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Pressure and Pressure Derivative of a Horizontal Well Subjected to a Single Edge and Bottom Water Drive Mechanism in an Anisotropic Reservoir

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Abstract

The goal of this study is to develop a mathematical model using the existing source and Green's functions for a horizontal well completed in an oil reservoir at steady state flow period for anisotropic reservoirs, where the reservoir is bounded by an edge and bottom constant pressure boundaries for the interpretation of pressure responses in the reservoir based on dimensionless pressure and derivatives.Using reservoir and well parameters as well as the variation in permeability in different directions, Excel software was used to investigate which set of reservoir (anisotropic ratios) and well parameters would prolong productivity before steady state set in. Results show that higher vertical permeability will produce much crude in less time before the encroachment of external fluid. Consequently, the production potential of the horizontal well will be reduced with time.The use of longer well lengths will tend to hasten the encroachment of unwanted fluid into the wellbore as wells were already feeling boundary effects beyond tD=1 while shorter well lengths will prolong production. Dimensionless pressure increases as reservoir pay thickness increases, delaying steady-state conditions. The higher the distance from the bottom of the reservoir in dimensionless variable (ZwD), the larger the dimensionless pressure and derivative and hence the better the productivity of the well and reservoir before the setting in of external reservoir fluid.

Keywords: Dimensionless Pressure. Single and Bottom Edge Water Drive, Horizontal Well, Anisotropic Reservoir

1. Introduction

One of the most challenging areas in petroleum industry is the analysis and development of horizontal well. Professionals predict that the number of horizontal wells will increase considerably in the next century and this technology will be applied increasingly to initial reservoir development. However, the cost of drilling of horizontal well is much higher than that of a vertical and also the pressure behavior of a horizontal well is significantly more difficult than that of a vertical well. To calculate pressure derivatives and significant characteristics on an oil reservoir, this study examines the pressure derivatives and important characteristics of a horizontal well subjected to edge and bottom water drive.

The main objective of this study is to determine the dimensionless pressure and derivatives of a late time flow period in a horizontal well subjected to single edge and bottom water drive mechanism in anisotropic reservoir using the dimensionless pressure and derivative equations and to investigate the necessary dimensionless parameters in order to identify the parameters that strongly affects dimensionless pressure responses and the minimum time for steady state period to set in. For years, oil and gas reservoir qualities have been assessed by interpreting pressure data collected during a well test. Interpretation of well test data and prediction of a horizontal well performance is more critical. Testing horizontal well performance is more critical and still challenging in terms of measurements and interpretation. The field experience documented in the last decade indicates that interpreting test for horizontal well is much more difficult than that of vertical wells. There have been a number of approaches to interpreting transient testing, but Horner's method is the most well-known and widely utilized by petroleum engineers. The available well testing and interpretive methods for a horizontal well are much more complex than the ones for a vertical well due to wellbore storage effect, boundary effects and partial penetration. In order to interpret well test data using existing techniques, more understanding of the characteristics and duration of each flow regime is needed. Type curves, which depict the pressure response of flowing wells under a variety of reservoir descriptions, were established only a few years ago as the only reliable method of determining the portion of the pressure data that can be analyzed using classic straight line analysis methods.

This study presents a method of interpretation based on the examination of the dimensionless pressures and derivatives with regard to the dimensionless time function with the use of log-log plot.

2. Methodology

The method employed in this work is to develop an equation for dimensionless pressure drop and dimensionless pressure derivative for horizontal wells located in a reservoir bounded by single edge and bottom water drives. The Gringarten et al (1973) and Adewole et al (2019) for steady state period will be utilized for appropriate instantaneous source function.

2.1Reservoir Model Description

The figure 3.1 shows the anisotropic rectangular shaped reservoir model under study. It consist of Horizontal well with directional permeability in the x, y, and z direction. In this case, the reservoir is consist of horizontal well where the horizontal permeability is less than the vertical permeability, $k_h<k_v$. The horizontal well is designed such that$d_x<<x_e-D_x$, $d_y=y_e-D_y$ and $d_z>>z_e-D_z$ (Mutili Peter Mutisya et al, 2020).

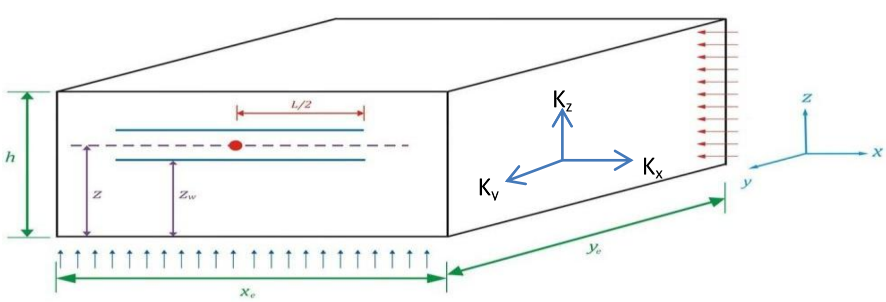

Figure 2.1: Horizontal well in a reservoir bounded by single edge and bottom water drive.

Where

L= Reservoir Thickness
X=Distance to the boundary in x-direction
Y=Distance to the boundary in Y-direction
Z=Distance to the boundary in Z-direction
X_e = Half the distance to the boundary in X-direction
Y_e =Half the distance to the boundary in Y-direction
Z_e =Half the distance to the boundary in the Z-direction
Z_w=The dimensionless distance from the bottom of the reservoir to the bottom of the wellbore

2.2 Source Functions

Instantaneous source or Green's functions are selected based on the type of boundary condition according to Gringarten et al (1973).

2.3Mathematical Model Description

Using dimensionless parameters and considering a point source as the intersection of three perpendicular infinite planes, the instantaneous point source function is obtained by Newman's product method, Gringarten et al (1973) as:

$$P_D = 2\pi h_D \int_0^{t_D} s(x_D,t_D)\cdot s(y_D,t_D)\cdot s(z_D,t_D)dt \quad (2.10)$$

Where:

$$s(x_D,t_D) = \frac{8}{\pi}\sum_{n=1}^{\infty}\frac{1}{n+1}\exp\left(-\frac{(2n+1)^2\pi^2 t_D}{4x_{eD}^2}\right)\sin\left(\frac{(2n+1)\pi x_{wD}}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right) \quad (3.11)$$

$$s(y_D,t_D) = \frac{1}{y_{eD}}\left(1+2\sum_{n=1}^{\infty}\exp\left(-\frac{n^2\pi^2 t_D}{y_{eD}^2}\right)\cos\left(\frac{n\pi y_{wD}}{y_{eD}}\right)\cos\left(\frac{n\pi y_D}{y_{eD}}\right)\right) \quad (2.12)$$

And

$$s(z_D,t_D) = \frac{1}{h_D}\sum_{n=1}^{\infty}\exp\left(-\frac{(2n-1)^2\pi^2 t_D}{4h_D^2}\right)\sin\left(\frac{(2n-1)\pi z_{wD}}{2h_D}\right)\sin\left(\frac{(2n-1)\pi z_D}{2h_D}\right) \quad (2.13)$$

The dimensionless pressure derivative at steady-state is given as:

$$P_D' = t_D\frac{\partial P_D}{\partial t_D} \quad (2.14)$$

By Substitution we have;

$$P_D' = \frac{16t_D}{y_{eD}} \begin{bmatrix} \sum_{n=1}^{\infty} \frac{1}{n+1} \exp\left(-\frac{(2n+1)^2 \pi^2 t_D}{4x_{eD}^2}\right) \sin\left(\frac{(2n+1)\pi x_{wD}}{2x_{eD}}\right) \cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right) \\ \cos\left(\frac{(2n+1)\pi x_{eD}}{2x_{eD}}\right) * \left(1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2 t_D}{y_{eD}^2}\right) \cos\left(\frac{n\pi y_{wD}}{y_{eD}}\right) \cos\left(\frac{n\pi y_D}{y_{eD}}\right)\right) \\ * \sum_{n=1}^{\infty} \exp\left(-\frac{(2n-1)^2 \pi^2 t_D}{4h_D^2}\right) \sin\left(\frac{(2n-1)\pi z_{wD}}{2h_D}\right) \sin\left(\frac{(2n-1)\pi z_D}{2h_D}\right) \end{bmatrix} \quad (2.15)$$

2.4 Dimensionless Expressions for Anisotropic Reservoir

$$h_D = \frac{2h}{L}\sqrt{\frac{k}{k_z}}, L_D = \frac{L}{2h}\sqrt{\frac{k_z}{k}} \quad (2.16)$$

$$X_{wD} = \frac{2X_w}{L}\sqrt{\frac{k}{k_x}} \quad (2.17)$$

$$Y_{wD} = \frac{2Y_w}{L}\sqrt{\frac{k}{k_y}} \quad (2.18)$$

$$Z_{wD} = \frac{2Z_w}{L}\sqrt{\frac{k}{k_z}} \quad (2.19)$$

$$X_{eD} = \frac{2X_e}{L}\sqrt{\frac{k}{k_x}} \quad (2.20)$$

$$Y_{eD} = \frac{2Y_e}{L}\sqrt{\frac{k}{k_y}} \quad (2.21)$$

$$Z_{eD} = \frac{2Z_e}{L}\sqrt{\frac{k}{k_z}} \quad (2.22)$$

$$X_D = \frac{2X}{L}\sqrt{\frac{k}{k_x}} \quad (2.23)$$

$$Y_D = \frac{2Y}{L}\sqrt{\frac{k}{k_y}} \quad (2.24)$$

$$Z_D = \frac{2Z}{L}\sqrt{\frac{k}{k_z}} \quad (2.25)$$

2.5Model Parameters

Consider the following numerical data of rock and reservoir characteristics properties in a bounded anisotropic reservoir;

$L = 500ft$

$x = x_w = 100ft, y = y_w = 200ft, z = 150ft, z_w = 160ft$

$x_e = 1000ft, y_e = 500ft, z_e = 300ft$

$h = 200ft, d_x = 134ft, d_y = 200ft, d_z = 160ft$

$D_x = 650ft, D_y = 210ft, D_z = 170ft$

K_x=30md,K_y=50md, K_z=70md

3. Results and Discussion

3.1 Results Presentation

3.1.1. The Effect of Well Lengths on PD and PD’ for a Given Reservoir Length

The effect of well length on dimensionless pressure and derivative was investigated, keeping the external lateral extent (XeD) of the reservoir constant at 5.016 and different values of well lengths (L=500ft, 800ft, 1000ft and 1500ft) were investigated for their effect on dimensionless pressures and derivative. From the Table 1, result shows that well length is inversely related to the dimensionless pressure and derivatives.

Table 1 Dimensionless Pressures and derivative results for varying well length (L) when XeD=5.016

tD	PD, L=500ft	PD', L=500ft	PD, L=800ft	PD', L=800ft	PD, L=1000ft	PD', L=1000ft	PD, L=1500ft	PD', L=1500ft
0.0001	4.5757E-05	4.57574E-09	4.5699E-05	4.5699E-09	4.56442E-05	4.56443E-09	4.54581E-05	4.54545E-09
0.001	4.5379E-05	4.53792E-08	4.4794E-05	4.4794E-08	4.42593E-05	4.42595E-08	4.24557E-05	4.24524E-08
0.01	4.1765E-05	4.17655E-07	3.6673E-05	3.6673E-07	3.25236E-05	3.25237E-07	2.1438E-05	2.14364E-07
0.1	1.8215E-05	1.82147E-06	4.9609E-06	4.9609E-07	1.49326E-06	1.49326E-07	2.31034E-08	2.31015E-09
1	4.5339E-09	4.53389E-09	1.018E-14	1.0179E-14	6.21579E-20	6.21581E-20	4.88176E-38	4.88137E-38
10	4.1396E-45	4.1396E-44	1.347E-101	1.347E-100	9.7077E-154	9.7077E-153	0	0
100	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0
10000	0	0	0	0	0	0	0	0

3.1.2. The Effect of Dimensionless Reservoir Height on PD and PD' for a Given Reservoir Length.

The effect of dimensionless pay thickness on dimensionless pressure and derivative was investigated, keeping the external lateral extent (XeD) of the reservoir constant at 5.016 with different values of dimensionless pay thickness (hD=0.8, 1 and 2) were investigated for their effect on dimensionless pressures and derivative. The results are presented in Table 2 and Figure1

Table 3.2: Dimensionless Pressures and derivative results for varying dimensionless pay thickness (hD)

tD	PD, hD=0.8	PD', hD=0.8	PD, hD=1	PD', hD=1	PD, hD=2	PD', hD=2
0.0001	4.57677E-05	4.57677E-09	4.5774E-05	4.57741E-09	4.57825E-05	4.57825E-09
0.001	4.54657E-05	4.54657E-08	4.55289E-05	4.55289E-08	4.56132E-05	4.56133E-08
0.01	4.25536E-05	4.25536E-07	4.31485E-05	4.31485E-07	4.39546E-05	4.39546E-07
0.1	2.19513E-05	2.19513E-06	2.52204E-05	2.52204E-06	3.03488E-05	3.03488E-06
1	2.92883E-08	2.92883E-08	1.17385E-07	1.17385E-07	7.47319E-07	7.4732E-07
10	5.23649E-37	5.23649E-36	5.60059E-31	5.60059E-30	6.12573E-23	6.12574E-22
100	0	0	3.4232E-264	3.4232E-262	8.3883E-184	8.3883E-182
1000	0	0	0	0	0	0
10000	0	0	0	0	0	0

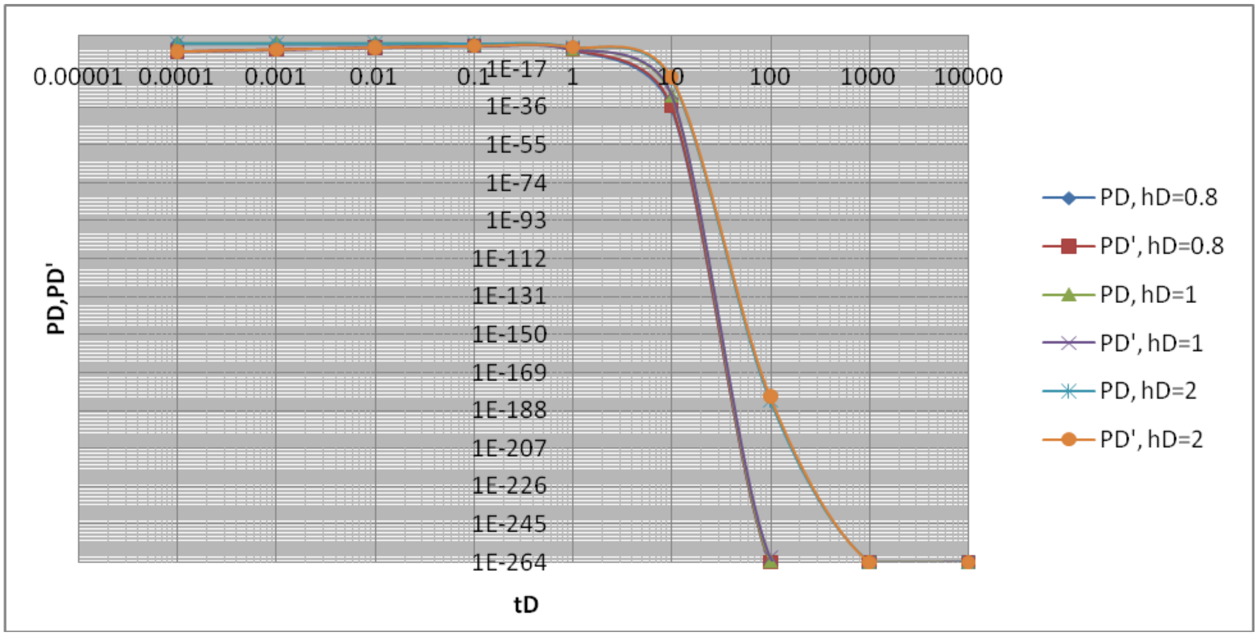

Figure1: Log-log plot showing the effect of hD on PD and PD'

The Figure1 shows that, at early time (pseudo-steady state) at higher value of dimensionless pay thickness (hD), the dimensionless pressures increases and when approaching the late period, a combine pressure effect become noticeable. At late period (steady state) that is beyond tD=1, the wellbore was observed to have begun to feel the constant pressure boundaries. Therefore, this indicate that the higher the pay thickness, the more the external fluid encroachment toward wellbore is delayed.

3.1.3. Effect of Reservoir Length on Dimensionless Pressures and Derivative

The effect of dimensionless lateral extent on dimensionless pressure and derivative was investigated, keeping dimensionless wellbore and reservoir parameters constant with different values of dimensionless lateral extent (XeD=4, 8 and 15) were investigated for their effect on dimensionless pressures and derivative. The results are presented in Table 3 and Figure 3.

Table 3: Dimensionless Pressures and derivative results for varying external lateral extent XeD

tD	PD, XeD=4	PD', XeD=4	PD, XeD=8	PD', XeD=8	PD, XeD=15	PD', XeD=15
0.0001	5.7371E-05	5.7374E-09	2.869E-05	2.869E-09	1.5303E-05	1.53037E-09
0.001	5.6871E-05	5.6874E-08	2.847E-05	2.847E-08	1.5187E-05	1.5188E-08
0.01	5.2104E-05	5.2108E-07	2.633E-05	2.633E-07	1.4077E-05	1.40775E-07

0.1	2.1713E-05	2.1714E-06	1.205E-05	1.205E-06	6.5879E-06	6.58836E-07
1	3.4293E-09	3.4295E-09	4.857E-09	4.858E-09	3.321E-09	3.32123E-09
10	3.3114E-47	3.3116E-46	5.507E-43	5.507E-42	3.5195E-42	3.51972E-41
100	0	0	0	0	0	0
1000	0	0	0	0	0	0
10000	0	0	0	0	0	0

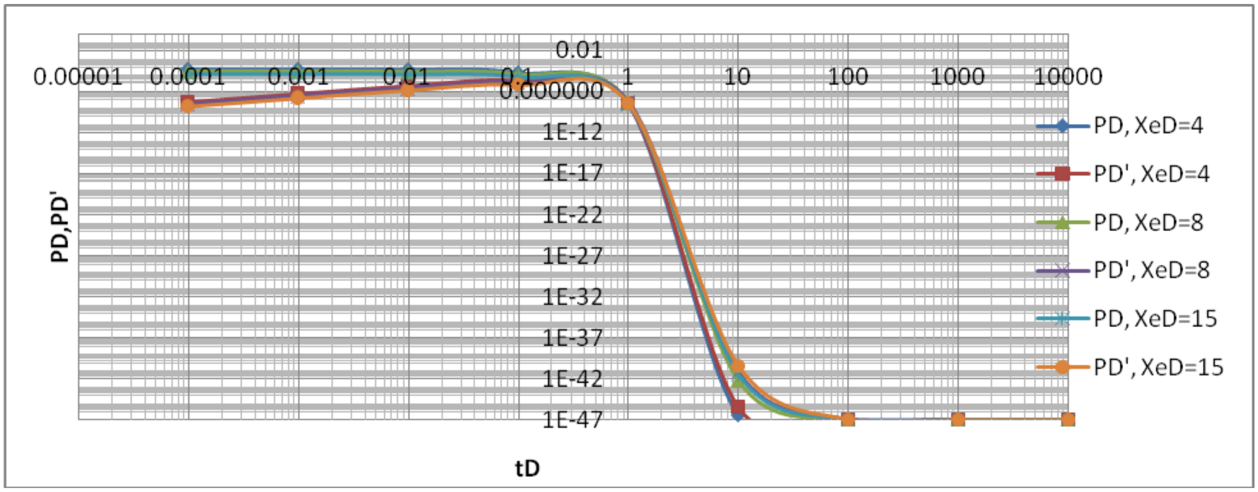

Figure 3: Log-log plot showing the effect of XeD on PD and PD'

In Figure 3, it was observed that different dimensionless lateral extent has minimal impact on dimensionless pressure and derivative owing to the fact that other parameters are held constant thereby creating a narrow path along the reservoir in the x-direction.

3.1.4. Effect of Distance between the Reservoir Bottom and the Wellbore on Dimensionless Pressures and Derivative

The effect of dimensionless distance from the bottom of the reservoir to the wellbore, ZwD on dimensionless pressure and derivative was investigated, keeping dimensionless wellbore and reservoir parameters constant with different values of dimensionless distance from the bottom of the reservoir to the wellbore, (ZwD=0.64, 0.8, 1 and 2) were investigated for their effect on dimensionless pressures and derivative.

Table 4: Dimensionless Pressures and Derivative results for varying Dimensionless Distance from the bottom of the Reservoir to the wellbore, ZwD

tD	PD, ZwD=0.64	PD', ZwD=0.64	PD, ZwD=0.8	PD', ZwD=0.8	PD, ZwD=1	PD', ZwD=1	PD, ZwD=2	PD', ZwD=2
0.0001	5.57401E-05	5.57437E-09	6.96706E-05	6.96751E-09	8.70791E-05	8.70847E-09	0.000174006	1.74018E-08
0.001	5.52795E-05	5.5283E-08	6.90948E-05	6.90993E-08	8.63595E-05	8.6365E-08	0.000172568	1.7258E-07
0.01	5.08774E-05	5.08806E-07	6.35925E-05	6.35966E-07	7.94823E-05	7.94874E-07	0.000158826	1.58836E-06
0.1	2.21886E-05	2.219E-06	2.77339E-05	2.77357E-06	3.46637E-05	3.4666E-06	6.92671E-05	6.92715E-06
1	5.52304E-09	5.52339E-09	6.90334E-09	6.90379E-09	8.62828E-09	8.62883E-09	1.72415E-08	1.72426E-08
10	5.04272E-45	5.04304E-44	6.30299E-45	6.30339E-44	7.87791E-45	7.87841E-44	1.57421E-44	1.57431E-43
100	0	0	0	0	0	0	0	0
1000	0	0	0	0	0	0	0	0
10000	0	0	0	0	0	0	0	0

In Table4, it was observed that dimensionless distance from the bottom of the reservoir to the wellbore has effect on dimensionless pressures and derivative.

3.1.5 Effect of Anisotropic Ratio on Dimensionless Pressures and Derivative

The effect of vertical permeability to horizontal permeability, kv/k on dimensionless pressure and derivative was investigated, keeping dimensionless wellbore and reservoir parameters constant with different values of vertical to horizontal permeability ratios, (kv/k=0.10, 0.60, 1.30 and 2.00) were investigated for their effect on dimensionless pressures and derivative. Results are presented in Table 5.

Table 5: Dimensionless Pressures and Derivative results for varying Vertical to Horizontal Permeability Ratio, Kz/K

Td	PD, kz/k=0.10	PD', kz/k=0.10	PD, kz/k=0.60	PD', kz/k=0.60	PD, kz/k=1.30	PD', kz/k=1.30	PD, kz/k=2.0	PD', kz/k=2.0
0.0001	3.08643E-06	3.08643E-10	1.85138E-05	1.85139E-09	4.00994E-05	4.00996E-09	6.16698E-05	6.16704E-09
0.001	3.07566E-06	3.07566E-09	1.84172E-05	1.84173E-08	3.97934E-05	3.97936E-08	6.10507E-05	6.10512E-08
0.01	2.97E-06	2.97E-08	1.74785E-05	1.74786E-07	3.68588E-05	3.6859E-07	5.51912E-05	5.51917E-07
0.1	2.09381E-06	2.09381E-07	1.03591E-05	1.03591E-06	1.71335E-05	1.71336E-06	2.01217E-05	2.01219E-06
1	6.34967E-08	6.34967E-08	5.53969E-08	5.53972E-08	8.07054E-09	8.07059E-09	8.34855E-10	8.34863E-10
10	4.1772E-23	4.1772E-22	1.05957E-30	1.05957E-29	4.33968E-42	4.3397E-41	1.26205E-53	1.26206E-52
100	6.3421E-175	6.3421E-173	6.9432E-258	6.9432E-256	0	0	0	0
1000	0	0	0	0	0	0	0	0
10000	0	0	0	0	0	0	0	0

3.2 Discussion of Results

Dimensionless pressure and dimensionless pressure derivatives were computed for the various reservoir and well parametersand results from Table1 show that, the higher the value of well length, the smaller the dimensionless pressure and derivatives for an anisotropic reservoir. It was also observed that at higher well length, the effect of constant pressure boundary was felt on time due to the edge water drive. Therefore, this indicates that for a given anisotropic reservoir subjected to a single edge and bottom water drive mechanism, the use of longer well lengths will tend to hasten the encroachment of unwanted fluid into the wellbore while shorter well lengths will prolong production. Results from Table2 and Figure1 indicate that at higher reservoir pay thickness there was a delay of external fluid encroachment toward the wellbore as others were already feeling the constant pressure boundary effects.

Results from table 3.4 indicates that,the higher the distance from the bottom of the reservoir the larger the dimensionless pressure and derivative and hence the better the productivity of the well and reservoir before the setting in of external reservoir fluid.

Finally, results fromTable5, show that, as vertical permeability increases, the magnitude of dimensionless pressures and derivatives increases at early time and decreases as it approaches late time period which the indicates the effect of boundaries. This implies that higher vertical permeability will produce much crude in less time before the encroachment of external fluid. Consequently, the production potential of the horizontal well will be reduced with time.

Conclusion

A model for dimensionless pressure and dimensionless pressure derivative distribution of a horizontal well subjected to a single edge and bottom drive mechanism in ananisotropic reservoir is presented. Type curves were also generated for the analysis of a horizontal well subjected to a single edge and bottom drive mechanism. The effect of reservoir and well characteristics on the distribution of dimensionless pressure and dimensionless pressure derivatives of a horizontal well in a constrained anisotropic reservoir with constant pressure at the bottom and edge has been investigated. The following conclusions were made:

1. The use of longer well lengths will tend to hasten the encroachment of unwanted fluid into the wellbore while shorter well lengths will prolong production.

2. The higher the pay thickness, the more the external fluid encroachment toward wellbore is delayed and hence the better the productivity of the well.

3. Dimensionless external lateral extent also increases productivity. But for very short well lengths and pay thickness, the effect of dimensionless external lateral extent become insignificant at late time because of the presence of constant pressure boundaries.

4. The higher the distance from the bottom of the reservoir the larger the dimensionless pressure and derivative and hence the better the productivity of the well and reservoir before the setting in of external reservoir fluid.

5. Higher vertical permeability will produce much crude in less time before the encroachment of external fluid. Consequently, the production potential of the horizontal well will be reduced with time.

6. Distance from the constant pressure boundaries, well length and pay thickness and anisotropic ratios are the parameters that determine time to reach steady state.

Finally, this study will serve as guidelines to oil producers in well design and appropriate well positioning for efficient withdrawal of crude in a reservoir subjected to single edge and bottom water drive.

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Nomenclature

B	*oil volumetric factor, bbl/STB*
c_t	*total compressibility, 1/psi*
h	*formation thickness, ft*
k	*effective permeability, md*
k_x, k_y, k_z,	*permeability in the x, y, z direction respectively, md*
L	*total length of horizontal well, ft*
Δp	*pressure drop, psi*
h_D	*dimensionless reservoir height or pay thickness*
L_D	*dimensionless well length*
n	*number of image wells*
P_D	*dimensionless pressure*
P_D'	*dimensionless pressure derivative*
t_D	*dimensionless time*
X_{eD}	*dimensionless reservoir length*
X_D	*perforated length*
Y_{eD}	*dimensionless reservoir width*
Z_D	*the dimensionless distance from the bottom of the reservoir to the center of the wellbore*
Z_{wD}	*the dimensionless distance from the bottom of the reservoir to the bottom of the wellbore*
d_x	*the shortest distance between the well and the x-boundary, ft*
d_y	*the shortest distance between the well and the y-boundary, ft*
d_z	*the shortest distance between the well and the z-boundary, ft*
D_x	*the longest distance between the well and the x-boundary, ft*
D_y	*the longest distance between the well and the y-boundary, ft*
D_z	*the longest distance between the well and the z-boundary, ft*

Greek Symbols

τ	*dummy variable of time*
η	*Diffusivity constant, md-psi/cp*
ϕ	*porosity, fraction*
μ	*viscosity, cp*