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A Generalized Correlation for Predicting Gas Breakthrough Time

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Abstract— Numerous methods have been presented to avoid gas breakthrough because of coning. These approaches include: keeping oil production rates beneath a certain value, forming a gas-blocking region nearby the well by inserting crosslinking gels or creating perforation as far from the original gas-oil contact (GOC) as possible. In some cases, it is uneconomical to retain oil production rate below the critical rate. Perforating far above the GOC decreases the perforation interval length, thus, rises pressure drawdown nearby the bore hole. The increased pressure drawdown may increase gas coning. Since the fifties, the coning has been investigated broadly, but it is still difficult to answer to the following questions, how to perforate a well coming undergo to the coning? And what is the optimum oil flow rate of the well?

In this research a numerical approach is utilized to investigate the gas coning using a 3-D radial model. In the first section, a sensitivity analysis was achieved to study the most related factors that affect the coning. In the second part of this study, regression analysis was accomplished to develop empirical gas coning correlation to predict gas breakthrough time for vertical wells.

Key words: gas coning, breakthrough time, oil production.

1 Introduction

Once oil is produced by primary mechanisms, production economics may be affected by managing the amount and position of wells and the production rate of each well. But, production rates are commonly constrained when encountering coning problems. Coning of gas or water is a common problem in oil reservoirs with gas cap or bottom water, or in gas reservoir with bottom water. It causes a serious trouble in several oil field implementations. It can minimize oil production remarkably. Consequently, it is significant to reduce or at any rate delay coning.

In oil reservoirs accompanied by a gas cap, vertical oil wells are usually penetrated as low as practical to decrease or slow down the gas coning. This supposes that there is no bottom water. In similar fashion, in an oil reservoir accompanied by bottom water, vertical oil wells are generally perforated in the highest part of the pay zone to keep down or delay water coning, if there is no gas cap. If an oil reservoir has both, bottom water as well as gas cap, then the vertical oil well is usually completed either close the middle of the oil zone or under the midpoint, in the direction of the water zone. This is owing to the fact that coning tendencies are inversely proportionate to the viscosity and the density difference of the oil, gas and water. The density distinction between oil and gas is usually greater than the density distinction between oil and water. As a consequence, gas has less tendency to cone than water. Nevertheless, gas viscosity is much lesser than the water viscosity, hence, for the identical pressure drawdown in a specified oil reservoir, the gas production rate will be higher than the water production rate. Therefore, viscosity and density variations between gas and water resort to stabilize each other. Consequently to keep down gas in addition to water coning, a chosen penetrated interval is at the midpoint of the oil pay zone. From the applied point of view, however, several oil wells are perforated nearer to water–oil contact than to the gas-oil contact.

2 Literature Review

Generally, the early study and engineering attempts in the area of coning were focused on its removal. Howard and Fast [1] (Amoco) presented the proposal of inserting a "pancake" of cement just further down the perforation interval to work as a barrier to the vertical motion of water. In the same field, various other methods were tried but with restricted achievement. Consequently, for the removal of coning, oil industry experts had to come back to the involvements of the stability equation (equilibrium between the gravity pressure difference and the pressure drawdown), i.e. decrease the pressure drawdown by minimizing oil production rate. The problem of gas-coning has been treated and connected further to the critical rate (the highest oil rate in the absence of producing gas). In reality, it has been addressed to discussion since 1935 with the occurrence of the original work by Muskat and Wyckoff [2]. Chaney et al. [3] followed the problem of coning critical rate in terms of experimentally and analytically, the experiment work was accomplished with an electric-resistance-capacity-network simulator. In the same direction, Chierici et al.[4] defined the highest allowable oil flow rates unaccompanied by gas and/or water flow rate for a homogeneous reservoir by means of a potentiometric prototype (electrical analog approach). Chaperon [5] contrasted the critical rates in horizontal and vertical oil wells and uncomplicated equations are supplied to assess what improvement in critical rate possibly gained from a horizontal oil well. Addington [6] presented the first applied technique for determining a GOR for oil wells operate above the critical rate. He introduced a group of gas-coning equations for 3-D coarse grid simulation. The initial coning paper did not take into consideration the time for gas breakthrough. Confronted with the expectation of zero profit, several operators would rather to produce their oils at higher production rates and resolve water or/and gas problems later. Cornelius and Sobocinski [7] investigated the water-coning problem to estimate the breakthrough time when producing an oil well at a flow rate larger than the critical value. Bournazel and Jeanson [8] critically assessed the equation of Cornelius and Sobocinski, they discovered that the real breakthrough time gauged in their field experiments and research laboratory was less than the breakthrough time forecasted by Cornelius and Sobocinski equation. Papatzacos et al. [9] researched the time to breakthrough for coning in horizontal oil wells utilizing moving boundary approach with gravity equilibrium supposed in the gas or water cones. The outcomes in their work are founded on semi-analytical solutions for gas or water cone time, and concurrent gas and water cones with a horizontal well in an anisotropic infinite reservoir. The key presumption they presented concerning gas and water is that they are, at every time, in static equilibrium. Their method is adequate only at low flow rates in the infinite acting period. Joshi [10] made an increase of oil productivity with horizontal and incline oil wells utilizing Giger's theory [11]. Guo and Lee [12] introduced a graphical solution of the physical procedure of gas-oil border dipping and a simple analytic correlation is supplied to approximate the critical oil flow rate of a horizontal oil well in an anisotropic reservoir.

Benamara and Tiab [13] used a numerical approach to study the gas coning using a 3-D radial model, and gas dipping using a 3-D irregular cartesian model, where well A, from Hassi-R'mel field in Algeria, was chosen for a case study.

They performed a regression analysis to develop empirical gas coning correlations to predict critical oil rate, gas breakthrough time and gas oil ratio (GOR) after breakthrough for both vertical and horizontal wells. Ike and Debasmita [14] derived breakthrough time expressions for vertical and horizontal wells, a technique have been developed to semi-analytically predict the rate of oil and water production after cone breakthrough in vertical and horizontal wells. Adewole [15] investigated breakthrough times theoretically for a vertically-stacked two layered reservoir with letter 'H' architecture and completed with vertical and horizontal well at the top and bottom layer, respectively. He considered both crossflow and no-crossflow interface cases. Siddiqui et al [16] presented an analytical approach that predicts water breakthrough timing of producing wells in the absence of surveillance (sparse Production Logging Tool, reservoir pressure and Rate Transient Analysis) and seismic data.The objective of this work is to study the most relevant parameters that affect the gas coning and using regression analysis to develop empirical correlation to predict, gas breakthrough time for vertical wells.

3 Methodology

In this study, it has been observed that a straight line results when gas oil ratio is plotted against average oil saturation before and after gas breakthrough on a semi log scale as shown in figure 1. From this observation one can determine the gas breakthrough time precisely.

To investigate the effect of reservoir and fluid properties and production constraints on gas coning, numerical reservoir model should be built. A single well 3D radial reservoir model using Eclipse100 (Schlumberger computer tool) reservoir simulator was built. The model was for a vertical well in a cylindrical geometry (r, θ, z). The numbers of layers in the reservoir are: twenty four (24) layers in radial direction (r), one (1) layer in the angular direction (θ), and twenty four (24) layer in the vertical direction (z). The single producing vertical well was completed in the center of these layers. The values of geometric reservoir properties were representative of unconsolidated sands. The exponential function was used to distribute the grids in the radial direction to consider the pressure and saturation changes expected to happen on the cells closer to the well-bore than to the external radial layers. Fluid properties are pressure dependent properties and variation of these properties with pressure must be known. The best way to obtain the pressure and fluid properties relationship is to use pressure-volume-temperature (PVT) tests data. The absence of these data lead the researcher to use empirical correlations that predict this relationship. PVTi (Schlumberger computer tool) program was used to generate the fluid properties data and PETREL program (Schlumberger computer tool) was used to generate the relative permeability curves using Corey correlation. Table 1 illustrates the relative data.

Table 2 illustrates the ranges of reservoir and fluid properties and production constraints data utilized in the development of the proposed breakthrough time model. As shown from this Table, Parameter properties varies as follows: oil production rate of 600 to 2000 m^3/d; horizontal permeability of 100 to 2000 md; vertical permeability of 20 to 200 md; oil density of 500 to 950 kg/m^3; gas density of 0.3 to 3 kg/m^3; oil viscosity of 0.0114 to 0.569 cp; gas viscosity of 0.00276 to 0.276 cp; oil thickness of 100 to 200 m; thickness below perforation of 8.33 to 41.65 m; perforation thickness of 8.33 to 41.65 m; porosity of 10% to 30%.

4 Sensitivity analysis

The parameter sensitivity analysis was accomplished to supply data for developing predictive correlation of calculating time to breakthrough. To initiate the variable sensitivity analysis, a base case was setup primary and all the simulation cases were run by varying base case information. Eleven parameters were changed to found the 45 simulation cases for vertical oil wells. In the parametric study the principle variables considered are: oil flow rate, horizontal and vertical permeabilities, porosity, oil and gas densities, oil and gas viscosities, perforated thickness, height below perforations and oil reservoir thickness.

4.1 Effect of oil production rate

Five simulation cases were run for vertical wells, with different oil production rates. Table 2 illustrates that the decrease in oil production rate decreases the time to breakthrough and consequently delays the gas coning, however, raise in the oil production rate speed up the recovery.

4.2 Effect of horizontal permeability

Five simulation cases were carried out for vertical wells, with different permeabilities in the horizontal direction. Table 2 illustrates that the increase in horizontal permeability delays the time to breakthrough, and consequently increase the ultimate recovery.

4.3 Effect of vertical permeability

Five simulation cases were accomplished for vertical wells, with different vertical permeabilities. Table 2 illustrates that the decrease in vertical permeability delays coning.

4.4 Effect of porosity
Five simulation cases were achieved for vertical wells, with different porosity values, Table 2 illustrates that the increase in the values of porosity decreases the time to breakthrough.

4.5 Effect of oil reservoir thickness
Five simulation cases were run for vertical wells, with different oil reservoir thicknesses. Table 2 illustrates that the increase in the oil reservoir thickness delays the coning.

4.6 Effect of perforated interval thickness
Five simulation cases were carried out for vertical wells, with different perforated interval thicknesses, Table 2 illustrates that the decrease in the perforated interval thickness delays the coning. However an increase in the perforated interval thickness increases the ultimate recovery.

4.7 Effect of below perforation height
Five simulation cases were accomplished for a vertical well, with different below perforations heights. Table 2 illustrates that the decrease in the below-perforation height delays the time to breakthrough. However a minimum below-perforation height is required to avoid the water coning.

4.8 Effect of oil density
Five simulation cases were achieved for vertical wells, with different oil densities. Table 2 illustrates that the increase in the oil density delays the coning, and increases the ultimate the recovery.

4.9 Effect of gas density
Five simulation cases were run for vertical wells, with different gas densities. Table 2 illustrates that the decrease in the gas density delays the breakthrough time, and increases the ultimate the recovery.

4.10 Effect of oil viscosity
Five simulation cases were carried out for vertical wells, with different oil viscosities. Table 2 illustrates that the decrease in the oil viscosity delays the breakthrough time.

4.11 Effect of gas viscosity
Five simulation cases were accomplished for vertical wells, with different gas viscosities. Table 2 illustrates that the increase in the oil viscosity delays the coning.

5. Breakthrough time generalized correlation
Based on parameter sensitivity analysis and regression analysis, following correlation was developed:

$$t_{Bt} = a_0 \frac{kh^{a_1}\ \rho o^{a_2}\ \mu g^{a_3}\ ho^{a_4}\ \phi^{a_5}}{qo^{a_6}\ kv^{a_7}\rho g^{a_8}\ \mu o^{a_9}\ hbp^{a_{10}}\ hp^{a_{11}}} \quad (1)$$

where

a0 = 7.774484647 a4 = 2.138965518 a8= 0.082245299
a1 =0.158708112 a5 =1.079170074 a9 = 0.302151351
a2 =0.730775328 a6 =1.430253756 a10 = 0.231993651
a3 =0.081768475 a7 =0.050519747 a11 = 0.128210059

4 Correlation validation
In order to validate the accuracy of the derived correlation, statistical analysis has been used to evaluate its performance. The statistical indicators are presented in the appendix.
The obtained outcomes include an average relative error (ARE) of -0.025, an average absolute error (AARE) of 0.14 and coefficient of regression (R^2) of 0.974 for t_{Bt} correlation.

5 Calculation example

Q_o, m^3/d	=	550	μ_o, cp	=	0.057
kh, md	=	200	μ_g, cp	=	0.028
kv, md	=	20	ρ_o, kg/m^3	=	795
h, m	=	200	ρ_g, kg/m^3	=	1.112
h_{bp}, m	=	8.33	Φ	=	0.2
h_p, m	=	33.33			

5.1 Obtained results
Equation 1 for t_{Bt} is used to calculate the breakthrough time. As illustrated from Table 3, the developed correlation for predicting the time to breakthrough in this study for vertical wells exhibited best result comparing to simulation result. Knowing that, the value of oil production rate that used for comparison is outside the correlation parameter range.

6. Conclusions
1. A gas coning numerical approach is achieved to investigate the effect of the different parameters on the breakthrough time.
2. Simple correlation is obtained to predict the breakthrough time for vertical wells.
3. The decrease in the oil flow rate, vertical permeability, perforated thickness, below perforation height, gas density and oil viscosity delays the breakthrough time.
4. The increase in the horizontal permeability, porosity, oil thickness, oil density and gas viscosity delays the breakthrough time.

Nomenclature

a0-a11	regression coefficients
ho	oil formation thickness, m
hbp	oil column height below perforation, m
hp	Perforated interval thickness, m
Kh	vertical permeability, md
Kv	vertical permeability, md
qo	Oil production rate, STm^3/d
t_{Bt}	breakthrough time, days
μo	oil viscosity, cp
μg	gas viscosity, cp
ρo	oil density, kg/m^3
ρg	gas density, kg/m^3
ϕ	porosity, fraction

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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

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

Where

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

2- Average absolute percent relative error

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

3- Coefficient of correlation

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

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 coefficient of correlation approaches +1, it means there is a strong positive relationship between these two variables.

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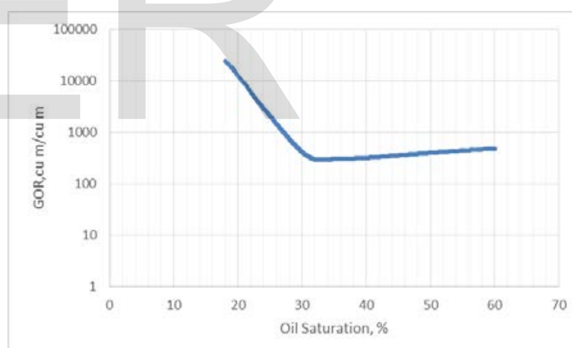

Fig.1 Gas oil ratio versus average oil saturation

Table 1. Relative permeability data

Sg	Krg	Kro		Sw	Krw	Kro
0	0	0.9		0.2	0	0.9
0.05	0	0.6932		0.22	0	0.813
0.1188	0	0.4644		0.2925	0.0002	0.5446
0.1875	0.0002	0.2925		0.365	0.0031	0.343
0.2563	0.0022	0.1692		0.4375	0.0158	0.1985
0.325	0.0125	0.0867		0.51	0.05	0.1016
0.3937	0.0477	0.0366		0.5825	0.1221	0.0429
0.4625	0.1424	0.0108		0.655	0.2531	0.0127
0.5312	0.359	0.0014		0.7275	0.4689	0.0016
0.6	0.8	0		0.8	0.8	0
0.8	0.9	0		1	1	0

Table 2. Simulation input data and its results

Case	q	kh	kv	do	dg	uo	ug	hbp	hp	ho	phi	tBt
	m3/d	md	md	kg/m3	kg/m3	cp	cp	m	m	m	fraction	day
base	750	200	20	795	1.112	0.057	0.028	8.33	33.33	200	0.2	1681
2	600											2181
3	1000											931
4	1500											611
5	2000											451
6		100										1271
7		500										1961
8		1000										2101
9		2000										2191
10			50									1551
11			70									1511
12			100									1461
13			200									1391
14				500								1181
15				650								1231
16				850								1701
17				950								1741
18					0.3							1701
19					0.5							1691
20					1.5							1661
21					3							1311
22						0.011						2451
23						0.022						2131
24						0.142						1081
25						0.569						591
26							0.003					1371
27							0.006					1451
28							0.138					1821
29							0.276					1981
30								16.66				1241
31								24.99				1211
32								33.32				1171
33								41.65				1151
34									41.65			1601
35									25			1740
36									16.66			1801
37									8.33			1861
38										100		261
39										125		591
40										150		891
41										175		1291
42											0.1	841
43											0.15	1261
44											0.25	2091
45											0.3	2511

Note: a blank entry in the table indicates that the variable has the same value as base case.

Table 3. Simulation and correlations results

Method	Time to braekthrough,day	Error %
Simulation	2411	0
Benamara and Tiab	6063	-151
This study	2476	-2.6