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Effects of Fluid and Reservoir Characteristics on Dimensionless Pressure and Derivative of a Horizontal Well in a Bounded Oil Reservoir with Simultaneous SingleEdge and Bottom Water Drive

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Abstract
This study investigates the effects of fluid, wellbore and reservoir characteristics on dimensionless pressure and dimensionless pressure derivatives at late time flow of a horizontal well in a bounded oil reservoir subjected to a single edge and bottom water drive mechanisms. The properties considered in this paper include the dimensionless well length, dimensionless reservoir width and dimensionless pay thickness. The main objective is achieved by using the source and Green's functions together with Newman product method. Spline functions for interpolation in curve fitting was used to plot the graphs aided by MATLAB program. Results show that the dimensionless pressure increases with decrease in dimensionless reservoir width and pay thickness. The dimensionless pressure derivative potentially collapses to zero when the dimensionless pressure becomes constant. Higher oil production is indicated by larger magnitudes of dimensionless pressure derivatives. Information in this study will assist in designing and completion of horizontal wells in a bounded reservoir for prolonged enhanced oil production.

Keywords: *Dimensionless Pressure,BoundedOil Reservoir, Horizontal Well, Edge and Bottom Water Drive, Late Flow Period.*

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I. Introduction

Subjecting the reservoir to single edge and bottom water drive poses some challenges in clean oil production due to influx and production of unwanted fluids. In order to minimize the effects of this unwanted fluids, the horizontal well is designed such that, it is far from the edge and bottom water drives boundaries of the reservoir as demonstrated in the assumed wellbore, fluid and reservoir properties discussed. The effects of dimensionless well length, dimensionless reservoir thickness, dimensionless reservoir width, uniform flux completions and infinite conductivity at late time is considered in this study. Various studies have been developed by several researchers in determining the transient flow behavior of horizontal wells.

The analysis of wells with a finite-conductivity fracture was presented by[1]**.** The technique simultaneously used the pressure and pressure derivative for cases with no fracture skin and no wellbore storage and for cases with fracture skin and wellbore storage during the bilinear-flow period. Their results showed that, the use of the pressure derivative with pressure behavior type curves reduces the uniqueness problem in type-curve matching and gives greater confidence in the results.

Horizontal well test design and interpretation methods was presented by [2], were analytical solutions were developed to carry out design as well as interpretation with semi log and log-log analysis which pointed out the distinctive behavior of horizontal wells. Practical time criteria were proposed to determine the beginning and the end of each type of flow and to provide a guide to semi log analysis and well test design. The behavior of uniform flux or infinite conductivity of horizontal wells with wellbore storage and skin was discussed.

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Type curves based on the derivative of dimensionless pressure with respect to the logarithm of dimensionless time which enhances the likelihood of obtaining a unique type-curve match and consistent analysis was presented by [3].

Illustrations of a new general procedure for constructing type curves on the basis of a new pressure-derivative group that involves the dimensionless pressure change divided by its logarithmic derivative was presented by [4].Their results showed that the basic idea used in constructing the type curves can be used to ensure that proper semi log straight lines are chosen when well-test pressure data are analyzed by semi log methods.

Application of pressure type curves into the analysis of buildup tests with linear or bilinear flow periods was discussed by [5].The result showed the conventional logarithmic superposition derivative type curve will not plot as a straight line. As a result, it may be difficult to identify possible linear or bilinear flow periods from conventional type or pressure derivative type curves. Superposition function depends on the particular combination of flow periods believed to particular combination of flow periods believed to have an impact on the buildup behavior.

The use of numerical integration to evaluate an analytical solution for the transient pressure response of a horizontal well located in a closed, box-shaped, anisotropic reservoir was studied by [6].Results from their study showed numerical integration can be used to evaluate the solution with a comparative degree of accuracy, while avoiding the convergence problems associated with the analytical integration. For well test analysis and design purposes, they proposed time criteria, based on the semi-log pressure derivative response and discussed the effects of well radius, well location and reservoir size on the drawdown pressure derivative response. Results show that for a horizontal well in a closed reservoir, the late linear flow period will not occur on the buildup response for any case, even when the late linear flow period is present on the drawdown response.

A number of possible derivative responses of horizontal wells in homogeneous and dual porosity reservoirs with a variety of reservoir geometries was presented by [7]. In their study, detailed evaluation of possible responses and derivative type curve analysis was provided and new diagnostic rules, analytical procedures and type-curves were presented. The effects of the location of the well relative to the boundaries, and wellbore effective flowing length on flow patterns was also discussed.

New equation for the first radial flow was proposed by[8] where the type curve matching techniques of pressure and pressure derivative to determine several reservoir parameters and new techniques, known as direct synthesis, for interpreting the pressure behavior of a horizontal well without type-curve matching was presented. Their results showed that, characteristic points are obtained at intersections of various straight-line portions of the pressure and pressure derivative curves, slopes and starting times of these straight lines. The points, slopes and times are then used with appropriate equations to solve directly for reservoir characteristics.

An evaluative analysis of the pressure derivative performed by comparing the results from different algorithms was presented by [9].They deduced that pressure derivative function has become the most popular technique to interpret well pressure data but it suffers of noise since it is based on numerical differentiation on discrete pressure data points. The Spline function is a powerful tool to calculate pressure derivative data for well test applications. Their results found that the Spline function provides the best results to estimate pressure derivative data.

The effects of both wellbore and reservoir properties on dimensionless pressure and dimensionless pressure derivatives of a horizontal well in a reservoir subject to bottom water, gas cap and single edge water drive mechanisms was investigated by [10]. They also considered the effects of rectangular and square reservoir geometries where the results showed that dimensionless pressure increases with reservoir thickness and the dimensionless wellbore radius was found to be inversely related to dimensionless pressure.

A mathematical model using Source and Green's functions for a Horizontal Wells in a Bounded Reservoir with Constant Pressure at the Top and Bottom for the interpretation of pressure responses in the reservoir based on dimensionless pressure and pressure derivative was developed by [11]. Results showed that dimensionless lateral extent does not directly affect the dimensionless pressure and dimensionless pressure derivative for very short well lengths.

In this paper we are providing solutions to the mathematical model developed by [12]. This is achieved by selecting a set of fluid, wellbore and reservoir properties as outlined below.

II. Reservoir Model Description

The wellbore and reservoir model are illustrated in figure 1. below. Slightly compressible fluid is considered flowing towards the horizontal well of dimensionless length, L_D. The horizontal well is considered as a line source designed such that $y_{eD} = 2y_{wD}$ with the right edge and bottom boundary permeable assuming that the skin and wellbore storage effects are negligible.

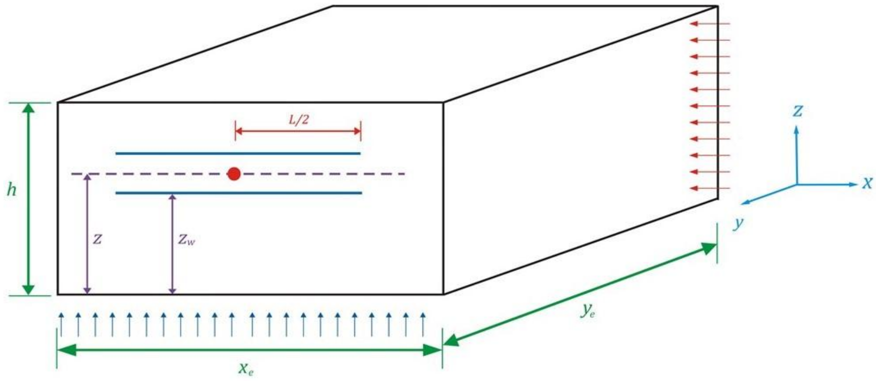

Figure 1. Reservoir model description

III. Mathematical Model Description

The mathematical relationships of the axis of the fluid flow is outlined by the instantaneous point source function obtained by the green's functions and the Newman's product method as: -

$$P_D = 2\pi h_D \int_0^{\tau_D} s(x_D, t_D).s(y_D, t_D).s(z_D, t_D)d\tau \quad (1)$$

Where: -

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

$$s(y_D, t_D) = \frac{1}{y_{eD}}\left(1 + 2\sum_{n=1}^{\infty}exp\left(-\frac{n^2\pi^2 t_D}{y_{eD}^2}\right)\cos\left(\frac{n\pi y_{wD}}{y_{eD}}\right)\cos\left(\frac{n\pi y_D}{y_{eD}}\right)\right) \quad (3)$$

and

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

Since we are considering anisotropic reservoir, the dimensionless pressure distribution at steady state at late time is given by: -

$$P_D = \frac{16}{y_{eD}}\int_0^{\tau_D}\left[\sum_{n=1}^{\infty}\frac{1}{n+1}exp\left(-\frac{(2n+1)^2\pi^2\tau_{Di}}{4x_{eD}^2}\right)\sin\left(\frac{(2n+1)\pi x_{wD}}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right) * \left(1 + 2\sum_{n=1}^{\infty}exp\left(-\frac{n^2\pi^2\tau_{Di}}{y_{eD}^2}\right)\cos\left(\frac{n\pi y_{wD}}{y_{eD}}\right)\cos\left(\frac{n\pi y_D}{y_{eD}}\right)\right) * \sum_{n=1}^{\infty}exp\left(-\frac{(2n-1)^2\pi^2\tau_{Di}}{4h_D^2}\right)\sin\left(\frac{(2n-1)\pi z_{wD}}{2h_D}\right)\sin\left(\frac{(2n-1)\pi z_D}{2h_D}\right)\right]d\tau_D \quad (5)$$

Well test analysis on dimensionless pressure derivatives are used to enhance the possibilities of obtaining a unique solution. The dimensionless pressure derivative at steady-state is defined as: -

$$P_D' = t_D\frac{\partial P_D}{\partial t_D}[13] \quad (6)$$

Substituting equation (5) into equation (6), we have: -

$$P_D^{'} = \frac{16t_{Di}}{y_{eD}}\left[\sum_{n=1}^{\infty}\frac{1}{n+1}exp\left(-\frac{(2n+1)^2\pi^2 t_{Di}}{4x_{eD}^2}\right)\sin\left(\frac{(2n+1)\pi x_{wD}}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right)\cos\left(\frac{(2n+1)\pi x_D}{2x_{eD}}\right)\right.$$
$$* \left(1+2\sum_{n=1}^{\infty}exp\left(-\frac{n^2\pi^2 t_{Di}}{y_{eD}^2}\right)\cos\left(\frac{n\pi y_{wD}}{y_{eD}}\right)\cos\left(\frac{n\pi y_D}{y_{eD}}\right)\right)$$
$$\left. * \sum_{n=1}^{\infty}exp\left(-\frac{(2n-1)^2\pi^2 t_{Di}}{4h_D^2}\right)\sin\left(\frac{(2n-1)\pi z_{wD}}{2h_D}\right)\sin\left(\frac{(2n-1)\pi z_D}{2h_D}\right)\right] \quad (7)$$

IV. Methodology And Demonstration Of The Problem

In this study, for the interpretation of the results we have used the cubic spline data interpolation. Splines are popular curves which are simple to construct and are characterized by accuracy of evaluation, ease and capacity to approximate complex shapes, interactive curve design and curve fitting. Consider the following numerical data of rock, fluid and reservoir characteristics in an infinite acting reservoir: -

$L = 500ft, 1000ft, 1500ft, 2000ft, 2500ft, 3000ft, 3500ft, x = x_w = 134ft,$
$y = y_w = 200ft, z = 160.5ft, z_w = 160ft, x_e = 6000ft, y_e = 400ft, z_e = 200ft,$
$h = 200ft,\ d_x = 134ft,\ d_y = 200ft,\ d_z = 160ft,\ D_x = 634ft,\ D_y = 201ft,\ D_z = 161ft,\ k_x = 22md, k_y = 16md, k_z = 20md, \sqrt{\frac{k}{k_x}} = 0.9335, \sqrt{\frac{k}{k_y}} = 1.0946, \sqrt{\frac{k}{k_z}} = 0.9790,$
$\sqrt{\frac{k_h}{k_v}} = 0.9685$. Hence $k = \sqrt[3]{k_x.k_y.k_z} = 19.17md$, For a horizontal well; $k_v > k_h$ where
$k_v = k_z$ and $k_h = \sqrt{k_x k_y} = 18.76md$

The following tables and figures were used to analyse the relationship between dimensionless variables and the dimensionless pressure and derivatives of a horizontal well in a rectangular reservoir geometry. Computation of dimensionless parameters, dimensionless pressure and dimensionless pressure derivatives are analysed in tables and figures below.

Table I. Computed Dimensionless Reservoir, Wellbore and Fluid data

Dimensionless parameter	$L(ft)$	500	1000	1500	2000	2500	3000	3500
	L_D	1.1669	2.3338	3.5006	4.6675	5.8344	7.0013	8.1681
	h_D	0.7832	0.3916	0.2611	0.1958	0.1566	0.1305	0.1119
x_D		0.5	0.5	0.5	0.5	0.5	0.5	0.5
y_D		0.8757	0.4378	0.2919	0.2189	0.1751	0.1459	0.1251
z_D		0.6285	0.2653	0.1442	0.0837	0.0474	0.0232	0.0059
x_{wD}		0.5	0.5	0.5	0.5	0.5	0.5	0.5
y_{wD}		0.8757	0.4378	0.2919	0.2189	0.1751	0.1459	0.1251
z_{wD}		0.6266	0.2643	0.1436	0.0832	0.0470	0.0228	0.0056
x_{eD}		22.404	11.155	7.4058	5.5310	4.4061	3.6562	3.1206
y_{eD}		1.7514	0.8757	0.5838	0.4378	0.3503	0.2919	0.2502
z_{eD}		0.7832	0.3427	0.1958	0.1224	0.0783	0.0490	0.0280
$\propto$		1.4783	4.9891	8.5536	10.146	8.6521	4.6448	0.8547

Table II. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.7832$).

	$L_D = 1.1669, x_D = 0.5, y_{eD} = 1.7514$								
t_D	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
P_D	0	3.1504	3.6590	3.7410	3.7543	3.7564	3.7568	3.7568	3.7568
$P_D^{'}$	0	1.1060	0.3570	0.0864	0.0186	3.75E-3	7.27E-4	1.37E-4	2.53E-5

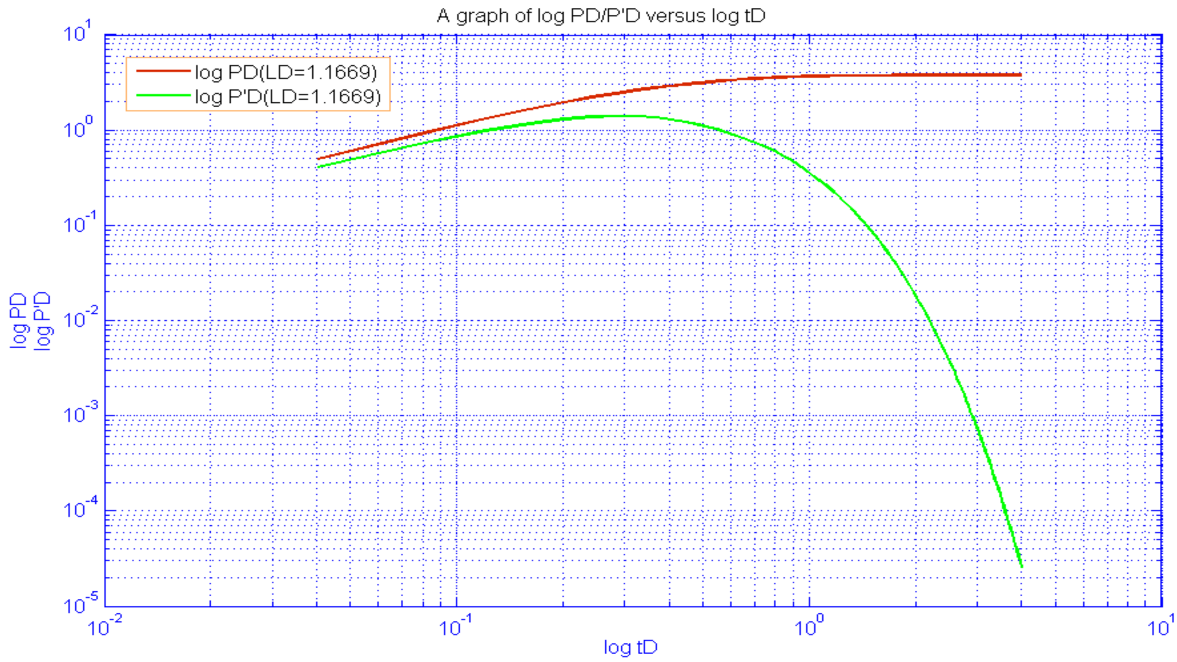

Figure 2. Log – log plot of dimensionless pressure and derivative for $L_D = 1.1669$

Table III. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime ($h_D = 0.3916$).

	$L_D = 2.3338$, $x_D = 0.5$, $y_{eD} = 0.8757$								
t_D	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
P_D	0	1.5763	2.0365	2.1709	2.2102	2.2216	2.2250	2.2259	2.2262
P_D'	0	0.8003	0.4674	0.2047	0.0797	0.0291	0.0102	3.47E-3	1.16E-3

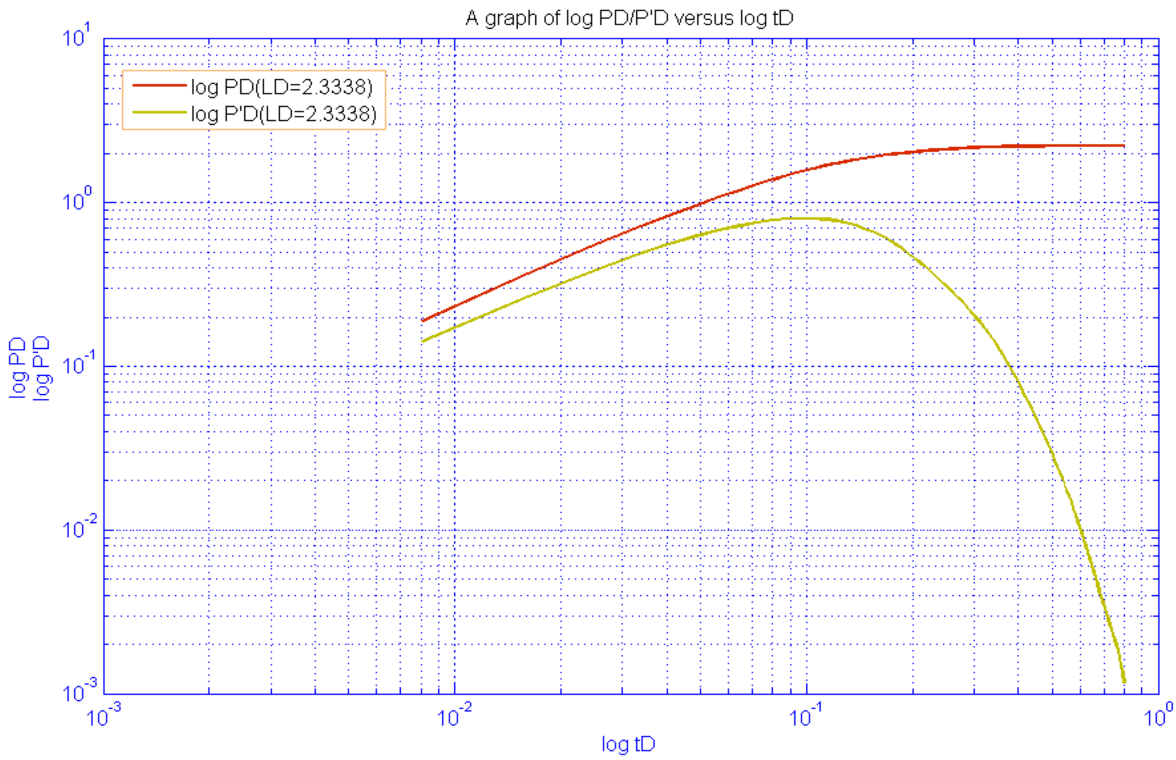

Figure 3. Log – log plot of dimensionless pressure and derivative for $L_D = 2.3338$

Table IV. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.2611$).

	$L_D = 3.5006$, $x_D = 0.5$, $y_{eD} = 0.5838$								
t_D	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
P_D	0	1.7118	1.9193	1.9444	1.9474	1.9478	1.9479	1.9479	1.9479
P_D'	0	0.4982	0.1207	0.0219	3.55E-3	5.37E-4	7.81E-5	1.10E-5	1.53E-6

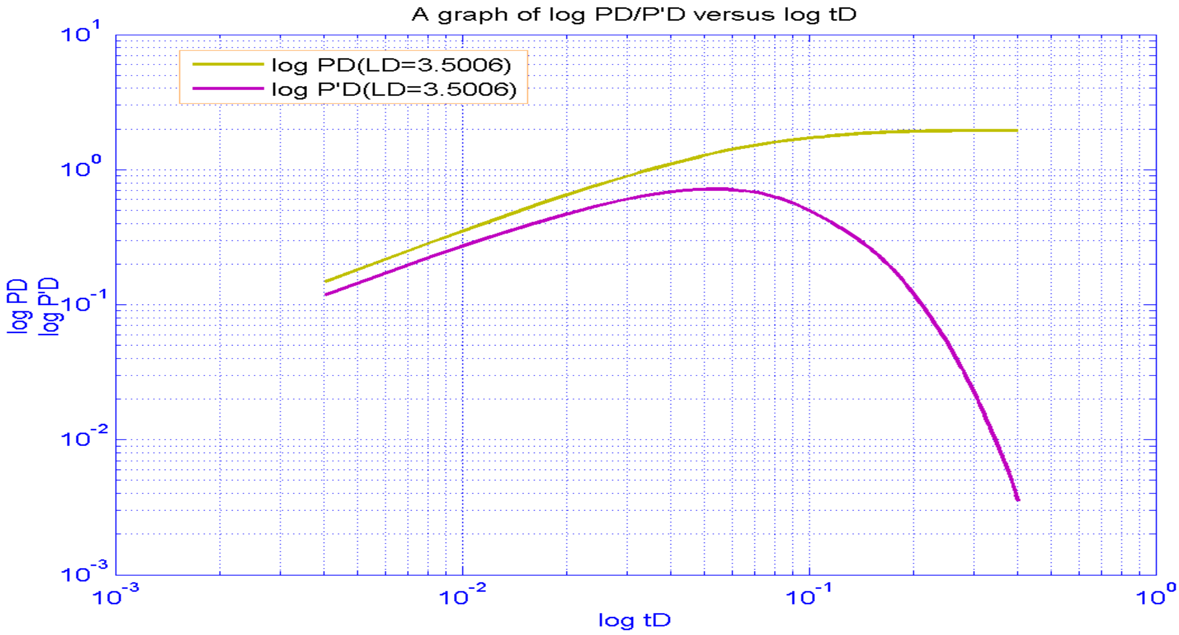

Figure 4. Log – log plot of dimensionless pressure and derivative for $L_D = 3.5006$

Table V. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.1958$).

	$L_D = 4.6675$, $x_D = 0.5$, $y_{eD} = 0.4378$								
t_D	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
P_D	0	2.0106	2.1751	2.1886	2.1897	2.1898	2.1898	2.1898	2.1898
P_D'	0	0.4484	0.0734	9.00E-3	9.82E-4	1.00E-4	9.86E-6	9.41E-7	8.79E-8

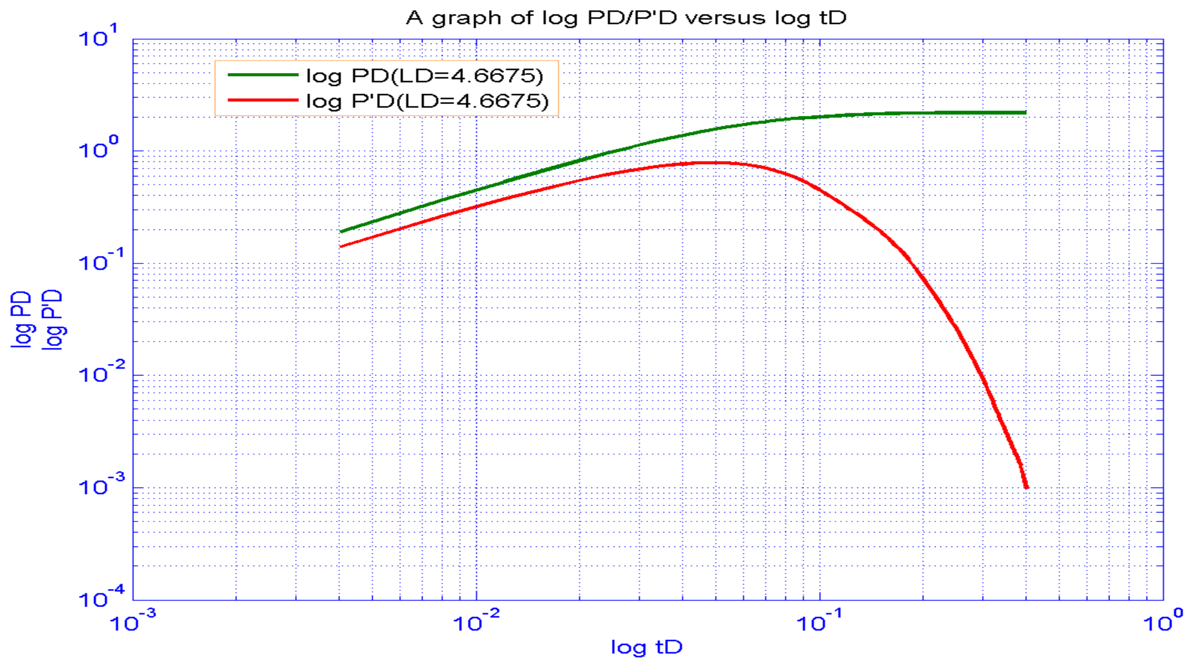

Figure 5. Log – log plot of dimensionless pressure and derivative for $L_D = 4.6675$

Table VI. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.1566$).

	$L_D = 5.8344$, $x_D = 0.5$, $y_{eD} = 0.3503$								
t_D	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
P_D	0	2.8297	3.1644	3.2040	3.2087	3.2092	3.2093	3.2093	3.2093
P_D'	0	0.8103	0.1917	0.0340	5.36E-3	7.93E-4	1.12E-4	1.55E-5	2.10E-6

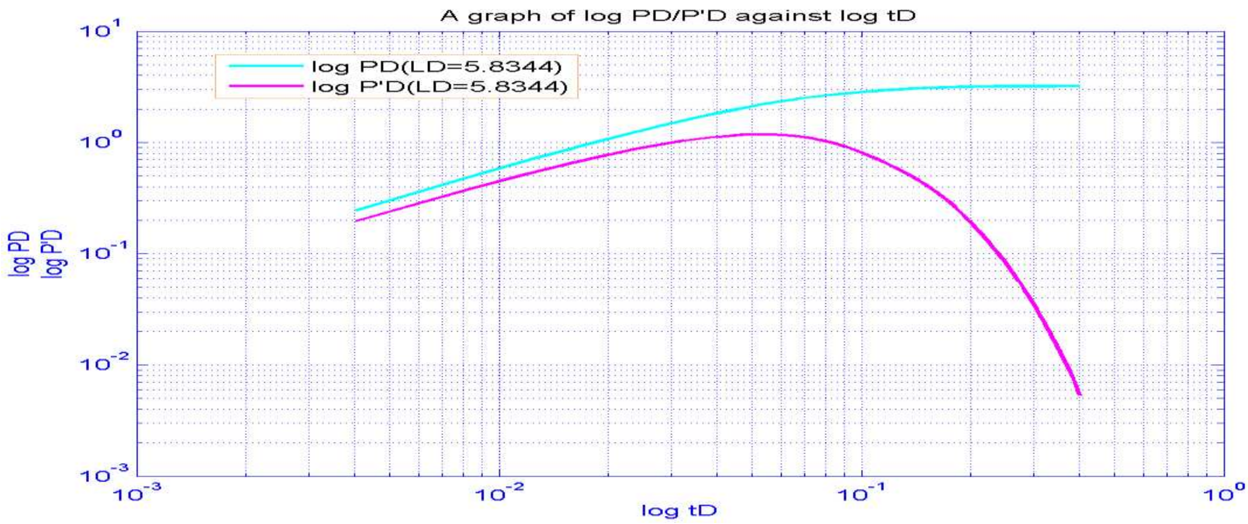

Figure 6. Log – log plot of dimensionless pressure and derivative for $L_D = 5.8344$

Table VII. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.1305$).

	$L_D = 7.0013$, $x_D = 0.5$, $y_{eD} = 0.2919$								
t_D	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
P_D	0	4.8936	6.4492	6.9437	7.1009	7.1509	7.1667	7.1718	7.1734
P_D'	0	2.6137	1.6617	0.7924	0.3358	0.1334	0.0509	0.0189	6.86E-3

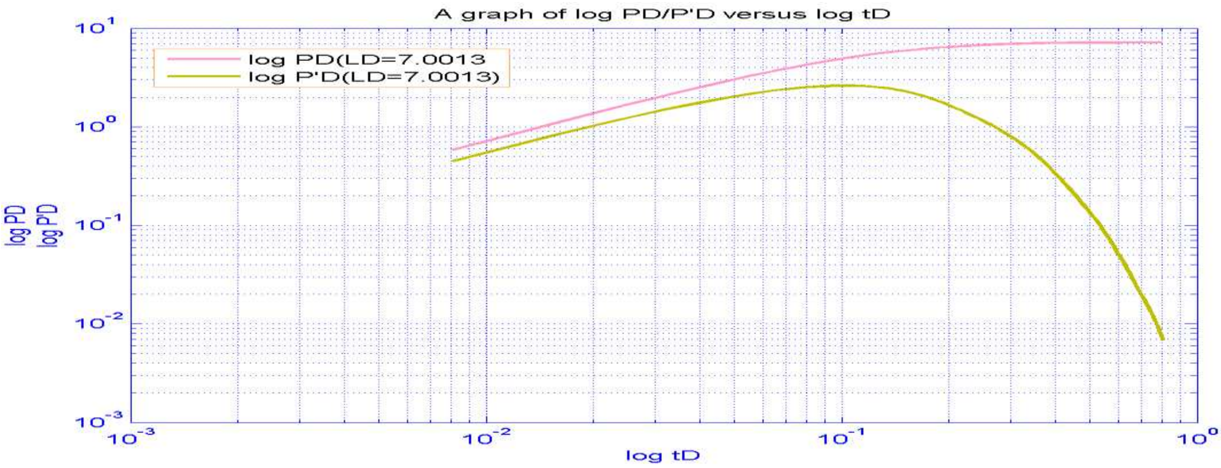

Figure 7. Log – log plot of dimensionless pressure and derivative for $L_D = 7.0013$

Table VIII. Dimensionless pressure and dimensionless pressure derivative as a function of dimensionless time during late time flow regime, ($h_D = 0.1119$).

	$L_D = 8.1681$, $x_D = 0.5$, $y_{eD} = 0.2502$								
t_D	0	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00
P_D	0	29.639	39.965	43.562	44.815	45.252	45.404	45.457	45.475
$P_D^{'}$	0	16.709	11.642	6.0841	2.8262	1.2307	0.5145	0.2091	0.0833

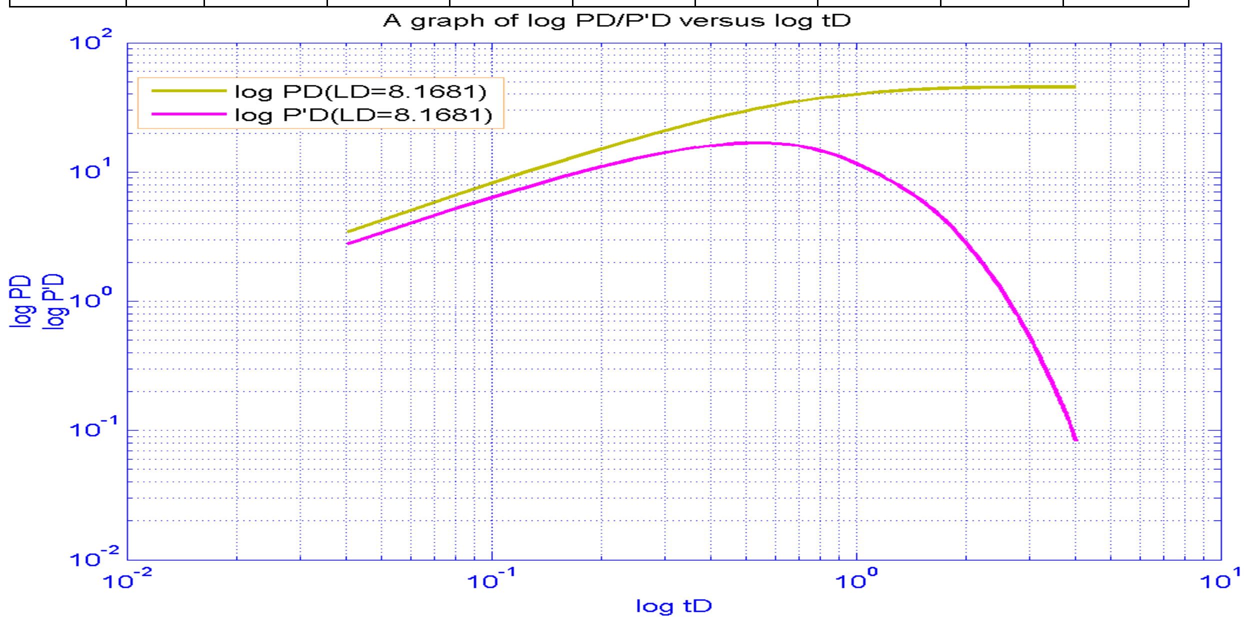

Figure 8. Log – log plot of dimensionless pressure and derivative for $L_D = 8.1681$

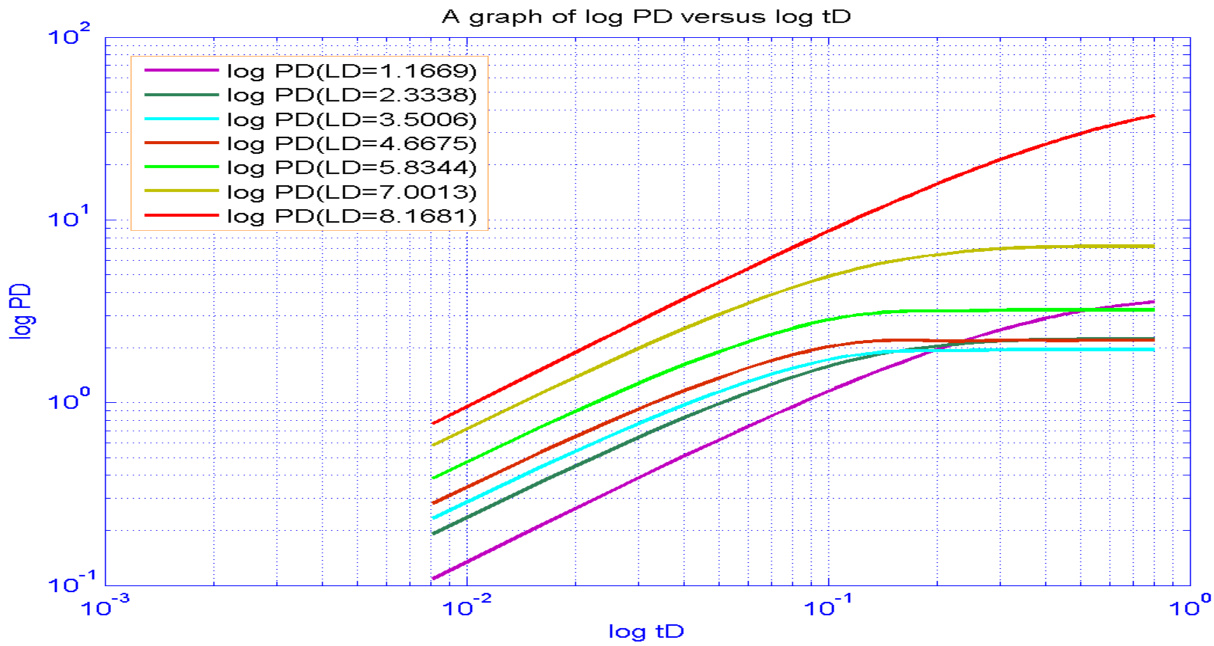

Figure 9. Log – log plot of dimensionless pressure for varying dimensionless well length, L_D

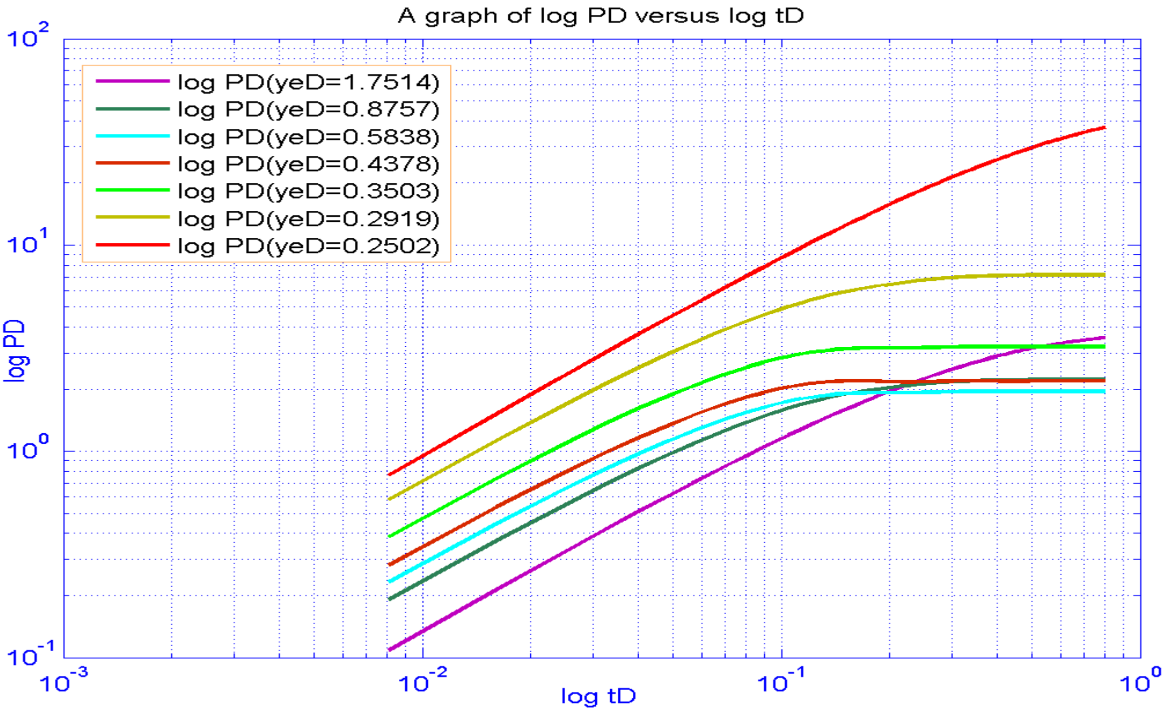

Figure 10. Log – log plot of dimensionless pressure for varying dimensionless reservoir width, y_{eD}

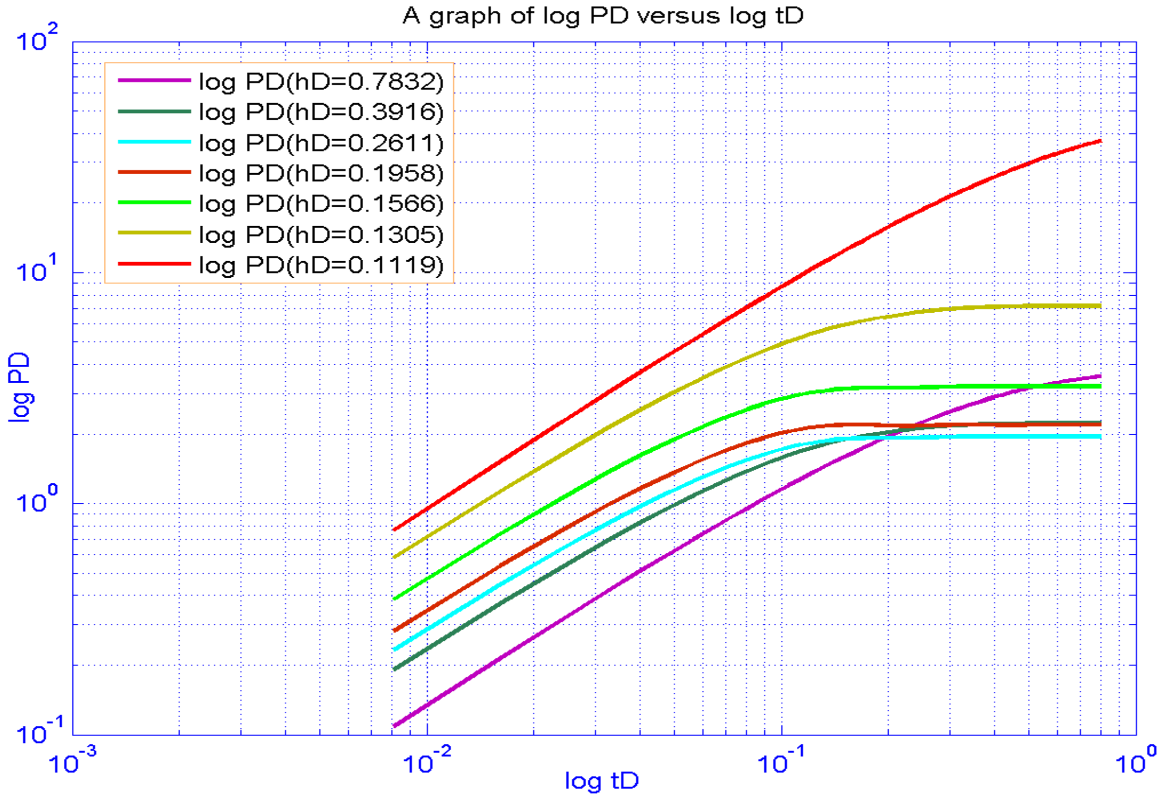

Figure 11. Log – log plot of dimensionless pressure for varying dimensionless pay thickness, h_D

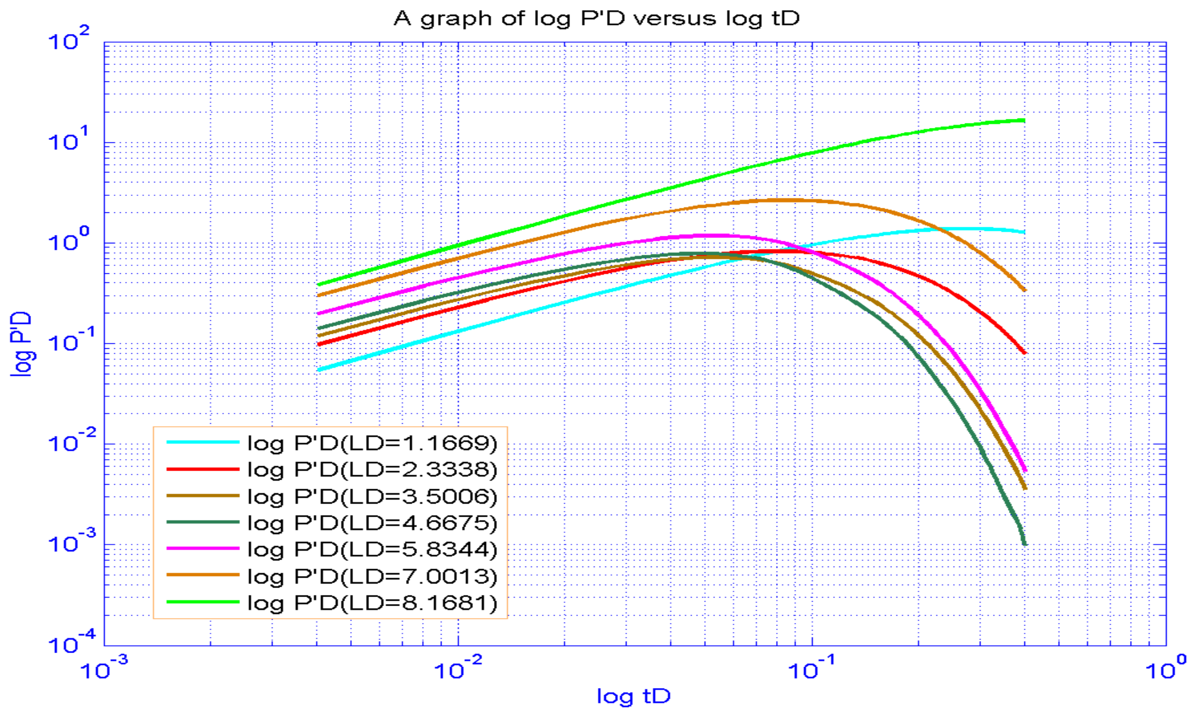

Figure 12. Log – log plot of dimensionless pressure derivative for varying dimensionless well length, L_D

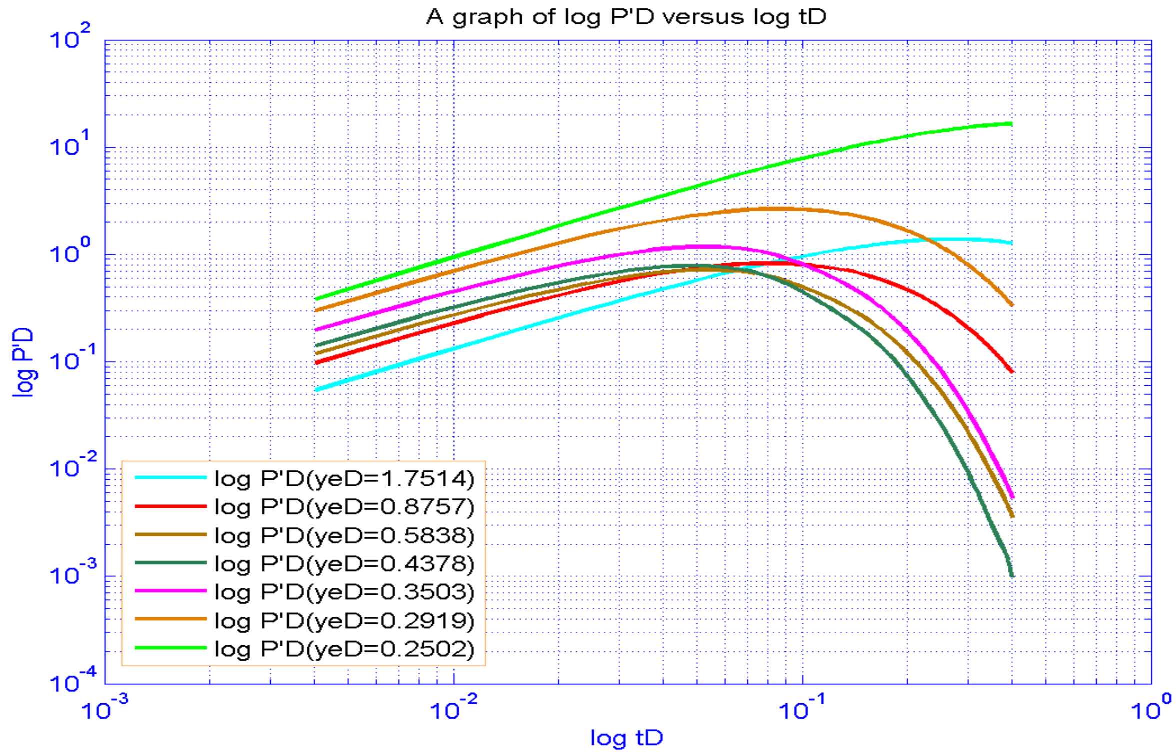

Figure 13. Log – log plot of dimensionless pressure derivative for varying dimensionless reservoir width, y_{eD}

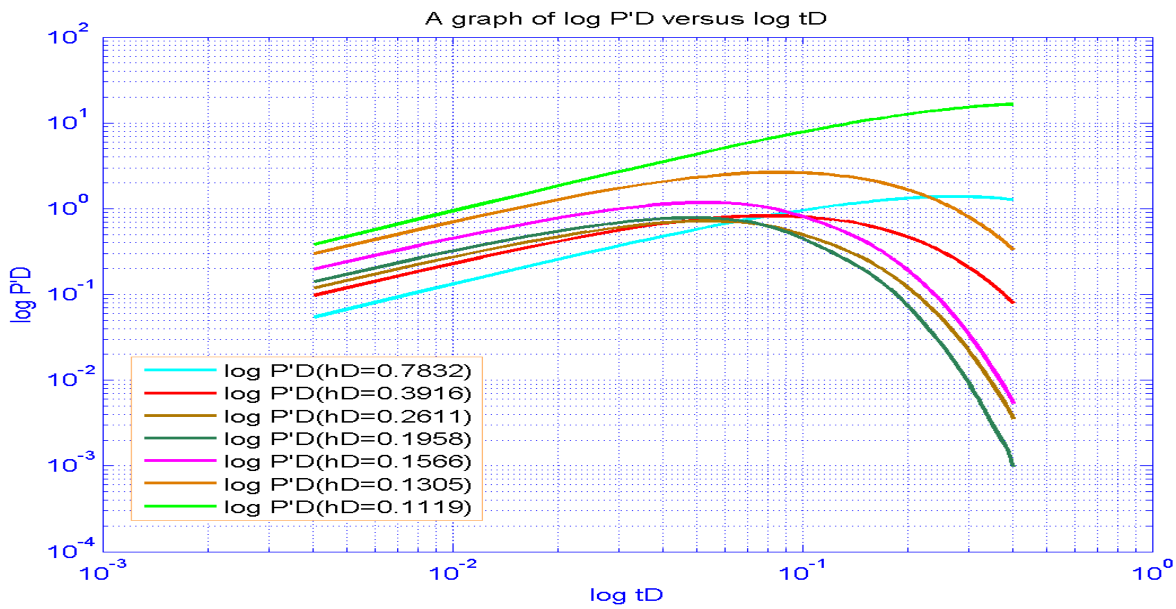

Figure 14. Log – log plot of dimensionless pressure derivative for varying dimensionless pay thickness, h_D

V. Results And Discussions

Table I shows the computed dimensionless parameters of reservoir, wellbore and fluid data. All the parameters are computed at $x_D = 0.5$, the dimensionless reservoir width, y_{eD} and dimensionless pay thickness, h_D varies inversely as dimensionless well length, L_D.

Table II-VIII shows how the dimensionless pressure and derivative varies with dimensionless time. Increase in dimensionless time produces a corresponding increase in dimensionless pressure derivative until a constant trend is exhibited. The dimensionless pressure derivative initially increases with increase in dimensionless time until a point where it declines to zero at corresponding dimensionless pressure constant.

The horizontal well is designed such that it is away from the edge water drive along the $x - axis$. From the analysis of this study, figure 2-8 demonstrates a log-log plot of dimensionless pressure and derivative as the dimensionless well length is varied from $L_D = 1.1669$to $L_D = 8.1681$. In all the figures, a similar trend is clearly seen, the dimensionless pressure derivative is at a declining rate as shown in figure 2-8

i.e. $\left(\frac{\partial P_D}{\partial t_D}\right)_i = f(x_D, y_D, z_D, t)$at i^{th} position hence the flow is characterized as unsteady state flow. Since the well test interpretation usually focuses on the transient pressure response, the wellbore conditions are seen early and later when the drainage area expands and the pressure response is characterized by reservoir propertied until the effects of the boundaries are seen at late time.

Figure 9 shows, the dimensionless pressure, P_D increases with increase in dimensionless well length, L_D. At large L_D, the pressure of the well is large consequently a higher oil production. Figure 10-11 shows the dimensionless reservoir width, y_{eD} and dimensionless pay thickness, h_D are inversely related to dimensionless pressure respectively.

From the reservoir data, the horizontal well is designed such that it is far from the bottom boundary owing the fact that the vertical permeability is greater than the horizontal permeability and eccentric along the reservoir width. This ensures that there is enhanced oil production during the time the well is put on production before the encroachment of the external fluid breakthrough. figure 12 show the dimensionless pressure derivative increases with increase in dimensionless well length while figure 13-14 show that the dimensionless reservoir width and the dimensionless pay thickness are inversely related to dimensionless pressure derivative respectively.

VI. Conclusions

Effects of fluid, wellbore and reservoir properties on dimensionless pressure and dimensionless pressure derivative have been studied. The following conclusion can be deduced from the study: -

a. Dimensionless pressure and its derivatives are inversely affected by the width of the reservoir and the pay thickness.
b. Increase in dimensionless well length prolongs the fluid breakthrough for all well completions.
c. The position of the well adversely affects the clean oil production.
d. Maximum oil production is achieved on a higher dimensionless well length.
e. When the dimensionless pressure exhibits constant trend, the dimensionless pressure derivative reduces to zero.
f. From the graphs, the flow is characterized by unsteady, pseudosteady and steady state flow regimes.

Competing interests

Authors have declared that no competing interests exists.

DIMENSIONLESS PARAMETERS

$$P_D = \frac{kh\Delta p}{141.2q\mu B}$$
$$t_D = \frac{4kt_i}{\phi\mu c_t L^2}$$
$$\eta_i = \frac{k_i}{\phi\mu c_t}$$
$$i_D = \frac{2i}{L}\sqrt{\frac{k}{k_i}}$$
$$i_{wD} = \frac{2i_w}{L}\sqrt{\frac{k}{k_i}}$$
$$i_{eD} = \frac{2i_e}{L}\sqrt{\frac{k}{k_i}}$$
$$h_D = \frac{2h}{L}\sqrt{\frac{k}{k_z}}$$
$$L_D = \frac{L}{2h}\sqrt{\frac{k}{k_x}}$$
$$h_D = \frac{1}{L_D}\sqrt{\frac{k^2}{k_x k_z}}$$
$$i = x, y, z$$

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NOMENCLATURES

B oil volumetric factor, rbbl/STB
cttotal compressibility, 1/psi
i axial flow directions x, y, or z
h formation thickness, ft
k average geometric permeability, md
k_i formation permeability in the i^{th} direction, md
L total length of horizontal well, ft.
L_D dimensionless well length
Δp pressure drop, psi
P_D dimensionless pressure

$P_D^{'}$ *dimensionless pressure derivative*
x_e *half the distance to the boundary in the* $x-$ *direction*
y_e *half the distance to the boundary in the* $y-$ *direction*
x_w *the X coordinate of the production point*
y_w *the Y coordinate of the production point*
z_w *the Z coordinate of the production point*
z_D *the dimensionless distance from the bottom of the reservoir to the centre 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*
q *flow rate, bbl/day*
s *source*
t *time, hours*
D *dimensionless*
e *external*
w *wellbore*

Greek symbols
� *reservoir fluid viscosity, cp*
ϕ *porosity, fraction*
τ *dummy variable of time*
η *Diffusivity constant, md-psi/cp*

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