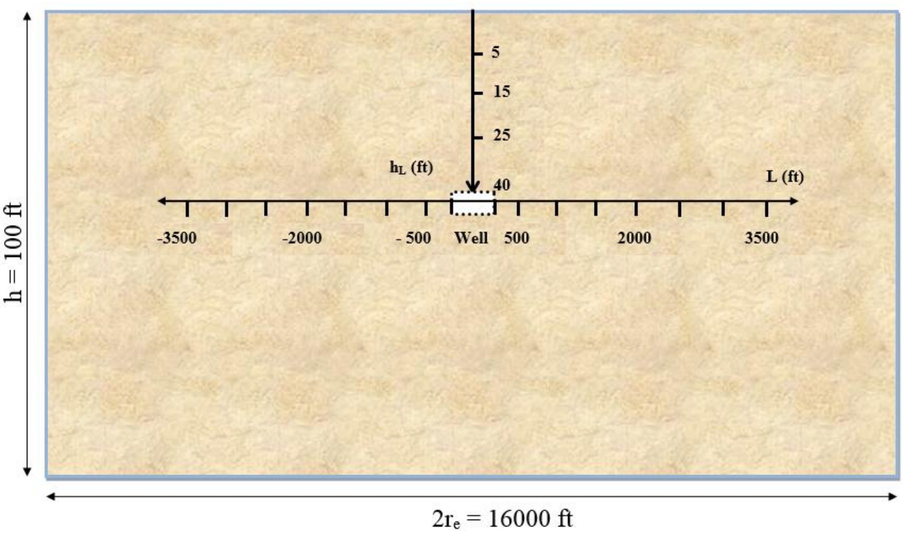

Figure 6 – Schematic diagram for the optimization of horizontal well length (h_L=40 ft)

Change in the reservoir pressure is not considerable since the reservoir is assumed as infinitely large and a single well is drilled for production (**Table 2, Table 3, and Table 4**). The bottomhole flowing pressure shows significant change in case of vertical wells, especially at upper part of the reservoir as can be seen from **Table 2**. From**Table 2**it can be seen that when the vertical well is completed at the top, cumulative water production is lower and it is increasing with the depth in the reservoir. From **Table 3**, when the horizontal well is placed close to the top of the reservoir, again cumulative water production is low. Completion of the well at the top of the reservoir delays water coning. When the well is close to WOC, there is a high tendency for the water cone to breakthrough into the well.

Horizontal well length is also used as one of the significant criteria for optimization in case of horizontal wells. Increase in the horizontal well length delays water production, which can also be observed from **Table 4.**The longer the horizontal well, the lower the drawdown in the reservoir andbottomhole flowing pressures.

It is important to note that in the economic analysis considered here only well cost, water disposal cost, and the money earned from selling the oil is taken into account in a simple manner. Results could change if other criteria or economic assumptions are assumed.

Table 2 – Data from RUBIS for optimization process at a constant production rate for the vertical well at 10000 days

	h_w (ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	p_{wf} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit ($)
							Well	Water Disposal		
q_o = 300 STB/day	5	3.0	1.9088	4996.56	450	0.0062	1500	5.73E+06	3.0E+08	**2.943E+08**
	15	3.0	1.9170	4996.56	3077	0.0062	4500	5.75E+06	3.0E+08	2.942E+08
	25	3.0	1.9349	4996.55	3729	0.0062	7500	5.80E+06	3.0E+08	2.942E+08
	40	3.0	1.9781	4996.54	4140	0.0062	12000	5.93E+06	3.0E+08	2.941E+08
	50	3.0	2.0170	4996.52	4288	0.0062	15000	6.05E+06	3.0E+08	2.939E+08
	70	3.0	2.1152	4996.5	4466	0.0062	21000	6.35E+06	3.0E+08	2.936E+08
	80	3.0	2.1753	4996.47	4525	0.0062	24000	6.53E+06	3.0E+08	2.935E+08

Table 3 – Data from RUBIS for optimization process at a constant production rate for the horizontal well based on the vertical position at 10000 days (L=4000 ft)

	h_L (ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	p_{wf} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit ($)
							Well	Water Disposal		
q_o = 300 STB/day	5	3,0	0,03318	4998,22	4938,11	0,0062	3,00E+06	9,95E+04	3,0E+08	**2,969E+08**
	15	3,0	0,07953	4998,06	4942,95	0,0062	3,01E+06	2,39E+05	3,0E+08	2,968E+08
	25	3,0	0,20866	4997,77	4944,14	0,0062	3,02E+06	6,26E+05	3,0E+08	2,964E+08
	40	3,0	0,65676	4997,2	4944,25	0,0062	3,03E+06	1,97E+06	3,0E+08	2,950E+08
	50	3,0	0,99612	4997,08	4946,91	0,0062	3,04E+06	2,99E+06	3,0E+08	2,940E+08
	70	3,0	1,75513	4996,72	4951,58	0,0062	3,05E+06	5,27E+06	3,0E+08	2,917E+08
	80	3,0	1,88236	4996,74	4953,77	0,0062	3,06E+06	5,65E+06	3,0E+08	2,913E+08
	90	3,0	2,06204	4996,66	4954,82	0,0062	3,07E+06	6,19E+06	3,0E+08	2,907E+08

Table 4 – Data from RUBIS for optimization process at a constant production rate for the horizontal well based on the well length at 10000 days (h_w=40 ft)

	L (ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	p_{wf} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit($)
							Well	Water Disposal		
q_o = 300 STB/day	500	3.0	2.2556	4996.38	4746	0.0062	375000	6.767E+06	3.0E+08	2.9286E+08
	1000	3.0	2.0191	4996.5	4843	0.0062	750000	6.057E+06	3.0E+08	2.9319E+08
	2000	3.0	1.6526	4996.66	4902	0.0062	1500000	4.958E+06	3.0E+08	2.9354E+08
	3000	3.0	1.1429	4996.92	4928	0.0062	2250000	3.429E+06	3.0E+08	2.9432E+08
	4000	3.0	0.6568	4997.2	4944	0.0062	3000000	1.970E+06	3.0E+08	2.9503E+08
	5000	3.0	0.2786	4997.6	4958	0.0062	3750000	8.358E+05	3.0E+08	**2.9541E+08**
	6000	3.0	0.0320	4998.22	4969	0.0062	4500000	9.590E+04	3.0E+08	2.9540E+08
	7000	3.0	0.0001	4998.44	4976	0.0062	5250000	2.133E+02	3.0E+08	2.9475E+08

OPTIMIZATION PROCESS FOR CONSTANT BOTTOMHOLE FLOWING PRESSURE SCENARIO

The bottomhole flowing pressure is set constant as 4800 psia and as in case of constant production rate scenario two types of wells are considered. The same parameters are chosen to be optimized. As can be seen from **Table 5**, both cumulative oil and water production increases as the vertical well is completed deeper in the reservoir. Cumulative water and oil production is too low for the vertical well compared to the horizontal one. Although the recovery factor increases when the true vertical depth is increased, it is still too low.

According to the results summarized in **Table 6**, again the location of the horizontal well which minimizes the cumulative water production is the top of the reservoir. It can also be seen that after 50 ft of completion, cumulative oil and recovery factor start to decrease.

As can be seen from **Table 7**, difference between the profits for different lengths is more noticeable rather than in case of vertical position. Cumulative oil and water production increases significantly when the horizontal well length increases. However, in other cases there is no such a remarkable difference in cumulative production.

From **Table 5** it can be deduced that the maximum profit is observed when the vertical well is completed at 80 ft. This might have happened as a result of high cumulative oil production. **Table 6** shows that the optimum portion of the reservoir thickness the well should be placed, is 50 ft. However, the difference between the profit values is not considerable. Thus, the well can be positioned at any depth of the reservoir. The horizontal well length proved to be as the primary criterion for optimization. Hence, one may decide to drill as long horizontal well as possible regardless of the vertical completion in order to maximize the profit as can be seen from **Table 7**.

Table 5 – Data from RUBIS for optimization process at a constant bottomhole flowing pressure for the vertical well at 10000 days

	h_w(ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit ($)
						Well	Water Disposal		
p_{wf} = 4800 psia	5	0.177778	4.28E-07	4999.91	3.68E-04	1500	1.282713	1.8E+07	1.778E+07
	15	0.420335	3.88E-06	4999.78	8.69E-04	4500	11.64402	4.2E+07	4.203E+07
	25	0.629545	0.004548	4999.67	0.0013	7500	13644	6.3E+07	6.293E+07
	40	0.860067	0.107888	4999.45	0.00178	12000	323664	8.6E+07	8.567E+07
	50	1.00067	0.196634	4999.31	0.00207	15000	589902	1.0E+08	9.946E+07
	70	1.263388	0.410167	4999.01	0.00261	21000	1230501	1.3E+08	1.251E+08
	80	1.38973	0.532016	4998.85	0.00288	24000	1596048	1.4E+08	**1.374E+08**

Table 6 – Data from RUBIS for optimization process at a constant bottomhole flowing pressure for the horizontal well based on the vertical position at 10000 days (L=4000 ft)

	h_L (ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit ($)
						Well	Water Disposal		
p_{wf} = 4800 psia	5	9,24342	8,63991	4988,7	0,01912	3,00E+06	2,59E+07	9,2E+08	8,954E+08
	15	9,84273	10,1485	4987,2	0,02036	3,01E+06	3,04E+07	9,8E+08	9,508E+08
	25	10,1198	11,2632	4986,2	0,02093	3,02E+06	3,38E+07	1,0E+09	9,752E+08
	40	10,2552	12,6182	4985,5	0,02121	3,03E+06	3,79E+07	1,0E+09	9,846E+08
	50	10,2827	13,4673	4985	0,02127	3,04E+06	4,04E+07	1,0E+09	**9,848E+08**
	70	10,2264	14,889	4984,2	0,02115	3,05E+06	4,47E+07	1,0E+09	9,749E+08
	80	10,1785	15,4177	4983,9	0,02105	3,06E+06	4,63E+07	1,0E+09	9,685E+08
	90	9,96543	15,3242	4984,1	0,02061	3,07E+06	4,60E+07	1,0E+09	9,475E+08

Table 7 – Data from RUBIS for optimization process at a constant bottomhole flowing pressure for the horizontal well based on the well length at 10000 days (h_L=40 ft)

	L (ft)	Q_o (MMSTB)	Q_w (MMSTB)	p_{res} (psia)	Recovery Factor	Cost ($)		Revenues ($)	Profit ($)
						Well	Water Disposal		
p_{wf} = 4800 psia	500	2.66312	1.72506	4997.3	0.00551	405000	5175180	2.7E+08	2.61E+08
	1000	4.11902	3.4857	4995.2	0.00852	780000	10457100	4.1E+08	4.01E+08
	2000	6.38694	6.70012	4991.7	0.01321	1530000	20100360	6.4E+08	6.17E+08
	3000	8.35546	9.71869	4988.5	0.01728	2280000	29156070	8.4E+08	8.04E+08
	4000	10.2552	12.6182	4985.5	0.02121	3030000	37854600	1.0E+09	9.85E+08
	5000	12.0782	15.3425	4982.6	0.02498	3780000	46027500	1.2E+09	1.16E+09
	6000	13.84364	17.8489	4980	0.02863	4530000	53546700	1.4E+09	1.33E+09
	7000	15.5105	20.191	4977.6	0.03208	5280000	60573000	1.6E+09	**1.49E+09**

EFFECTS OF VARIOUS RESERVOIR AND WELL PARAMETERS ON THE CRITICAL RATE

The most studies have been concentrated on water coning problem in terms of critical rate, breakthrough time and prediction of WOR after breakthrough. However, there are some studies, which give effort to understand the effects of some parameters on behavior of water coning in horizontal wells. These parameters are horizontal permeability, thickness of oil reservoir, length of completion, density difference, mobility ratio, length of horizontal well, vertical position of the well, anisotropy ratio, etc. In order to understand the effects of some of these parameters on critical production rate in horizontal wells, several cases were run in RUBIS.

In this study the critical rate was found as 188 STB/days. As can be observed from **Figure 7**, if the well is produced at 188 STB/day water cone does not reach the well. However, **Figure 8** indicates the different situation where the critical rate is outpaced. In this case the cone reaches the well.

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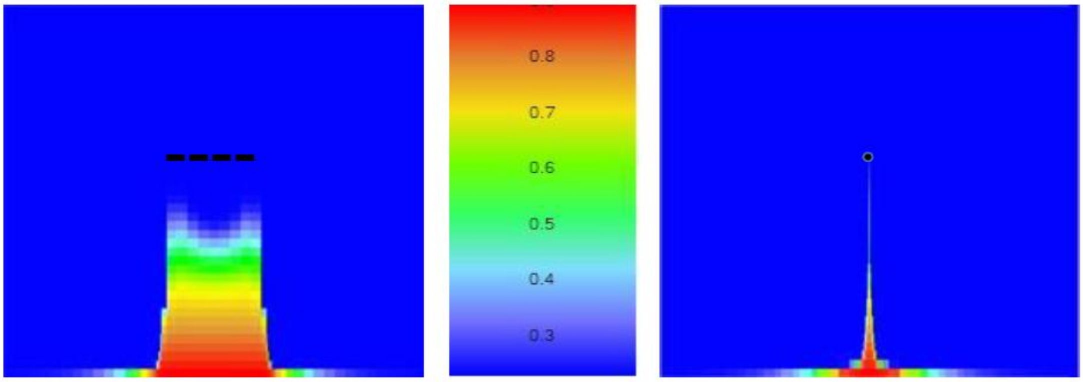
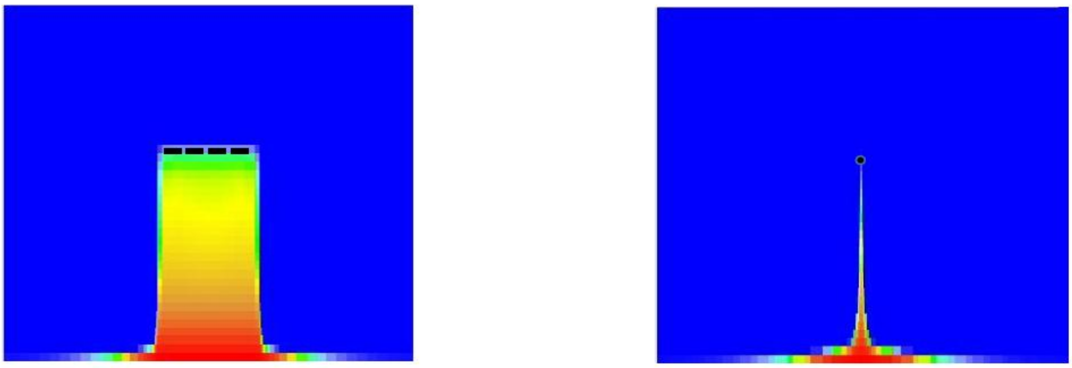


(a) t = 10 000 days S_w (b) t = 10 000 days

Figure 7 – Water saturation distribution at q_{oc} = 188 STB/days, (h_L = 40 ft, L = 4000ft)



(a) t = 10 000 days (b) t = 10 000 days

Figure 8 – Water saturation distribution at q_o = 300 STB/days, (h_L = 40 ft, L = 4000 ft)

In order to understand the effect of vertical anisotropy on behavior of water coning, six different values of k_v/k_h have been used and the result are given in **Figure 9**. When k_v/k_hdecreases, this means that the vertical permeability is decreasing, since horizontal permeability is kept constant. It is observed that the critical rate is increasing with decreasing k_v/k_h. This is expected, since if the vertical permeability is reduced, the upward flow of water is delayed more. This results in a higher critical rate.

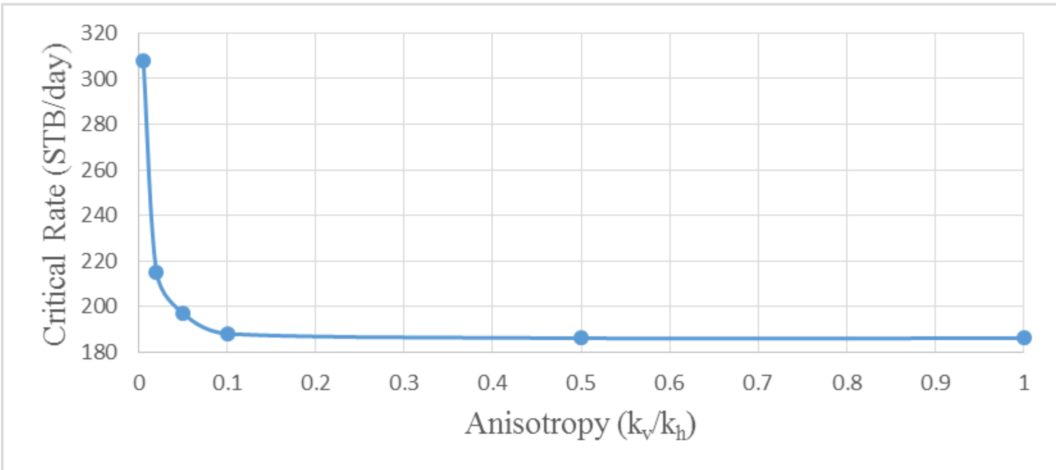


Figure 9 – The effect of vertical anisotropy on critical production rate

For studying the effect of the length of horizontal well on performance of water coning in horizontal wells, seven cases were run in simulation program. The results of simulation are shown in **Figure 10**. As results indicated, the longer horizontal well provides higher critical production rate. This is owing to the larger area open to flow in case of horizontal wells. The direct relation between the critical rate and the horizontal well length is also seen from correlations derived by Chaperon (1986), Ozkan-Raghavan (1990), Joshi (1988, 1991) and Giger (1989) for predicting critical production rate in horizontal wells.

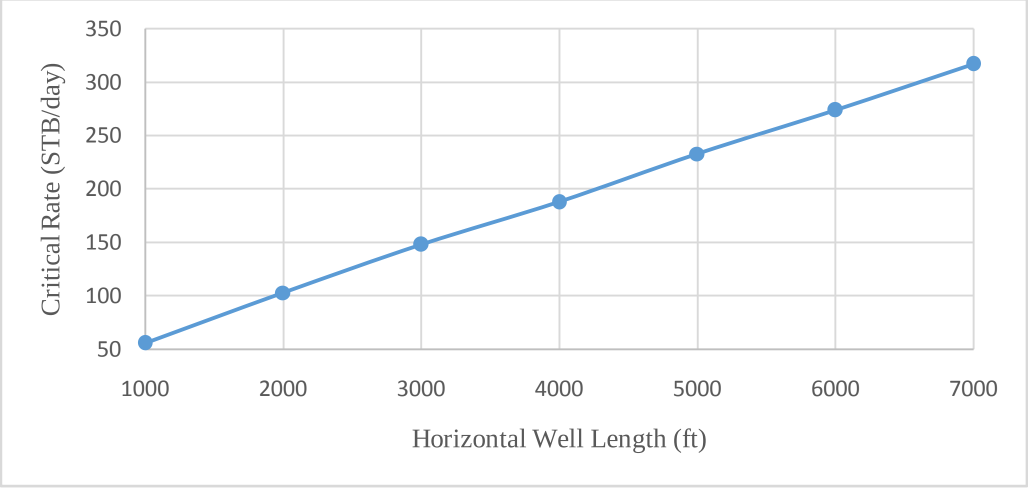


Figure 10 – The effect horizontal well length on critical rate

Difference between water and oil densities has also an influence on critical rate. Six cases for horizontal wells with different water and oil densities were run. Other parameters are kept constant as in base model. The results of simulation are shown in **Figure 11**. It can be concluded that increase in difference between water and oil densities results in increase of oil production and retard of water coning. Therefore, it can be said that the light oil reservoir has less tendency for coning than heavy oil reservoir.

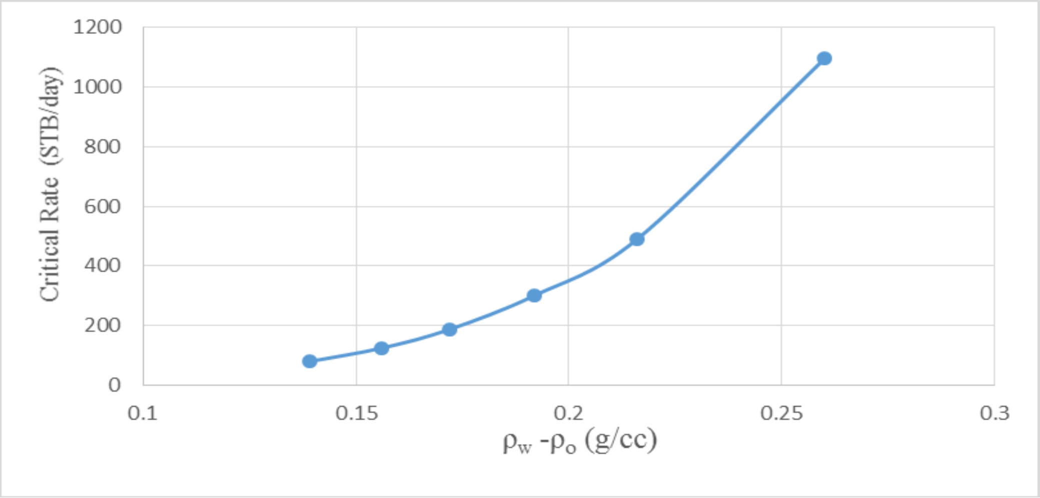


Figure 11 – The effect of the density difference on critical rate

In the study, Schilthuis model of water influx was used as the aquifer recharge. Several cases were run for the observation of the effect of Schilthuis constant on the critical production rate. The results are plotted as in **Figure 12**. Increase in Schilthuis recharge caused decrease in the critical production rate, which is not surprising, since increase in Schilthuis constant means increase for water that influx into the reservoir. This phenomenon is also mentioned by an author Ahmed (2010) in his course book. This increase requires the production rate to be lowered in order for the water breakthrough to be avoidable.

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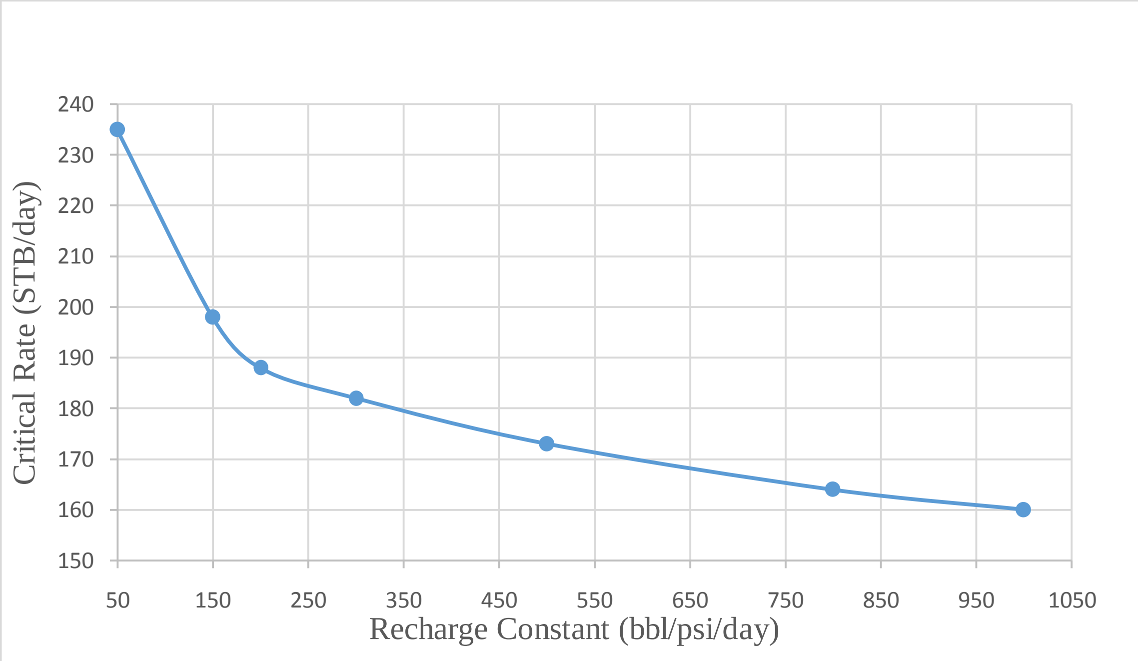

Figure 12– Effect of recharge constant on critical rate

From **Figure 13** it can be seen that the deeper the well location, the lower the critical production rate. As the well is placed closer to the WOC, the effect of the pressure drop becomes more sustainable and tendency of water to break into the well becomes higher. Thus, production rate should be decreased when the well is produced in deeper parts of the reservoir so that water tendency for breakthrough cannot become higher.

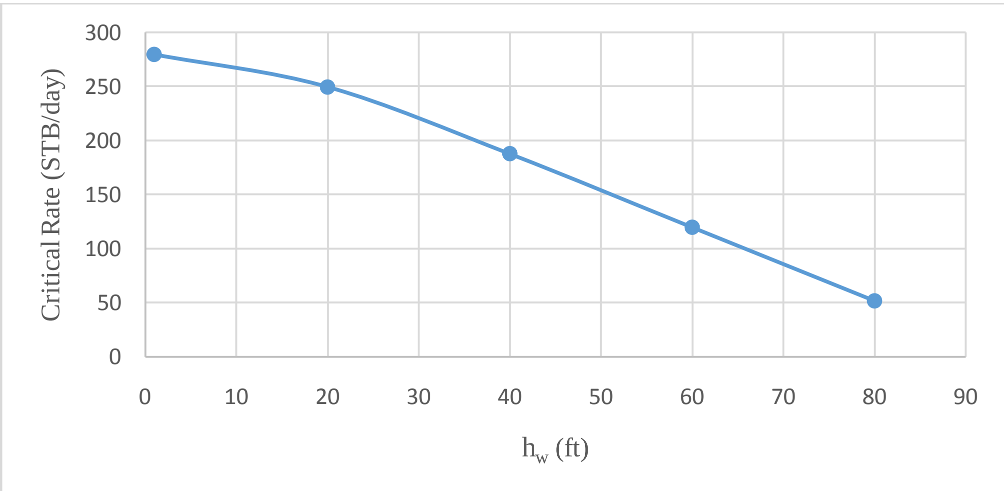

Figure 13 – Effect of vertical position of horizontal well on critical rate

SUMMARY

One of the main subjects discussed in this study is development of the field in terms of optimization of length and position of wells in the given reservoir. The horizontal well proved to be more cost-effective than the vertical well. In addition, sensitivity analysis was conducted to observe the effect of some reservoir and fluid parameters on the critical rate as well as the influence of grid numbers in RUBIS on the results.

Optimization process was performed for two scenarios: constant production rate and constant bottomhole flowing pressure. For the first case, lower cumulative water production occurs at the top of the reservoir. In case of longer horizontal well, cumulative water production is also low. It means, placement of the horizontal well at the top and making it as long as possible retard the water coning. For constant bottomhole flowing pressure scenario, the longer the horizontal well results in higher cumulative oil production. The true vertical depth of this well should be the middle of the reservoir thickness, since cumulative oil production is the highest at this interval.

CONCLUSION

From the study on the effects of some parameters on the critical rate the following results are obtained.

- Increase in vertical anisotropy causes decrease in critical production rate.
- Critical production rate is directly proportional to the horizontal well length.
- Heavy oil is more vulnerable to water coning than light oil.
- The higher the initial reservoir pressure, the lower the critical rate.
- Higher recharge constant results in lower critical rate.
- As the well is placed closer to WOC, there is a higher tendency for water breakthrough.
- Increase in the grid number in RUBIS leads to higher results for the critical rate.

CONFLICT OF INTEREST

The author confirms that the data do not contain any conflict of interest.

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