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Water Coning in Horizontal Wells

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Abstract: Water production from oil wells is a common event which augment the cost of producing processes and may decrease the efficiency of the reserve recovery. We will deal with the reason of this production of water, namely, coning. Several approaches have been exhibited to overcome this problem, whatever before or after the taking place of water coning. The critical rate is the widely method used to overcome this problem before its occurring. The objective of this research is to present a method to calculate the critical rate, breakthrough time, and WOR (water oil ratio) after breakthrough in horizontal wells. A 3-D numerical simulator model was used to perform a comprehensive sensitivity analysis of water coning process. From this analysis, an empirical coning correlation was developed based on regression analysis. The format of the correlation is similar to Yang's water coning correlation. The correlations presented in this paper provide a hand calculation fashion of coning prediction for horizontal wells. The correlations were tested and found to be reliable and accurate in predicting the critical rate, breakthrough time and WOR, within the correlations parameter ranges.

Keywords: Water coning; Critical rate; horizontal well; Water production.

INTRODUCTION

Pressure gradients which are developed in the region around the well bore through fluid production lead to water coning. As a result of the pressure gradients water oil contact can be raised in regions where there is great severity of gradients. Differences in fluid densities lead to gravity forces which counter balance the pressure gradient that is flowing and keep the oil zone free from any water. Therefore, there is balance present between the viscous forces and gravitational forces away and on points from the interval of completion. When the gravitational forces are exceeded by the dynamic forces, an ultimate break of water zone will occur leading to production of water with oil. The coning problem has been addressed by several authors in terms of critical production rate, which is the rate above which the flowing pressure gradient at the well causes water to cone into the well. Many correlations were developed to predict the critical rate. In general, these correlations can be splitted into two categories. The first category defines critical rate analytically based on the equilibrium conditions of gravity forces and pressure gradients. In this category the critical rate is calculated by allowing the gravity forces equal the viscous forces in the proposed oil potential function.

Computer simulation runs or laboratory experiments are used to obtain data that used to develop an empirical correlation in the second category. Because of The complication of recent reservoir engineering problems which make laboratory models unpractical and the modern progress in computer technology, most studies on horizontal wells are either numerical or analytical.

Chaperon[1] postulated constant interface elevation at a finite distance and neglected the flow restriction as a result of the immobile water in an anisotropic formation to study the performance of cresting in the direction of horizontal wells. Her method is similar to that used by Muskat[2]. Also she compared the horizontal and vertical wells critical rates. In horizontal wells before breakthrough Giger[3] introduced an analytical two-dimensional (2-D) model of water cresting which is developed in a vertical plane upright to the axis of the horizontal well. He used three production mechanisms are bottom water drive, lateral edge drive, and gas-cap drive. As Giger used the free surface boundary condition and supposed that the free surface is at a great distance, the oil altitude in the model may be hard to choose. Actually, an ideal solution like to Giger's solution was also given by Efros[4] and Karcher[5]. The pressure transient behavior of horizontal wells with and without a gas cap or aquifer was investigated by Kuchuk et al[6]. They postulated that the gravity forces are neglected and the viscosity of fluid is constant. They consider the asymmetrical two-phase boundary as a constant pressure boundary. The existence of the gas or water crest does not affect the pressure response according to their solution. Ozkan and Raghavan[7] analyzed the performance of horizontal wells subject to bottom water drive. They postulated that the density difference between the oil and water to be negligible and the mobility of water in the flooded part of the oil zone is the same as the mobility of the oil. Joshi[8] increase well productivity with horizontal and inclined wells using Giger's theory. Joshi[9] also compared the outcomes given by the above theories and figure out that they are vary by a factor of up to 20 and inconsistent.

Papatzacos et al[10 ,11] postulated a gravity equilibrium in the water crest and used the moving boundary method to solve the water breakthrough time for horizontal wells. The fundamental hypothesis they presented concerning water and gas is that they are, at each time, in static balance. In

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other words they take part in the interface boundaries motion by extending when pressure drops, but their flow is ignored. Using regression analysis Yang and Wattenbarger[12], presented correlations to predict the critical rate, breakthrough time and WOR after breakthrough for water coning in vertical and horizontal wells. Guo and Lee[13,14] introduced correlation for determining the critical rate. Their outcomes of calculation using the correlation corresponded the outcomes given by a numerical simulator. Nevertheless, the critical cone height has to be evaluated first based on a model developed from numerical simulation model. Safin et al[15] investigated the water coning in heterogeneous formations with vertical flow barriers and presented water cut to recovery factor function of field block with horizontal well. Their function considers flow barrier distribution through variogram stochastic distribution method, oil column thickness, reservoir dip angle, well construction and offset.

The objective of this work is to present water-coning correlations for predicting critical rate, water breakthrough time and WOR after breakthrough for horizontal wells.

METHOD

Yang and Wattenbarger[12] observed that the relationship between the WOR plus a constant (c) and the average oil column height below perforations after water breakthrough (h_{bp}) on a semi-log scale is a straight line as shown in Fig.1. They described this diagram mathematically as follows:

$$\text{WOR} = 0 \qquad h_{bp} > h_{wb}$$

$$\text{Log}\,(\text{WOR} + C) = S\,(h_{bp} - h_{wb}) + \text{Log}(C) \qquad h_{bp} <= h_{wb} \qquad (1)$$

Where, h_{wb} is the average oil column height below perforation at breakthrough, S is the slope of the straight line and C is a constant.

In the presented work, a method for determining h_{wb}, S and C was developed from a stepwise procedure. First, a number of simulation runs was made to analyze the performance of coning at different reservoir and fluid properties. Then, for each run, (WOR + C) was graphed against h_{bp} on a semi-log scale, from which S and h_{wb} were determined using regression analysis. Once the h_{wb} and S data was obtained for all the simulation runs, regression analysis was then used to define the relationship between S, h_{Wb} and different reservoir and fluid properties, respectively.

CORRELATIONS DEVELOPMENT

In this work Eclipse, a black-oil, three-dimensional, commercial simulator was used to simulate the water coning in a horizontal well. The formation is considered to be homogeneous and anisotropic with taking into consideration the effect of capillary forces. The horizontal well is modeled with a 3-D, Cartesian (x-y-z) model as shown in Fig.2. To develop correlations to calculate the water breakthrough height and slope of the straight line after breakthrough, the parameters sensitivity analysis was made to supply the required data. The relative permeability data is illustrated in Table 1. A base case was installed to start the parameters sensitivity analysis. Afterwards each parameter was varied from the lower value to the upper value of its range in each simulation run. The parameters used in the sensitivity analysis are oil flow rate, porosity, horizontal and vertical permeabilities, thickness above perforation, oil and water viscosities, water-oil gravity difference, pay zone thickness, drainage width.

In Table 2 the simulation data and outcomes are illustrated. The base case variables values are shown in the top line. For the rest of the cases reported, the reservoir variables are varied independently over the range presented in the table while preserving the values of the remainder of the variables in the base case. A blank space in displays that the base case value is carried forward. The average oil column height below perforation at breakthrough h_{wb} and slope of the straight line S are recorded in the last two column. For a particular variable under investigation, a semi-log plot of (WOR+C) vs. h_{bp} was made. From the plot, h_{wb}, S and C are obtained. And it was found that the constant, C, is 8. Then, the WOR changes can be described by the following equation.

$$\text{WOR} = 0 \qquad h_{bp} > h_{wb}$$

$$\text{Log}\,(\text{WOR} + 8) = S\,(h_{bp} - h_{wb}) + \text{Log}\,(8) \qquad h_{bp} <= h_{wb} \qquad (2)$$

After investigation the effect of the different reservoir and fluid properties on h_{wp} and S, the following equations were defined using regression analysis.

$$hwp = a_0 \frac{qo^{a1}\, kh^{a2}\, kv^{a3} h^{a4}\, \mu o^{a7}}{hap^{a5}\, L^{a6}\, \mu w^{a8}\, \Delta\Upsilon^{a9} Xa^{a10}} \qquad (3)$$

Where

a0 = 8.4937
a1 0.0172
a2 0.0005
a3 0.0074

a4 = 0.8668
a5 = -0.134
a6 = -0.107
a7 = 0.0382

a8 = -0.022
a9 = -0.004
a10 = -0.09

$$S = b_0 \frac{qo^{b1} kh^{b2}\, h^{b4}\, hap^{b5}\; L^{b6}\, \mu w^{b8}\, \Delta\Upsilon^{b9}}{kv^{b3}\, \mu o^{b7}\, Xa^{b10}} - 1 \tag{4}$$

Where

b0	=	0.0748	b4	=	0.0882	b8	=	0.0185
b1	=	0.1315	b5	=	0.0084	b9	=	0.0166
b2	=	0.0867	b6	=	0.1599	b10	=	0.0705
b3	=	0.0573	b7	=	0.0197			

Correlations Validation

In order to validate the accuracy of the derived correlations, statistical analysis has been used to evaluate their performance. The statistical indicators are presented in the appendix.

The obtained outcomes include an average relative error (ARE) of 0.063, 0.041 an average absolute error (AARE) of 1.39, 1.28 and coefficient of regression (R^2) of 0.96, 0.81 for h_{wp} and S correlations respectively.

Calculation example

An oil well with the following data, calculate the critical rate, time at breakthrough and WOR performance after breakthrough.

h_{wp}, ft	=	183.5	μ_o, cp	=	1.11
L, ft	=	1100	μ_w, cp	=	0.3
kh, md	=	200	ρ_o, lb/ft^3	=	50
kv, md	=	20	ρ_w, lb/ft^3	=	62.4
h, ft	=	200	Φ	=	0.2
h_{ap}, ft	=	5	β_o, bbl/STB	=	1.23
Xa, ft	=	4500	r_w, ft	=	0.5
Ye, ft	=	550	Dp, ft	=	195

Obtained results

Equation 3 for h_{wb} can be used as a critical rate correlation. At the height h_{wb} water breaks into the well. Then the oil flow rate in this correlation is the critical coning rate. The following equation is used to calculate the breakthrough time.

$$t_{bt} = \frac{(N_p)_{bt}}{q_o} \tag{5}$$

Where $(N_p)_{bt}$ is cumulative oil production at breakthrough. From Fig. 3, the average oil column height below perforation h_{bp} is linearly related to the cumulative oil production Np. Then, the cumulative oil production at breakthrough can be calculated from the breakthrough height h_{wb}:

$$(N_p)_{bt} = A\phi(1 - S_{wc} - S_{or} - S_{gc})(h - h_{wp} - h_{ap}) \tag{6}$$

Table 3 illustrates the results obtained from the present research with those obtained from some other correlations and simulation. The present correlations show a good match of the critical rate and breakthrough time with the simulation results.

After calculation of S from Eq. 4, use Eq. 2 to calculate WOR for a horizontal well. The results were compared with the simulation results. The comparison is shown in Fig. 4. The figure shows that, the present correlation gives a good match with the simulation results.

CONCLUSIONS

As presented this study, the following items was achieved.

- Numerical method was used to study the water coning phenomenon in horizontal well.
- A sensitivity analysis was conducted to estimate the effects of the different reservoir rock and fluid properties on the average oil column height below perforations and slope.
- The developed empirical water coning correlations were derived based on three- dimensional simulation results to predict critical rate, breakthrough time and WOR after breakthrough for horizontal wells.
- The correlations were developed based on regression analysis using the data from numerical simulations.
- The developed correlations show a good match of the critical rate, breakthrough time and WOR after breakthrough with the simulation results.

NOMENCLATURE

A	cross sectional area, ft^2
a_0- a_{10}	correlation coefficients
b_0- b_{10}	correlation coefficients
B_o	oil formation volume factor, bbl/STB
C	constant
Dp	distance between the WOC and the horizontal well, ft
h	initial oil formation thickness, ft
h_{ap}	oil column height above perforations, ft
h_{bp}	average oil column height below perforation, ft
h_{wb}	average oil column height below perforations

	at breakthrough, ft
L	Horizontal well length, ft
k_h	horizontal permeability, md
K_v	vertical permeability, md
k_{rg}	gas relative permeability
k_{rw}	water relative permeability
k_{row}	oil relative permeability in oil-water system
k_{rog}	oil relative permeability in gas-oil-irreducible water system
N_p	cumulative oil production, STB
q_o	oil production rate, STB/d
P_{cog}	capillary pressure of gas-oil system, psi
P_{cow}	capillary pressure of water-oil system, psi
r_w	wellbore radius, ft
S	slope of the after breakthrough straight line
S_o	oil saturation, fraction
S_g	gas saturation, fraction
S_w	water saturation, fraction
S_{wc}	connate water saturation, fraction
S_{or}	residual oil saturation, fraction
S_{gc}	Critical gas saturation, fraction
t_{bt}	breakthrough time, days
WOR	water-oil ratio
Xa	drainage radius, ft
Ye	half distance between two lines of horizontal wells, ft
μ_o	oil viscosity, cp
μ_w	water viscosity, cp
ρ_o	oil density, lb/ft^3
ρ_w	water density, lb/ft^3
ϕ	porosity, fraction
$\Delta\Upsilon$	water-oil gravity difference, psi/ft

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APPENDIX

Statistical Error Analysis

The following three statistical parameters were used in this study to evaluate the accuracy of the correlations.

1- Average percent relative error (ARE)

$$E_r = \frac{1}{n_d}\sum_{1}^{n_d} E_i$$

Where

$$E_i = \left(\frac{x_{measured} - x_{estimated}}{x_{measured}}\right)_i * 100(i = 1,2, \dots n_d)$$

2- Average absolute percent relative error (AARE)

$$E_a = \frac{1}{n_d}\sum_{1}^{n_d} E_i$$

3- Coefficient of correlation

$$r^2 = 1 - \sum_{1}^{n_d} (x_{\text{measured}} - x_{\text{estimated}})^2 / \sum_{1}^{n_d} (x_{\text{measured}} - x_{\text{avarage}})^2$$

The lower the value of E_r the more equally distributed are the errors between positive and negative values. The lower value of E_a the better the correlation.

The correlation coefficient describes the range of connection between two variables namely experimental and estimated values obtained from the correlation.

The value of r^2 varies from -1 to +1. As the value of correlation coefficient approaches +1, it means there is a strong positive relationship between these two variables.

Table 1. Relative permeability data

Sw	Krw	Pcow		Sg	Krg	Pcog		So	Krow	Krog
0.22	0	1		0	0	0		0	0	0
0.3	0.051	0.5		0.04	0	0		0.2	0	0
0.4	0.12	0.3		0.1	0.022	0		0.35	0	0.02
0.5	0.218	0.16		0.2	0.1	0		0.4	0.0048	0.038
0.6	0.352	0.1		0.3	0.195	0		0.45	0.029	0.058
0.7	0.5	0.05		0.4	0.289	0		0.5	0.0649	0.102
0.8	0.65	0.03		0.5	0.42	0		0.55	0.11298	0.163
0.9	0.83	0.01		0.6	0.58	0		0.6	0.197	0.234
1	1	0		0.7	0.8125	0		0.65	0.287	0.33
				0.78	1	0		0.7	0.4	0.454
								0.75	0.637	0.67
								0.78	1	1

Table 2. Simulation input data and results

Parameters	qo	φ	Kh	Kv	h	hap	L	μo	μw	ΔΥ	Xa		
Case Base	4000	0.2	200	20	200	5	2600	1.11	0.3	0.086	4500	S	hwp
1	2000											-0.1790	165.00
2	3000											-0.1610	165.50
3	4000											-0.1000	166.50
4	5000											-0.0830	167.00
5	6000											-0.064	167.5
6		0.15										-0.1000	166.50
7		0.2										-0.1000	166.50
8		0.25										-0.0950	166.50
9		0.35										-0.0930	166.70
10		0.4										-0.0950	166.40
11			100									-0.1660	167.70
12			200									-0.1000	166.50
13			300									-0.0950	166.30
14			400									-0.0500	167.50
15			500									-0.0280	168.50
16				5								-0.0340	165.00
17				15								-0.1040	166.00
18				20								-0.1000	166.50
19				35								-0.1360	167.00
20				45								-0.1530	167.50
21					100							-0.1130	97.00
22					200							-0.1000	166.50
23					250							-0.0430	211.00
24					300							-0.0114	264.00
25						5						-0.1000	166.50
26						15						-0.0960	156.40
27						25						-0.0940	146.50
28						40						-0.0900	131.00
29						60						-0.0850	110.00
30							1100					-0.2360	183.50
31							1450					-0.1700	179.00
32							2300					-0.1500	169.60
33							2600					-0.1000	166.50
34								1.11				-0.1000	166.50
35								1.61				-0.1030	169.80
36								2.11				-0.1250	171.00
37								3.11				-0.1300	174.00
38								4.11				-0.1200	177.00
39									0.2			-0.1230	167.00
40									0.3			-0.1180	166.50

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Table 2. Continued

41									0.4			-0.1000	166.00
42									0.5			-0.0990	165.00
43									0.7			-0.0950	164.00
44										0.017		-0.1130	167.50
45										0.052		-0.1780	166.40
46										0.086		-0.1000	166.50
47										0.121		-0.1140	165.00
48										0.156		-0.1100	164.50
49											1125	-0.0220	188.30
50											2250	-0.0420	181.43
51											3375	-0.0870	173.00
52											4500	-0.1000	166.50

Table 3. Comparison with correlations

Correlation	qc, STB/D	Breakthrough time, day
Efros	535	
Karcher	538	
Joshi	719	
Ozkan and Raghavan		4980
Yang and Wattenbarger	2597	305
This Study	3648	217
Simulation	4000	198

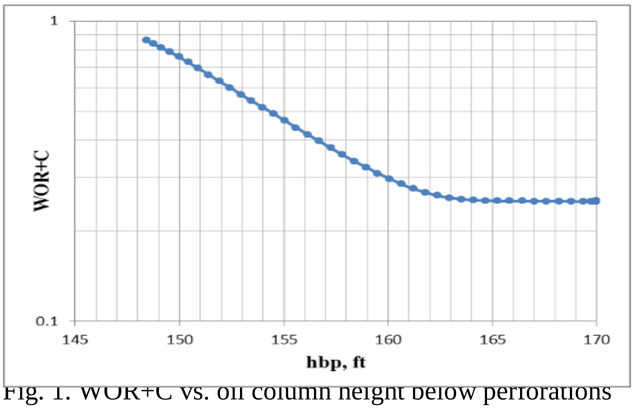

Fig. 1. WOR+C vs. oil column height below perforations from a simulation run

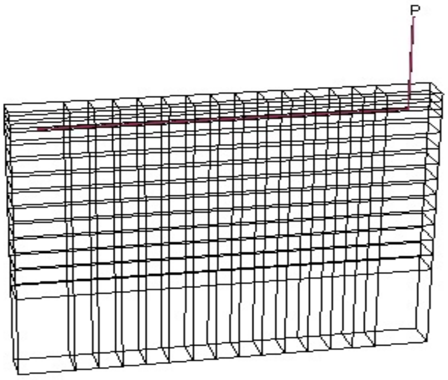

Fig. 2. Cross section of simulation grid for a horizontal well

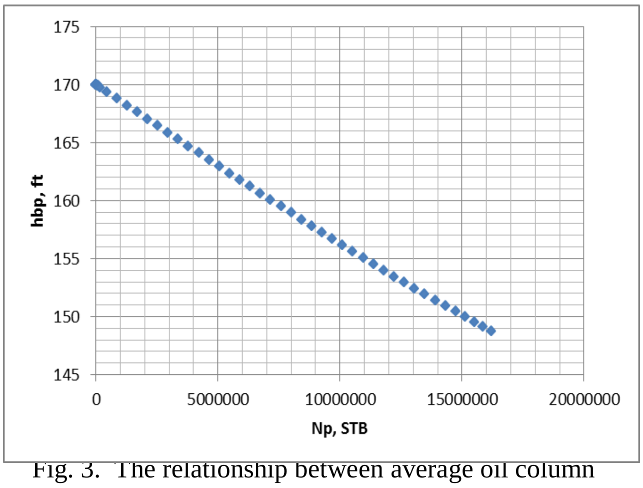

Fig. 3. The relationship between average oil column heights below perforations and the cumulative oil production

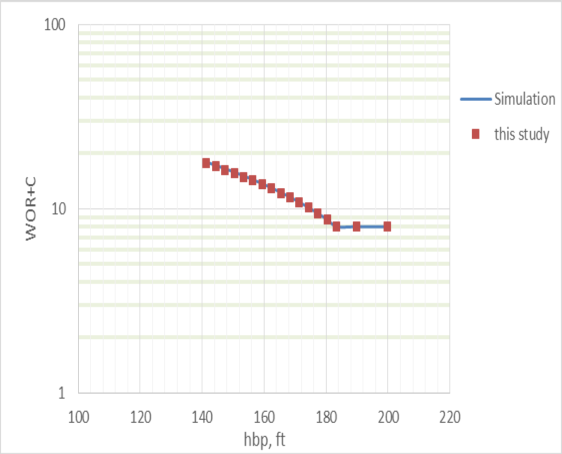

Fig. 4. WOR+C comparison between simulation and the present correlation