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Water Coning in Horizontal Wells: Prediction of Post-Breakthrough Performance

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ABSTRACT

This study attempts to predict post-breakthrough performance in horizontal wells as a result of water coning. The post breakthrough performance is measured in terms of the Water Oil Ratio (WOR). Correlations were developed to predict the WOR, time to breakthrough and the critical oil production rate in horizontal wells.

The reservoir studied was modelled using a 3D simulator (ECLIPSE100). PVT and Relative permeability data from literatures were used in modelling the reservoir. A one well model was simulated by setting up a 'base case' scenario of reservoir parameters, the WOR from this base case was observed. Sensitivity analysis was then carried out by varying each of the reservoir parameters and production rate independently. Regression analysis was done to develop correlation between the height above/below the perforations and the WOR. The developed correlations compared favourably well with the existing ones.

Keywords: Coning, Production rate, Horizontal permeability, Perforation thickness, Breakthrough time.

1.0. INTRODUCTION

Coning is a term used to describe the mechanism underlying the upward movement of water and/or the downward movement of gas into the perforations of a producing well. Petroleum reservoirs often have a gas cap and/or an aquifer. In these situations they are subjected to rapid gas or water movement towards the well as a result of a sharp pressure drop in the direction of the well. Prior to production, these reservoirs have defined fluid contacts: Water-Oil Contacts (WOC) and Gas-Oil Contacts (GOC). Once production commences, the previously defined contacts (WOC or GOC) now become deformed from its

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plane shape to form a cone or a crest. If a field is developed by vertical wells, the deformation is referred to as a cone. For horizontal wells, it is known as a crest. For the purpose of quantitative discussion, either the term "cresting" or "coning" may be used. Even in horizontal well cases, most engineers adapt the term "coning" to describe the simultaneous production of gas/water (Fig.1.1).

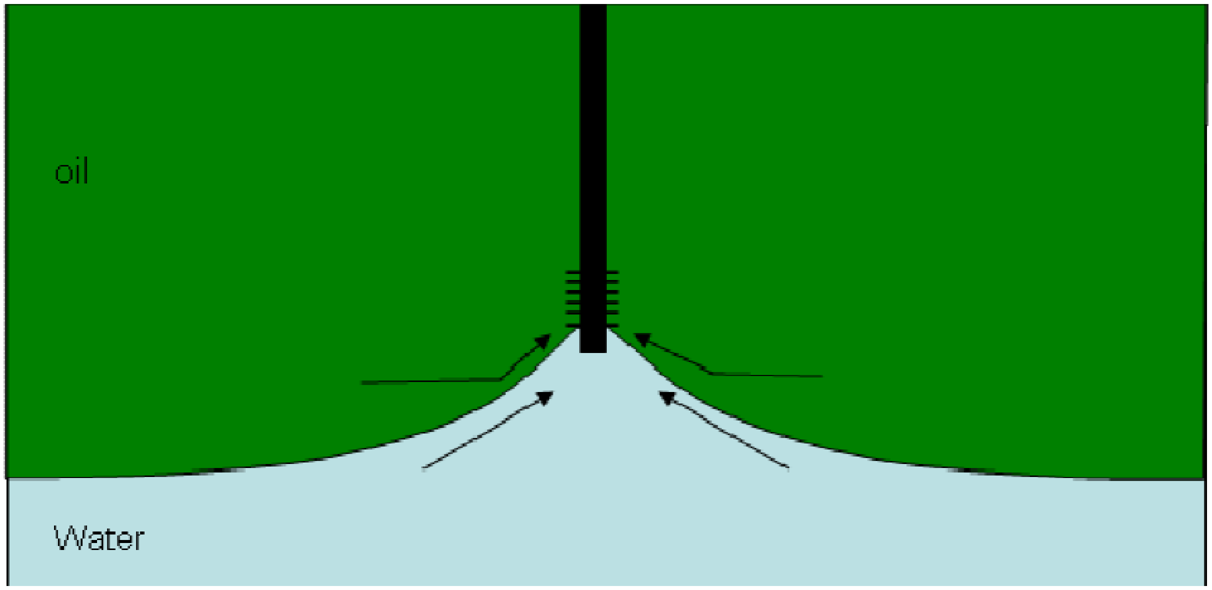


Figure 1.1: Water Coning

1.1. Horizontal Well Technology

One of the major causes of coning is pressure drawdown. A vertical well exhibits a large pressure drawdown near the wellbore. This large pressure drawdown causes coning. Therefore, coning can be eliminated or minimized by minimizing the pressure drawdown around the vicinity of the wellbore. However, the reduction of the pressure drawdown is impossible without an attendant reduction in the oil production rate, which in many cases is not economically viable. Horizontal wells provide a means of minimizing the pressure drawdown (reducing coning) while maintaining the oil production rates.

In general, a horizontal well is one that is drilled parallel to a bedding plane, as opposed to a vertical well which intersects the reservoir bedding plane at 90 degrees. In this paper, a horizontal well refers to any kind of well that has deviated from the vertical, extending substantially far into the reservoir. Horizontal wells are drilled to exploit the many distinct advantages they have over conventional vertical wells. One of such advantages, as mentioned earlier, is the reduced coning tendencies of horizontal wells. Horizontal wells have been successfully applied in reducing problems associated with water/gas coning. The application of horizontal well technology has been widely used in many countries to improve oil recovery from water drive reservoirs. At a low drawdown, a horizontal well can have larger capacity to produce oil as compared to a vertical well, other things being equal. Thus the critical rate may be higher in horizontal wells than in vertical wells. Horizontal wells may also be applied to reduce gas coning rate, in gas-cap driven wells.

1.2. Background to the Work

Although horizontal wells have been used to minimize coning, the use of horizontal wells cannot completely eliminate gas/water coning. Therefore, it is just as important as studying coning in horizontal wells. The production of a water or gas cone can greatly affect the productivity of a well and can affect the overall recovery efficiency of a reservoir. Therefore, it is important to minimize or at least delay water/gas coning. Thus, in the study of water/gas coning, 3 things should be determined. First, the maximum oil production rate (known as the critical rate) without simultaneous production of water or the gas cap. This is because the critical rate cannot be imposed upon a well due to economic reasons. Second, assuming a well is produced above its critical rate, a time will come when the cone will breakthrough. This time is called time to breakthrough. Lastly, it is important to be able to predict the performance of the well after breakthrough in terms of the gas cut or water cut (WOR).

2.0 REVIEW OF PREVIOUS WORKS

Historically, research into coning was initially concentrated on its elimination. [1] (Amoco) introduced the idea of injecting a “pancake” of cement just below the completion interval to prevent the vertical/upward flow of water into the wellbore. This and many other approaches to the elimination of coning were tested in field applications with limited success. Therefore, for the elimination of coning, analysts were forced to return to equations governed by the stability between the pressure drawdown and the gravity pressure differential.

2.1 Critical Rate Correlations

Many authors have addressed the problem associated with coning in terms of the critical rate, the time to breakthrough or breakthrough time and the performance after breakthrough in terms of WOR and Gas Oil Ratio, GOR. The critical rate is probably the topic which has been discussed the most. In fact the critical rate has been a major discussion point in addressing gas/water coning since the appearance of the first paper by [2]. Since this first paper, many correlations have been developed to determine the critical

rate. In general, these correlations can be divided into two categories: the first category determines critical rate **analytically** based on the equilibrium conditions of gravitational and viscous forces. The second category determines critical rate through **empirical correlations** from experiments/simulations.
The first of the analytical correlations was that developed by [2]. They solved a Laplace equation for single phase flow. [3] and [5] used potentiometric models to determine the critical rates in vertical wells. [3] pursued the coning critical rate problem both analytically and experimentally. The second category of critical rate correlations was developed from computer simulations and/or lab experiments. One of such correlation was presented by [4]. The equations are based on results obtained from a numerical simulator and from laboratory experiments. An empirical approach was also proposed by [8] to calculate critical rate for vertical wells. The correlation was obtained from regression analysis carried out on data obtained from more than 50 critical rate values. [9] also discussed critical rate solutions. However, his concept of critical rate was different from the others. [9] solved a closed outer boundary problem that never reaches steady state conditions while the others assumed open outer boundary problems at steady state conditions. In addition to this, [9]'s critical rate is decreasing with time or cumulative oil production, while others had a constant critical rate.

[6], [12] and [13] provide a detailed study of coning in horizontal wells using different approaches.

2.2. Time to Breakthrough

Several methods are also available for predicting the time to breakthrough. [14], based on experimental and computer simulation results, developed a dimensionless plot which traces the rise of cone apex from its build up to breakthrough. The plot allows us to predict breakthrough time as well as the critical rate.

Table 2.1: Sample Critical Rate Solutions for Horizontal wells

Efros (1963) [10]	$q_c = \dfrac{4.888 \times 10^{-4} k_h \Delta\rho h^2 L}{\mu_o B_o [2y_e +]\sqrt{2y_e + (h^2/3)}}$
Kracher (1986) [11]	$q_c = 4.888 \times 10^{-4} \left[\frac{k_h}{\mu_o B_o}\right]\left[\frac{\Delta\rho h^2}{2y_e}\right]\left[1-(1/6)\left(\frac{h}{2y_e}\right)^2\right]$L
Joshi (1991) [12]	$q_{cw} = \dfrac{1.535 \times 10^{-1}(\rho_o - \rho_g) k_h [h^2 - (h - l_v)^2]}{B_o \ln r_e/r_w}$ $\frac{q_{ch}}{q_{cv}} = \frac{[h^2-(h-l_h)^2]\ln(r_e/r_w)}{[h^2-(h-l_h)^2]\ln(r_e/r_w')}$Where $q_{c,v}$ is the critical rate for vertical wells & $q_{c,h}$ is the critical rate for horizontal wells.

The authors correlated the breakthrough time with two dimensionless functions of the reservoir and fluid properties, the dimensionless cone height and dimensionless breakthrough time.

Based on the same experimental data as [14], [15] in 1971 developed a similar method that uses the same dimensionless variables in the [14]. The model assumed a homogenous reservoir and radial flow of water and oil at the outer limit.

Several authors like [16], have proposed mathematical expressions for determining time to breakthrough in horizontal wells.

[17] developed correlations for breakthrough time for horizontal wells for both single-cone and two-cone cases in an infinite acting reservoir based on semi-analytical solutions for time development. Their solution only applies for infinite acting reservoirs. The validity of the solution has been tested by extensive numerical simulation. They correlated the time to breakthrough with a dimensionless oil rate (q_D).

[18] in 1991 derived numerical correlations for both vertical and horizontal wells. They used the same definitions as [9] and found correlations for breakthrough time, WOR and critical rate for a particular time. In developing a correlation for time to breakthrough, they assumed a tank reservoir. Thus, the average oil column height below perforation h_{bp} is linearly related to the cumulative oil production N_p. Then, the cumulative oil production at breakthrough can be calculated from the breakthrough height h_{wb}. This applies to both horizontal and vertical wells.

[28] in 2005 used a numerical simulation model to study the behaviour of water production as a function of reservoir parameters. The water cut versus time plot was the variable used for characterization. A database consisting of almost 20,000 cases was built. From analyzing the data, a formula for calculating break through time was proposed.

2.3. Post Breakthrough Performance

Due to economic reasons, wells are usually produced above the oil critical rate. Therefore, it is important to predict the production performance as a function of time. The production performance is evaluated based on the water cut and gas cut for a reservoir with bottom water drive and gas cap drive respectively.

The water-oil-ratio (WOR) after breakthrough in vertical wells has been addressed by some authors. [15] proposed a method assuming the water is separated from oil, the oil-water interface rises and stays at some point above the perforation interval. Thus, by calculating the length of the perforation interval in the water, WOR can be predicted.

[21] in 1983 applied the material balance equation to predict the rise in the oil-water contact in a homogenous reservoir. Using numerical simulation, the sensitivity of four reservoir parameters was investigated. They correlated their results with the several dimensionless parameters; dimensionless water cut, dimensionless breakthrough time, and dimensionless limiting water cut.

[22], [23], [24] investigated the effects of various reservoir and well parameters on WOR using numerical simulation. However, they did not come up with a general predictive method. [15] and [26] also developed different approaches for predicting WOR after water breakthrough in horizontal wells.

[9] developed a set of gas coning correlations for 3D coarse field using specific data in Purdoe Bay field. The correlation can be used to predict critical coning rate and gas-oil ratio (GOR) after coning has been achieved. He used a 2-D fully implicit radial simulator to model coning. The gas coning behaviour was correlated to the average oil column height above the perforated interval of the well. Three regions were modelled around the well – the gas cap, the gas invaded region and the oil column.

By writing an oil material balance around the 3 regions of the well, the average oil column height above the perforation was calculated. While studying gas coning in an oil well, [9] observed that a straight line results when GOR is plotted against the average oil column height above perforations after gas breakthrough on a semi-log scale.

[18] presented a water coning correlation to predict the critical rate, water breakthrough time and WOR after breakthrough for both vertical and horizontal wells. The correlation was developed following the same approach as [9]. [25] also used an approach similar to [9]. This model reveals that the plot is a straight line after breakthrough.

[27] investigated the influence of the forces of interaction on production performance of the horizontal well producing oil from a bottom water drive reservoir. The study was carried out by constructing a scaled model to simulate the production performance. The results showed a strong relationship between the interaction of the forces and well production, in which the production performance increases as the ratio of gravity to viscous forces increases for all cases examined.

[26] developed a mathematical model that can predict coning behaviour and the resulting rate dependent GOR. The mathematical model combines a dynamic model describing the essential reservoir behaviour and a highly simplified representation of the interaction between the well and the reservoir. The model has been tuned to oil wells on the Troll field with surprisingly good results. This model forms the basis of the GORM (Gas/Oil Ratio Model) computer program.

3.0 METHODOLOGY

As explained earlier, this study attempts to follow a similar approach to that used by the author in [9] in developing correlations capable of predicting post-breakthrough performance in vertical wells completed in a gas-cap driven reservoir. [18] also observed that this relationship with slight modification applies to water coning in vertical wells in reservoirs with strong aquifers.

In a similar manner, in this paper this approach was employed in investigating coning behaviour of horizontal wells in reservoirs supported by a strong aquifer. A single horizontal well was modelled on a 3D ECLIPSE black oil simulator. The water coning behaviour in the well was correlated to one critical parameter, the oil column height below the perforated interval of the well (h_{bp}) above the initial water oil contact. As production begins, since the reservoir is driven by the bottom water, water displaces oil from the region above the initial WOC. If we assume a piston like displacement, then an imaginary current WOC can be defined as shown in the figure. *The oil column height between the current WOC and the bottom of the well is the oil column height below perforation***.** It is important to note that this height does not exist and only serves analytical purposes since the current WOC cannot be defined by a straight line.

If we assume a tank reservoir, there is no flow across the outer boundary; as such the height of oil column below the perforation is uniquely related to the cumulative oil production [18].

This relationship can be derived by writing a material balance equation. Three regions must be depicted in the material balance equation; the aquifer, the water invaded region and the oil column between the top of the reservoir and the current oil contact. These are shown in the diagram below.

Several assumptions regarding the initial oil saturations in the different zones were made in order to simplify the material balance equation. The assumptions are:

- The initial oil saturation in the aquifer is zero i.e. the aquifer contains absolutely no oil.
- The region between the initial oil-water contact and the water contact (invaded zone) is assumed to be at residual oil saturation.
- In the region above the current oil-water contact (virgin zone), the oil saturation is assumed to still be at its initial level. ($1-S_{wc}$).

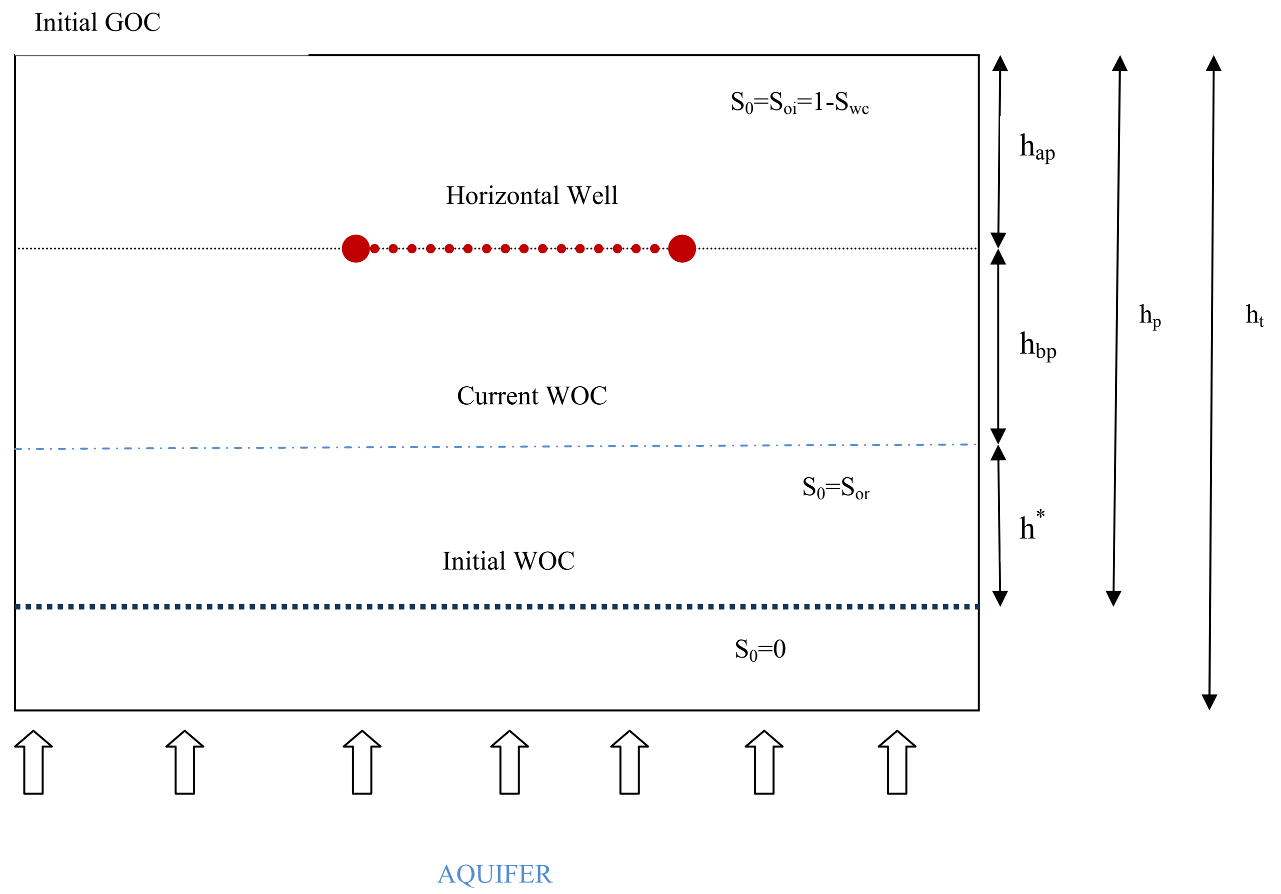


Figure 3.1: Schematic showing the 3 different zones simulated using ECLIPSE100 (2006)

The following equations are obtained from the previous assumptions:

$$h_t.S_{avg} = (h_t - h^*).(0) + (h - h^*).(1 - S_{wc}) + (h^*).(S_{or}) \ldots\ldots 3.1$$

$$h_t S_{avg} = (h - h^*).(1 - S_{wc}) + (h^*).(S_{or}) \ldots\ldots 3.2$$

Multiply both sides of equation 3.2 by cross-sectional area, A and the porosity to obtain the hydrocarbon pore volumes:

$$h_t A S_{avg}\Phi = (h - h^*).A\Phi.(1 - S_{wc}) + (h^*).(S_{or})A\Phi \ldots\ldots 3.3$$

The left hand side of the equation represents the oil left in the reservoir; therefore it should equal the original oil in place minus the oil produced:

$$h_t A S_{avg}\Phi = (N_t - N_p) \ldots\ldots 3.4$$

Substituting this equation into equation 3.3:

$$(N_t - N_p) = (h - h^*).A\Phi.(1 - S_{wc}) + (h^*).(S_{orw})A\Phi \; \ldots\ldots\ldots\ldots\ldots 3.5$$

$$(N_t - N_p) = hA\Phi.(1 - S_{wc}) - h^*A\Phi.(1 - S_{wc}) + (h^*).(S_{orw})A\Phi \; \ldots\ldots 3.6$$

But, the hydrocarbon volume of the initial oil in place is given as:

$$N_t = h.A\Phi.(1 - S_{wc}) \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

Therefore;

$$(N_t - N_p) = N_t - h^*A\Phi.(1 - S_{wc}) + (h^*).(S_{orw})A\Phi \; \ldots\ldots\ldots\ldots\ldots 3.8$$

$$-N_p = -h^*A\Phi.(1 - S_{wc}) + (h^*).(S_{orw})A\Phi \; \ldots\ldots\ldots\ldots\ldots 3.9$$

$$N_p = h^*A\Phi.(1 - S_{wc}) - (h^*).(S_{orw})A\Phi \; \ldots\ldots\ldots\ldots\ldots 3.10$$

$$h^*A\Phi(1 - S_{wc} - S_{orw}) - N_p \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Therefore, we have:

$$h^* = \frac{5.615N_p}{A\Phi(1 - S_{wc} - S_{orw})} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

Note that area in this equation is in ft^2.

Also from Figure 3.1, we can see that

$$h = h_{ap} + h_{bp} + h^* \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.13$$

Finally, the height of oil column below the perforation is given by the following equation:

$$h_{bp} = h - h_{ap} - h^* \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.14$$

Where h* is as defined by equation 3.12

3.1 Simulation with ECLIPSE100 (2006)

A base case scenario was simulated using a commercial black oil simulator. The ECLIPSE 2006 black oil simulator was used to carry out these simulations. Reservoir and fluid properties are detailed in the APPENDIX. The reservoir was completed with a horizontal well.

The WOR and the cumulative oil production (N_p) for the horizontal well were determined from the output from the simulator. The cumulative oil production (N_p) is then used to calculate the height of oil column below the perforation (h_{bp}) in accordance to equation 3.12 and equation 3.14.

3.2 Reservoir Model

A black oil reservoir was modelled using the data presented in the APPENDIX. The model mimics an oil reservoir, 4500' by 1250' by 169' thick. The reservoir fluid consists of live oil and gas, with an aquifer of uncertain value. The reservoir is subdivided into an 11 X 11 X 10 grid. Finer grid spacing were used in the vertical directions (1cell=16ft) to accurately simulate water coning into the horizontal well (see figure 3.4 and figure 3.5). The reservoir was completed with one horizontal well perforated at the centre of the reservoir. There are a total of 1210 cells in the model. Figure 3.2 and Figure 3.3 shows the initial conditions of the 3-D simulation model. The datum depth was 6384', pressure at datum depth taken as 2756 psi, WOC depth was 6535' while the GOC was at the 6384'. (No gas cap).

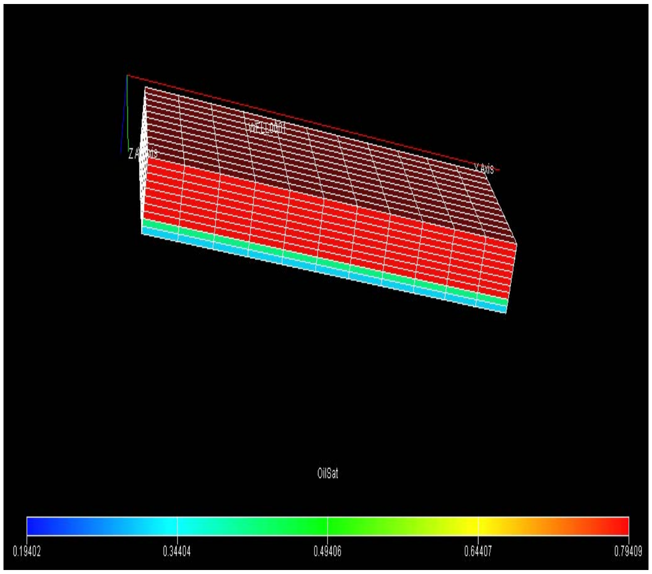


Figure 3.2: Initial conditions of 3-D Simulation Model (Initial Oil Saturations)

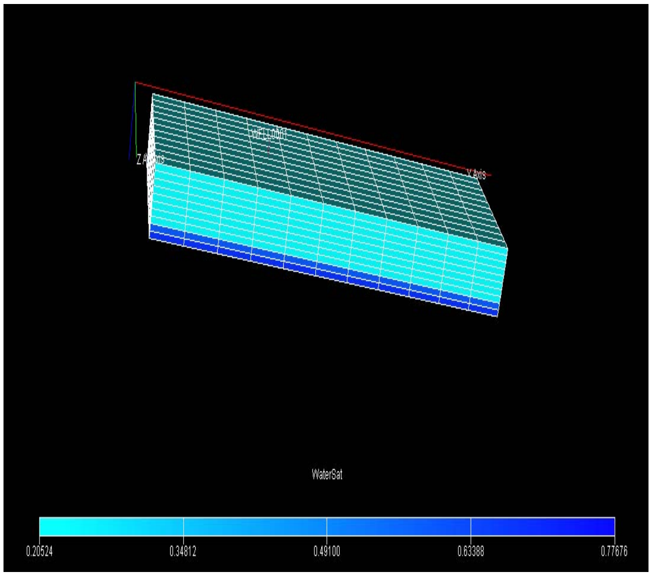
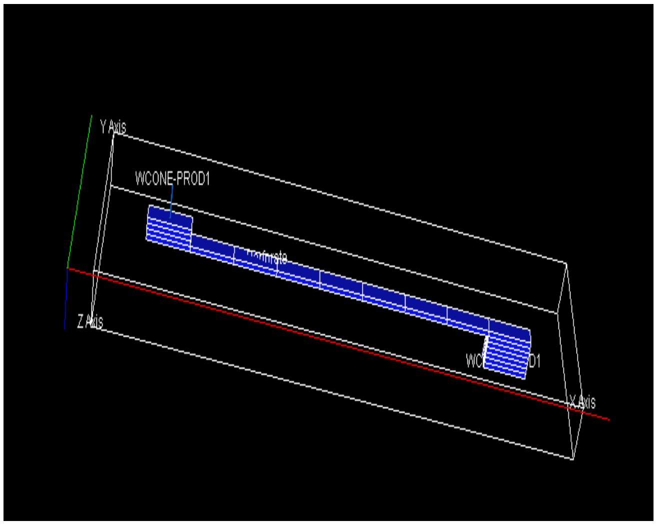


Figure 3.3: Initial conditions of 3-D Simulation Model (Initial water saturation)



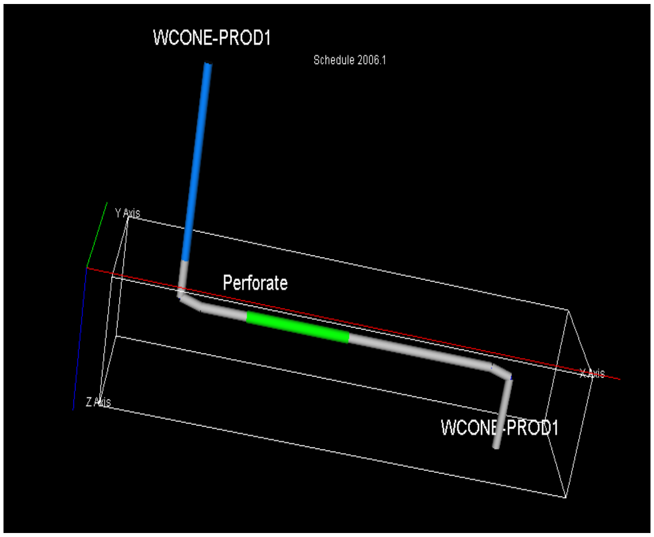
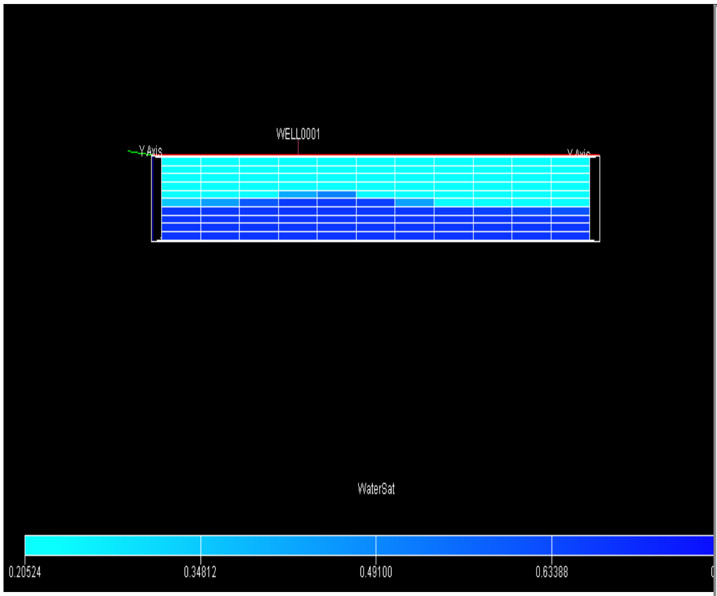


Figure 3.4: Horizontal well completion of the 3-D simulation model (a)

Figure 3.5: Horizontal well completion for the 3-D simulationn model (b)



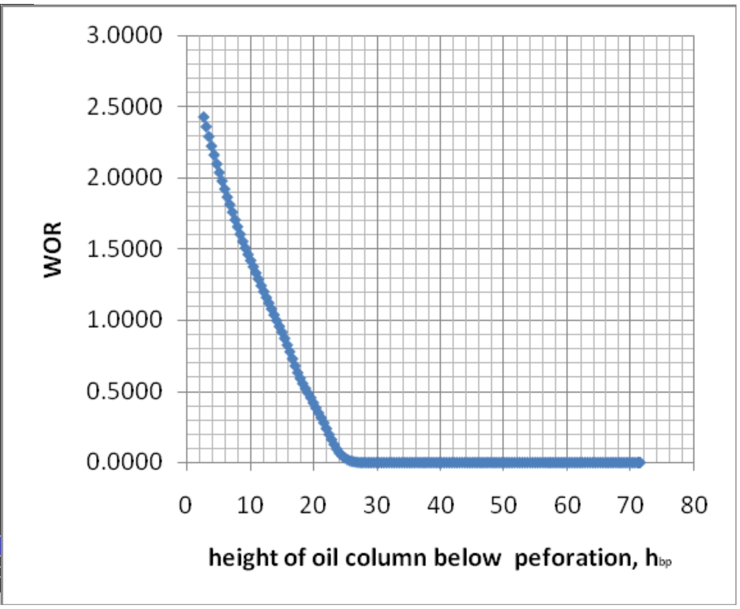


Figure 3.6: Figure showing the movement of water as a result of coning

Figure 3.7: WOR vs H_{bp} for the base case scenario

3.3 Plot of WOR against h_{bp}

Several observations were made from a plot of WOR against h_{bp} on a Cartesian graph. This is shown in figure 3.7 above. As oil production begins, the WOR is initially Zero. The height of oil column below the perforation (h_{bp}) decreases as production proceeds. At some point, water breaks into the wellbore (WOR $\neq 0$), the height of oil column below the perforation at this point is called the height of oil column below the perforation at breakthrough. This is denoted by h_{bg}. It was also observed that the post breakthrough performance of the well (in terms of WOR) varies linearly with the height of oil column below the perforation.

3.4 Parameter Sensitivity Analysis

An extensive parameter sensitivity analysis was carried out to determine the reservoir and fluid parameters that have the most influence on coning behaviour in horizontal wells. Of specific interest is how variations in the well parameters affect the oil column height below the perforations at breakthrough and the slope of the WOR curve after water breaks into the well. The breakthrough time of water into the well is also considered. The sensitivity of each parameter to the coning behaviour was investigated independently. (Only one of the well parameters was varied at a time). The simulations for the parameter sensitivity analysis were also carried out using the ECLIPSE black oil simulator. A total of 25 simulation runs were made during the parameter sensitivity analysis.

3.5 Model Development

In order to predict post breakthrough performance in horizontal wells, general correlations must be developed to determine the following;

- The oil column height below the perforation at breakthrough (h_{bg}). This is the point at which the WOR$\neq$0.
- The slope of WOR-h_{bp} line after breakthrough has occurred. The slope varies with each of the well parameters as corroborated by the parameter sensitivity analysis.

Once the slope, m and the oil column height below the perforation at breakthrough (h_{bg}) are determined, an equation for WOR after breakthrough can be derived using the general equation for a straight line.

The general equation for a straight line is given by;

$$m = \frac{y - y_1}{x - x_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.15$$

Where (x_1,y_1) is a point on the straight line.

In this case, (x_1, y_1) is the point at which breakthrough occurs. i.e. (0, h_{bg}). Therefore, the equation for the straight line written in terms of WOR and h_{bp} is given as;

$$WOR = -m(h_{bp} - h_{bg})\ for\ \ (h_{bp} < h_{bg}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.16$$

This equation applies only to post breakthrough performance of the well. In other words, prior to water breakthrough, the water oil ratio can be assumed to be zero. Before the breakthrough of water into the well, the WOR is given by the following;

$$WOR = 0\ for\ (h_{bp} > h_{bg}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.17$$

3.6 Generalized Correlations

Generalized correlations were developed for the slope, m and the oil column height below perforations at breakthrough (h_{bg}) by carrying out regression analysis on the results of the parameter sensitivity analysis.

3.7 NON-Linear Regression with SPSS 17.0

Non Linear Regression is a method of finding a non-linear model of the relationship between the dependent variable and a set of independent variables. Non linear regression can estimate models with arbitrary relationships between independent and dependent variables. This is achieved with the use of iterative estimation algorithms.

Generalized Correlation for Slope (m)

Non-linear regression analysis was used to determine the relationship between the slope of the WOR-h_{bp} curve after breakthrough and parameters that affect coning behaviour in horizontal wells.

In order to develop a reasonable model for the non-linear regression, the relationship between the Slope and each of the individual coning parameters was considered. From this relationship, the following assumptions were made;

1. $|m| \propto (1/q^{a})$
2. $|m| \propto {k_h}^{d}$
3. $|m| \propto (1/{k_v}^{c})$
4. $|m| \propto (1/\O^{e})$
5. $|m| \propto L^{b}$
6. $|m| \propto (1/{h_{ap}}^{f})$
7. $|m| = (1/A^{g})$

The constants a, b, c, d, e, f & g are regression parameters used to indicate the non-linear relationship between each of the coning parameters and the slope of the WOR-h$_{bp}$ curve. The constant X represents the constant of proportionality. From these assumptions, the following model equation was developed;

$$|m| = X\frac{k_h{}^{a}.L_p{}^{b}}{k_v{}^{c}.q^{d}.\emptyset^{e}.h_{ap}{}^{f}.A^{g}} \ldots\ldots\ldots\ldots\ldots\ldots 3.18$$

Non linear regression by SPSS 17.0 gave the following values for the unknown regression parameters;

$a = 0.374; b = 0.546; c = 0.001; d = 0.350; e = 0.392; f = 0.326; g = 0.050;$

$X = 0.004$

The **R-Squared value** for the non-linear regression analysis is **0.951**. Therefore, the slope of the WOR-h$_{bp}$ curve can be given by the following generalized correlation;

$$|m| = (0.004).\frac{k_h{}^{0.374}.L_p{}^{0.546}}{k_v{}^{0.001}.q^{0.350}.\emptyset^{0.392}.h_{ap}{}^{0.326}.A^{0.050}} \ldots\ldots\ldots\ldots\ldots 3.19$$

Generalized Correlation for Breakthrough Height (h$_{bg}$)

In a similar manner, the following assumptions were made from the observation of the relationship between the breakthrough heights and each of the coning parameters in order to develop a model equation to be used in non-linear regression analysis using SPSS 17.0. These assumptions are;

1. $h_{bg} \propto (q^{a})$
2. $h_{bg} \propto L_p{}^{b}$
3. $h_{bg} \propto (1/k_h{}^{c})$
4. $h_{bg} \propto (1/k_v{}^{d})$
5. $h_{bg} \propto (1/h_{ap}{}^{e})$
6. $h_{bg} \propto (1/\emptyset^{f})$
7. $h_{bg} \propto (1/A^{g})$

From these assumptions; the following model equation was developed as contained overleaf:

$$h_{bg} = X.\frac{q^{a}.L_p{}^{b}}{k_h{}^{c}.k_v{}^{d}.h_{ap}{}^{e}.\emptyset^{f}.A^{g}} \ldots\ldots\ldots\ldots\ldots\ldots 3.20$$

Non linear regression by SPSS 17.0 gave the following values for the unknown regression parameters;

$a = 0.456;\ b = -0.574;\ c = 0.464;\ d = 0.160;\ e = 1.164;\ f = 0.078;\ g = 0.131;$

$X = 1.437E + 6$

The **R-Squared value** for the non-linear regression analysis is **0.989**. The breakthrough height can thus be calculated using the following equation;

$$h_{bg} = (1.437E + 6).\frac{q^{0.456}.L^{-0.574}}{k_h^{\ 0.464}.k_v^{\ 0.160}.h_{ap}^{\ 1.164}.\emptyset^{0.078}.A^{0.131}} \ldots\ldots\ldots\ldots\ldots\ldots 3.21$$

Generalized Correlation for Breakthrough Time (T_{bg})

An attempt was also made to develop a generalized correlation to predict the breakthrough time of water into a horizontal well. A plot of WOR against time revealed a relationship similar to that between WOR and the height of oil column below the perforations.

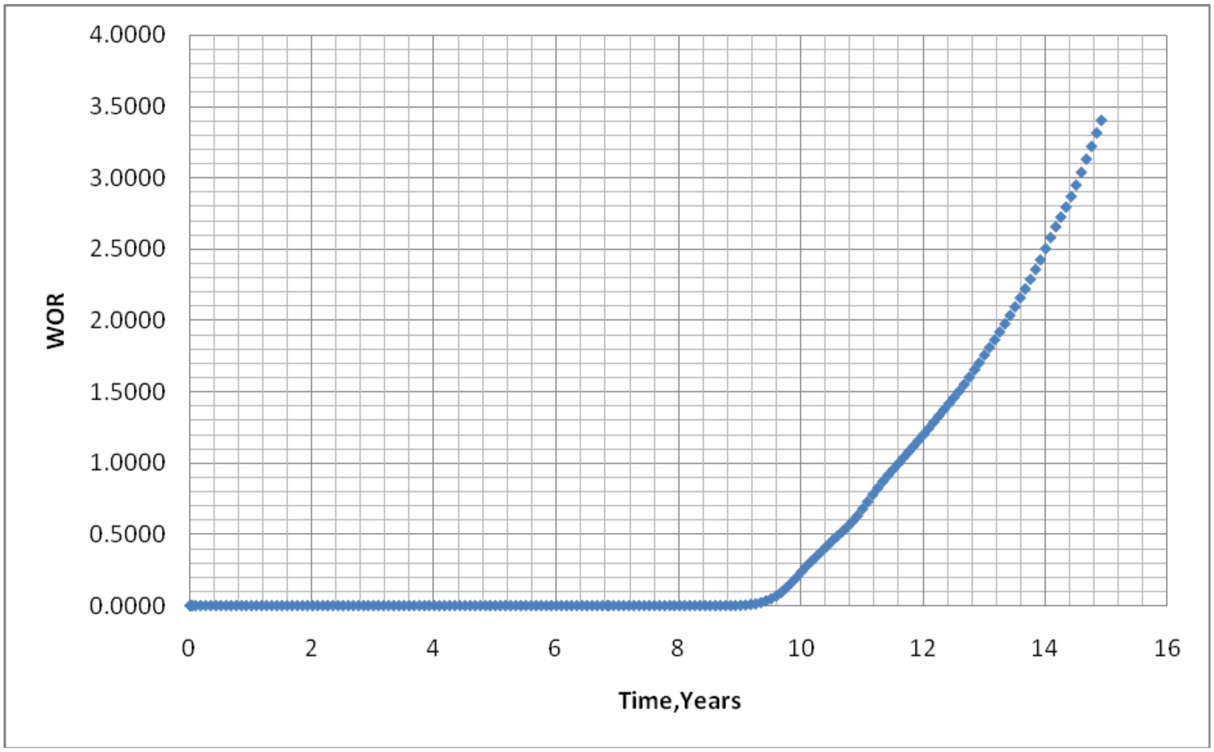


Figure 3.8: WOR-time curve for the base case scenario

Just as in the case of WOR-h_{bp}, it can be assumed that WOR remains zero until water breaks into the horizontal well. As this occurs, the WOR increases linearly as time increases. The time at which breakthrough occurs is known as the breakthrough time, denoted by T_{bg} (As shown in fig 3.3 above). The parameter sensitivity analysis that was carried out also included the effect of the coning parameters on the breakthrough time. The result of the parameter sensitivity analysis for breakthrough time is also detailed in the APPENDIX. The result from the parameter sensitivity analysis was then subjected to non-linear regression analysis using SPSS 17.0.

Just as in the case of the developing the model equation for slope and breakthrough height, the relationship between each of the coning parameters and the breakthrough time was observed to obtain the following assumptions;

1. $T_{bg} \propto (1/q^f)$
2. $T_{bg} \propto {k_h}^a$
3. $T_{bg} \propto {k_v}^b$
4. $T_{bg} \propto L^c$
5. $T_{bg} \propto Ø^d$
6. $T_{bg} \propto A^e$
7. $T_{bg} \propto (1/{h_{ap}}^g)$

From these assumptions; the following model equation was developed as the input for the non-linear regression using SPSS 17.0;

$$T_{bg} = X.\frac{{k_h}^a.{k_v}^b.{L_p}^c.Ø^d.A^e}{q^f.{h_{ap}}^g} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.22$$

The non linear regression gave the following values for the unknown regression parameters;

$a = 0.324, b = 0.108, c = 0.262, d = 1.092, e = 0.964, f = 1.490, g = 2.103,$

$X = 8.98E + 5$

The **R-Squared value** for the non-linear regression analysis is **0.991**.

Therefore, the Time to breakthrough (T_{bh}) can be given by the following generalized correlation:

$$T_{bg} = (8.98E + 5).\frac{{k_h}^{0.324}.{k_v}^{0.108}.{L_p}^{0.264}.Ø^{11.092}.A^{0.964}}{q^{1.490}.{h_{ap}}^{2.103}} \ldots\ldots\ldots\ldots\ldots\ldots 3.23$$

3.8 Predicting WOR after Breakthrough

In order to predict the post breakthrough performance of the horizontal well in terms of WOR, the following steps can be followed;

1. From the cumulative oil produced, calculate the current oil column height below the perforations using equation 3.12 and 3.14.
2. The oil column height below the perforations at breakthrough (h_{bg}) is then calculated using equation 3.21.
3. Using the predicted oil production rate, the changes in oil column height below the perforations can be calculated as production proceeds.
4. The absolute value of the slope of the WOR-h_{bp} curve after breakthrough can be calculated using equation 3.19.
5. WOR can then be calculated using equation 3.16 or 3.17 as the case may be.
6. The breakthrough time can be calculated using equation 3.23.

4.0 Result Analysis and Discussion

4.1. Parameter Sensitivity Analysis Results

The parameter sensitivity analysis was performed to provide data for developing generalized predictive correlations for calculating breakthrough time (T_{bg}), the height of oil column below the perforation at breakthrough (h_{bg}) and the WOR after breakthrough. The breakthrough time, as the name implies allows the prediction of the time water first breaks into the well. The height of oil column below the perforation gives an indication of oil recovery prior to the onset of water coning. The lower this height, the higher the quantity of oil that has been recovered before simultaneous production of water begins. The slope of the WOR curve gives an indication of the post-breakthrough performance of the horizontal well.

To begin the parameter sensitivity analysis, a base case was setup first, and all the remaining simulation runs were conducted by varying the base case data. Six parameters were varied to establish a total of 26 simulation cases for a horizontal well. The main parameters considered in the parametric study are; oil flow rate, horizontal permeability, vertical permeability, porosity, length of perforation, the height above the perforation and the area extent of the reservoir. The results of the parameter sensitivity analysis are shown in the APPENDIX.

4.2. CASE STUDY (Base Case Scenario)

4.2.1. PREDICTING POST BREAKTHROUGH PERFORMANCE

The generalized correlations developed are used to predict the post breakthrough performance of a horizontal well. The reservoir simulated in the base case scenario is used as a case study to prove the effectiveness of the correlations. Data regarding the reservoir geometry, fluid properties and well completion are listed in the APPENDIX. The WOR obtained using the generalized correlation is compared with the output from the ECLIPSE black oil simulator. The post breakthrough performance of the well was predicted following the steps outlined in section 3.8. The prediction for WOR is shown in Table 4.1 below. The table of values is shown in the APPENDIX.

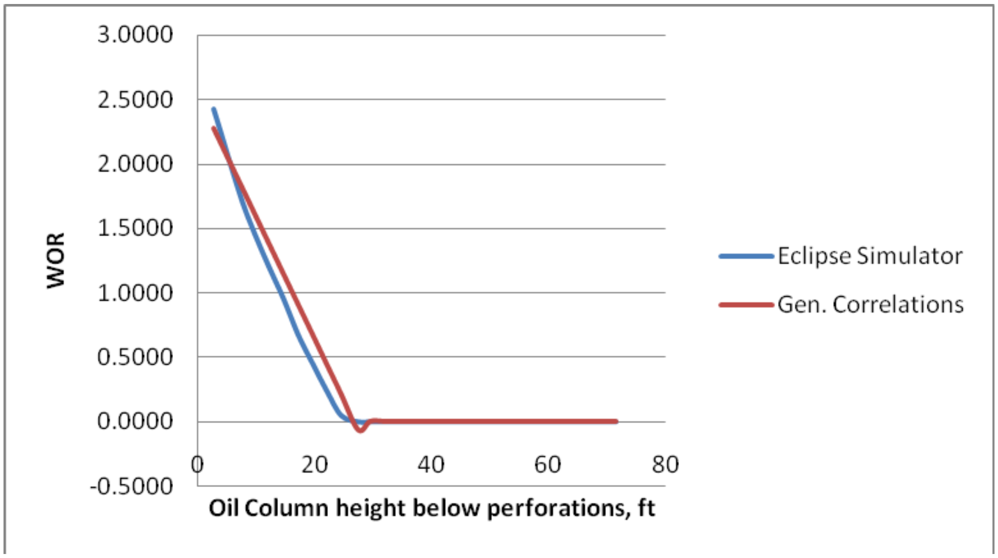


Figure 4.2: Comparison between Generalized Correlation and Eclipse Simiulation

The figure above shows that the prediction of post breakthrough performance using the generalized correlations is comparable to that obtained when using the ECLIPSE commercial black oil simulator. The slight variations in the WOR after breakthrough can be attributed to the complex nature of water coning into a horizontal well. Several other factors which affect coning behaviour were not considered in this work, and as such could be contributing factors to the variations between the predictions using the generalized correlations and that obtained using ECLIPSE. These factors include (but are not limited to the following);

- Viscosity of the fluids (oil and water)
- Density difference between the two fluids (oil and water)
- Mobility ratio
- Drainage radius of the reservoir
- Effect of pressure on coning behaviour

4.2.2 PREDICTING BREAKTHROUGH TIME

The breakthrough time of the base case scenario was calculated using equation 3.23. The breakthrough time obtained using the generalized correlation is compared to breakthrough time obtainable using the equations proposed by [18]. The results are summarized in the table below:

Table 4.1: Different breakthrough time correlations

S/N	**Method**	**Breakthrough Time (Years)**
1	Yang and Wattenbarger (1991) [18]	9.1
2	ECLIPSE Simulator	8.92
3	Generalized Correlation	8.87

The table above shows that the generalized correlation gives similar results for breakthrough time as the ECLIPSE black oil simulator. These values for breakthrough time is comparable to the values for breakthrough time obtainable using the correlations proposed by [18]. As such, the generalized correlation for breakthrough time is closely related to the breakthrough time correlation proposed by [18].

5.0 CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Water coning behaviour is an important reservoir phenomenon that occurs in reservoirs that are supported by aquifers. The production of a water cone can greatly affect the productivity of a well and the reservoir at large. Although, the use of horizontal wells reduces the rate of coning, it cannot completely eliminate the possibility if producing a water or gas cone. Therefore, in order to minimize or at least delay water coning, there must be a proper understanding of how various reservoir and fluid properties contribute to water coning behaviour. Water coning behaviour in horizontal wells was studied by simulating a reservoir supported by a strong aquifer, using ECLIPSE100 black oil simulator. The coning behaviour was correlated to one critical parameter-the oil column height below the perforations. During the course of this study, a parameter sensitivity analysis was conducted to determine how important coning parameters affect coning behaviour in horizontal wells. These parameters are; oil production rate, vertical and horizontal permeability, length of perforation, height above perforation, area extent of reservoir and the porosity of the formation. Non Linear regression analysis was then carried out on the results of the parameter sensitivity analysis to develop generalized correlations to predict coning behaviour. Special emphasis was given to predicting the WOR after breakthrough in addition to predicting the breakthrough time. The following conclusions can be drawn from this research work;

1. Increase in oil flow rate accelerates the rate of coning in horizontal wells.
2. Higher horizontal permeability delays coning in horizontal wells.
3. Prior to breakthrough, vertical permeability has little effect on coning behaviour. However, after breakthrough, the WOR increases with vertical permeability.

4. Porosity appears to have no correlation with the post breakthrough performance of the horizontal well. Increases in porosity however, cause a large delay in the onset of water coning into the horizontal well.
5. Increases in height above perforation (wells completed closer to the WOC) speeds up the rate of water coning into a horizontal well.
6. The length of perforations in horizontal wells also plays an important role in coning behaviour. Longer perforations bring about reductions in WOR after breakthrough.
7. A set of correlations for predicting breakthrough time, and post breakthrough performance in terms of the WOR is proposed. The correlations take into account the seven important coning parameters studied during the parameter sensitivity analysis.
8. A case study is presented to show that these correlations are reliable and can be used to predict breakthrough time and post breakthrough performance of horizontal wells prone to water coning.

5.2. Recomendations

1. Water coning is a complex phenomenon that depends on a large number of variables. The parameter sensitivity analysis in this work considers only seven of these variables. A more rigorous sensitivity analysis can be conducted to improve the versatility of the developed correlations. Some of the other factors which may be considered includes the following; viscosity, mobility ratio, density difference, effect of pressure, wellbore radius etc.
2. Reservoirs supported by both strong aquifers and gas caps are becoming more common. Wells completed in such reservoirs are prone to simultaneous gas and water coning. The approach to water coning used in this study may also be applied to cases where there is a tendency of simultaneous water and gas coning. The post breakthrough performance will be measured in terms of the WOR and GOR.

APPENDIX

Reservoir and Fluid Properties

Table A1: Reservoir Fluid Data

Gas Surface Density	0.04104 lbm/cu.ft
Oil Surface Density	56.85 lbm/cu.ft
Water Surface Density	65.55 lbm/cu.ft
Water Viscosity (V_w)	0.5 cp
Water FVF (B_w)	1.0 RB/STB
Water Compressibility (C)	3E-6 psi^{-1}

Relative Permeability Data

Table A2: Water-Oil Relative permeability Data

S_w	k_{rw}	k_{row}
0.206	0.00000	1.00000
0.250	0.00565	0.82296
0.300	0.01766	0.64270
0.350	0.03348	0.48469
0.400	0.05236	0.34894
0.450	0.07386	0.23545
0.500	0.09769	0.14420
0.550	0.12365	0.07521
0.600	0.1515	0.02848
0.650	0.18131	0.00400
0.680	0.2000	0.00000

Table A3: Gas-Oil Relative Permeability Data

S_g	K_{rg}	K_{rgo}
0.000	0.00000	1.00000
0.030	0.00000	0.92520
0.050	0.00020	0.87643
0.100	0.00251	0.75842
0.150	0.00740	0.64624
0.200	0.01485	0.54021
0.250	0.02487	0.44071
0.300	0.03746	0.34821
0.350	0.05263	0.26327
0.400	0.07036	0.18664
0.450	0.09066	0.11936
0.500	0.11353	0.06295
0.550	0.13897	0.02016
0.600	0.16698	0.00000
0.650	0.19756	0.00000
0.700	0.23071	0.00000
0.750	0.26643	0.00000
0.794	0.30000	0.00000

Table A4: Pressurization (PVT) Data

Pressure (psia)	B_g (RB/MSCF)	μ_g (cp)	R_s (MSCF/STB)	B_o (RB/STB)	μ_o (cp)
14.70	208.974	0.01280	0.0012250	1.04	18.57
500.00	5.86600	0.01320	0.0602210	1.07	8.285
1000.00	2.81000	0.01390	0.1285700	1.10	5.052
1470.00	1.85300	0.01480	0.2000000	1.13	3.680
1500.00	1.81300	0.01490	0.2003610	1.132	3.617
2000.00	1.33400	0.01610	0.2744900	1.16	2.821
2500.00	1.06400	0.01750	0.2503000	1.19	2.318
3000.00	0.89700	0.01900	0.4276000	1.22	1.973
3500.00	0.78600	0.02050	0.5000000	1.25	1.722
4000.00	0.70800	0.02200	0.6400000	1.28	1.531
4500.00	0.65200	0.02350	0.7000000	1.31	1.380
5000.00	0.60900	0.02500	0.8000000	1.345	1.258

Table A5: Reservoir Data

Length	4500’
Width	1250’
Thickness	169.0’
Depth of the resevoir	6384.0’
Length of Perforation	1000’
Thickness of the aquifer	30.0’
Datum depth	6384’
GOC depth	6384’
WOC depth	6535’
Rock Compressibilty	4.0E-6 psi^{-1}
Initial Datum Pressure	2756’
Oil zone thickness	139’
Average porosity	15.6 %
Average horizontal permeability	4000 md
Average vertical permeability	200 md

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Nomenclature

1. h_t = Thickness of reservoir (ft)
2. S_{avg} = Average oil saturation around the peforated interval
3. S_{wc}= Connate water saturation
4. S_{or} = Residual Oil Saturation
5. A = Area of Reservoir (acres)**
6. Φ= Porosity
7. N_i = Initial Oil-in-place (bbls)
8. N_p =Cumulative Oil Produced (bbls)
9. h_{ap} = height above the perforations (ft)
10. h_{bp} = oil column height below the perforations (ft)
11. m = slope of WOR-h_{bp} curve
12. WOR = Water Oil Ratio (stb/stb)
13. h_{bg} = oil column height below the perforations at breakthrough (ft)
14. q = Oil flow rate (bbls/D)
15. K_h = horizontal permeability (md)
16. K_v= Vertical permeability
17. L_p= Length of perforation
18. T_{bg}= Breakthrough Time

**Unless otherwise stated

Biography

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