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A COMPLEMENTARY CONVENTIONAL ANALYSIS FOR CHANNELIZED RESERVOIRS

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Many well pressure data coming from long and narrow reservoirs which result from either fluvial deposition of faulting cannot be completely interpreted by conventional analysis since some flow regimes are not conventionally recognized yet in the oil literature. This narrow geometry allows for the simultaneous development of two linear flow regimes coming from each one of the lateral sides of the system towards the well. This has been called dual linear flow regime. If the well is off-centered with regards to the two lateral boundaries, then, one of the linear flow regimes vanishes and, then, two possibilities can be presented. Firstly, if the closer lateral boundary is close to flow the unique linear flow persists along the longer lateral boundary. It has been called single linear flow. Following this, either steady or pseudosteady states will develop. Secondly, if a constant-pressure closer lateral boundary is dealt with, then parabolic flow develops along the longer lateral boundary. Steady state has to be developed once the disturbance reaches the farther boundary.

This study presents new equations for conventional analysis for the dual linear, linear and parabolic flow regimes recently introduced to the oil literature. The equations were validated by applying them to field and simulated examples.

Keywords: *reservoir, linear flow, radial flow, parabolic flow.*

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Muchos datos de presión procedentes de yacimientos alargados y angostos, resultado de depósitos fluviales o callamiento, no pueden interpretarse por métodos convencionales puesto que existen algunos regímenes de flujo desconocidos en la literatura referente al método convencional. Esta geometría estrecha del yacimiento permite el desarrollo simultáneo de dos regimenes de flujo lineales, actuando a ambos lados alargados del yacimiento y dirigiéndose al pozo. Éste ha sido llamado flujo dual lineal. Cuando el pozo está descentrado con respecto a una de las dos fronteras laterales, uno de los flujos lineales desaparece y pueden presentarse dos posibilidades: primero, si la frontera más cercana es cerrada, un único flujo lineal persiste a lo largo de la prueba. Éste ha sido llamado flujo lineal único. Después de éste, se desarrollará el estado pseudoestable o estable. Segundo, si la frontera cercana es de presión constante, entonces se desarrolla el flujo parabólico hacia el lado más largo del yacimiento. El estado estable deberá desarrollarse, una vez la perturbación haya alcanzado la frontera más lejana .

Este estudio presenta ecuaciones nuevas para análisis convencional para los regímenes de flujo dual lineal, lineal único y parabólico recientemente introducidos a la literatura petrolera. Las ecuaciones fueron validadas mediante su aplicación a ejemplos simulados y de campo.

Palabras clave: *yacimientos, flujo lineal, flujo radial, flujo parabólico.*

NOMENCLATURE

B	Oil formation factor, bbl/STB
b	Intercept of a cartesian plot
c_t	Compressibility, 1/psi
b_x	Well position along the x-direction, ft
b_y	Well position along the y-direction, ft
h	Formation thickness, ft
k	Permeability, md
m	Slope
N.C.	Not calculated
P	Pressure, psi
P_{wf}	Well-flowing pressure, psi
P_{ws}	Static well pressure, psi
P_i	Initial reservoir pressure, psia
q	Flow rate, BPD
r_w	Well radius, ft
s	Skin factor
s_r	Mechanical skin factor obtained from radial flow
t	Time, hrs
X_E	Reservoir length, ft
Y_E	Reservoir width, ft
X_D	Dimensionless reservoir length
Y_D	Dimensionless reservoir width
W_D	Dimensionless reservoir width

GREEK

Δ	Change, drop
ϕ	Porosity, fraction
μ	Viscosity, cp

SUBINDEXES

1hr	One hour
assum	Assumed
calc	Calculated
D	Dimensionless
DA	Dimensionless with respect to area
DL	Dual-linear
i	Intersection or initial conditions
L	Linear
PB	Parabolic
r	radial flow
t	total
w	Well

S.I. METRIC CONVERSION FACTORS

Bbl x 0,1589873	= m^3
cp x 0,001	= Pa·s
ft x 0,3048	= m
ft^2 x 0,09290304	= m^2
psi x 6,894 757	= KPa

INTRODUCTION

Very few researchers have focused their attention on long and narrow systems such as channel sands (Figure 1.a). Among them, we can name Ehlig-Economides and Economides (1985), Massonet, Norris, and Chalmette (1993), Mattar (1997), Nutakki and Mattar (1982) and Wong, Mothersele, Harrington, and Cinco-Ley (1986). A better description of channelized systems and a detailed interpretation technique was presented by Escobar, Saavedra, Hernández, C.M., Hernández, Y.A., Pilataxi, and Pinto (2004) who classified the linear flow regime into two closely related names: "*dual linear flow*" and "*single linear flow*" regimes as sketched in Figure 1.b. When the well is off-centered with respect to the lateral sides, firstly, we observe two linear flow regimes coming from both lateral sides of the well. They called this "*dual linear flow*". Once the close-to-flow closer boundary is reached by the transient wave, a unique linear flow remains throughout the longer lateral boundary. Single linear flow can also be present when the well is located very close to one lateral boundary as shown in Figure 1.c. Escobar *et al*. (2004) called this "*single linear flow*" or simply, "*linear flow*". However, if the closer boundary is at constant pressure, then "*parabolic flow*" develops and steady state follows this flow regime. The parabolic flow is recognized on the pressure derivative curve by a negative 0,5-slope straight line. The reader is referred to Escobar, Muñoz, Sepúlveda, Montealegre, and Hernández (2005a) and Escobar, Muñoz, Sepúlveda, J.A., and Montealegre (2005b) for a detailed explanation of the parabolic flow regime.

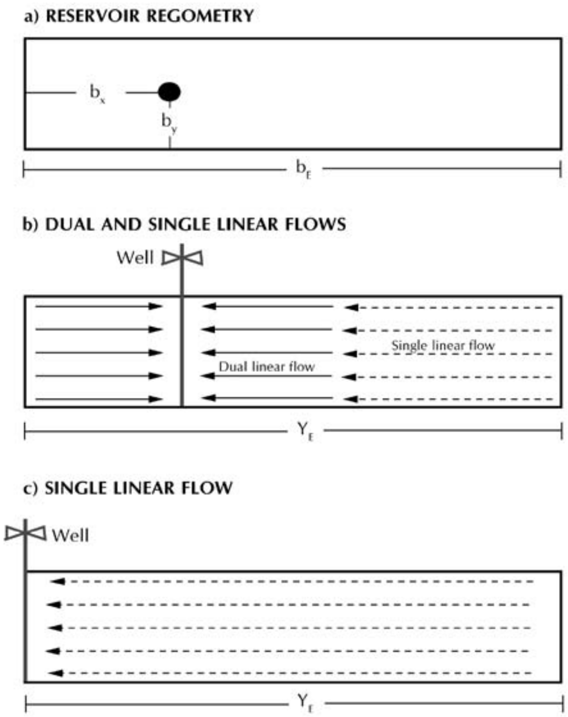

Figure 1. Linear flow regime configuration

MATHEMATICAL FORMULATION

The dimensionless time quantities used by Escobar *et al*. (2004) were:

$$t_D = \frac{0,0002637kt}{\phi\mu c_t r_w^2} \tag{1}$$

$$t_{DA} = \frac{0,0002637kt}{\phi\mu c_t A} \tag{2}$$

$$t_{D_L} = \frac{t_D}{W_D^2} \tag{3}$$

Dimensionless reservoir width and well position, as sketched in Figure 1.a, Escobar *et al*. (2004), are:

$$W_D = \frac{Y_E}{r_w} \tag{4}$$

$$X_D = \frac{2b_x}{X_E} \tag{5}$$

$$Y_D = \frac{2b_y}{Y_E} \tag{6}$$

Dimensionless pressure is defined by Earlougher (1977) as:

$$P_D = \frac{kh}{141,2q\mu B}\Delta P \tag{7}$$

Nutakki and Mattar (1982) presented an equation for the linear flow, as follows:

$$P_D = \sqrt{\pi t_{DL}} + s_L = \frac{\sqrt{\pi t_D}}{W_D} + s_L \tag{8}$$

Escobar *et al*. (2004) and Escobar, Hernández, Y.A., and Hernández, C.M. (2007) have described the differences between the dual linear flow and the single linear flow occurring in elongated systems. Escobar *et al*. (2004) found out that *Equation 8* was mistaken, so they proposed a new equation to describe dual linear, and single linear as well, flow regimes, such as:

$$P_{D_{DL}} = 2\sqrt{\pi t_{DL}} + s_{DL} = \frac{2\sqrt{\pi t_D}}{W_D} + s_{DL} \tag{9}$$

$$P_{D_L} = 2\pi\sqrt{t_{DL}} + s_L = \frac{2\pi\sqrt{t_D}}{W_D} + s_L \tag{10}$$

Dual linear flow analysis

As depicted in Figure 1.b, this type of flow is formed by to linear flows occurring from each lateral side of the reservoir towards the well, so that they have an opposite direction to each other.

Replacing *Equations 1* through *Equation 7*, into *Equation 9* will yield:

$$\Delta P = \frac{8,1282}{Y_E}\frac{qB}{kh}\left(\frac{\mu}{\phi c_t k}\right)^{0,5}\sqrt{t} + \frac{141,2q\mu B}{kh}s_{DL} \tag{11.a}$$

For pressure buildup analysis, application of time superposition is required, therefore *Equation 9* becomes:

$$\Delta P = \frac{8,1282}{Y_E}\frac{qB}{kh}\left(\frac{\mu}{\phi c_t k}\right)^{0,5}\left(\sqrt{t_p + \Delta t} - \sqrt{\Delta t}\right) \tag{11.b}$$

Which implies that a cartesian plot of ΔP vs. either $\sqrt{t}$ or $\left(\sqrt{t_p+\Delta t}-\sqrt{\Delta t}\right)$ will yield a straight line during dual linear flow behavior which slope, m_{DLF}, and intercept, b_{DLF}, are used to obtain reservoir width, Y_E, and dual linear skin factor, s_{DL}.

$$Y_E = 8{,}1282\frac{qB}{m_{DLF}h}\left[\frac{\mu}{k\phi c_t}\right]^{0{,}5} \tag{12}$$

$$s_{DL} = \frac{khb_{DLF}}{141{,}2q\mu B} \tag{13}$$

Notice that *Equation 13* is different to *Equation 14* presented by Wong *et al*. (1986). However, our mathematical model agrees with those presented by Nutakki and Mattar (1982) and Ehlig-Economides and Economides (1985).

$$s_{DL} = \frac{1}{2}\left[\frac{khb_{lf}}{141{,}2q\mu B}+\ln\left(\frac{r_w}{Y_E}\right)\right] \tag{14}$$

Single linear flow analysis

Regarding Figure 1.b, once the pressure disturbance reaches the first lateral boundary, one of the linear flow no longer exists, then a unique linear flow prevails which is called single linear flow regime. This flow also can take place when the well is very close to one of the lateral boundaries as sketched in Figure 1.c.

Replacement of *Equation 1* through *Equation 7* into *Equation 10* will yield:

$$\Delta P_{wf} = \frac{14{,}407}{Y_E}\frac{q\mu B}{kh}\sqrt{\frac{kt}{\phi\mu c_t}}+\frac{141{,}2q\mu B}{kh}s_L \tag{15.a}$$

For pressure buildup analisis:

$$\Delta P_{ws} = \frac{14{,}407}{Y_E}\frac{q\mu B}{kh}\sqrt{\frac{k}{\phi\mu c_t}}\left(\sqrt{t_p+\Delta t}-\sqrt{\Delta t}\right) \tag{15.b}$$

Equation 15.a and *Equation 15.b* indicates that a plot of ΔP vs. either $\sqrt{t}$ or $\left(\sqrt{t_p+\Delta t}-\sqrt{\Delta t}\right)$ in cartesian coordinates will yield a straight line during linear flow behavior which slope, m_{LF}, and intercept, b_{LF}, are used to obtain reservoir width, Y_E, and linear skin factor, s_L, respectively:

$$Y_E = \frac{14{,}407}{m_{LF}}\frac{qB}{h}\left(\frac{\mu}{\phi c_t k}\right)^{0{,}5} \tag{16}$$

$$s_L = \frac{khb_{LF}}{141{,}2q\mu B} \tag{17}$$

The total skin factor will then be:

$$s_t = s_r + s_{DL} + s_L \tag{18}$$

Parabolic flow analysis

The reader is referred to Escobar *et al*. (2005) for a better description of this type of flow. Escobar *et al*. (2004), Escobar *et al*. (2005a) and Escobar *et al*. (2005b) introduced the governing equation for pressure behavior dominated by parabolic flow, as follows:

$$P_D = -(W_D)(X_D)^2\left(\frac{X_E}{Y_E}\right)^2 t_D^{-0{,}5} + s_{PB} \tag{19}$$

Replacing of *Equation 1* through *Equation 7* into *Equation 18* will yield:

$$\Delta P_{wf} = -\frac{34780{,}8qBb_x^2\sqrt{\phi c_t}}{hY_E}\left(\frac{\mu}{k}\right)^{1{,}5}\frac{1}{\sqrt{t}}+\frac{141{,}2q\mu B}{kh}s_{PB} \tag{20.a}$$

For buildup analysis, superposition is required; then, the pressure equation is:

$$\Delta P_{ws} = -\frac{34780{,}8qBb_x^2\sqrt{\phi c_t}}{hY_E}\left(\frac{\mu}{k}\right)^{1{,}5}\left(\frac{1}{\sqrt{t_p+\Delta t}}-\frac{1}{\sqrt{\Delta t}}\right) \tag{20.b}$$

A cartesian plot of ΔP vs. either $1/\sqrt{t}$ or $\left(1/\sqrt{t_p+\Delta t}-1/\sqrt{\Delta t}\right)$ will yield a straight line during the parabolic dominated region which slope, m_{PB}, and intercept, b_{PB}, are used to obtain well position, b_x, and parabolic skin factor, s_{PB}, respectively, as:

$$b_x = \sqrt{-\frac{m_{PB}hY_E}{34780{,}8qB\sqrt{\phi c_t}}\left(\frac{k}{\mu}\right)^{1{,}5}} \tag{21}$$

$$s_{PB} = \frac{kh}{141{,}2q\mu B} b_{PB} \tag{22}$$

The total skin factor will be:

$$s_t = s_r + s_{DL} + s_{PB} \tag{23}$$

Sui, Mou, Bi, Den, and Ehlig-Economides (2007) have also found the behavior depicted by a negative half-slope once linear flow regime has vanished in elongated reservoirs. However, they called it "dipolar flow".

NUMERICAL EXAMPLES

Simulated example

The synthetic pressure drawdown reported in Figure 2 was performed for a well inside a rectangular reservoir using the data given in the second column of Table 1.

The slope and intercept (m_{DLF} = 1077 psi/h^{0,5}, b_{DLF} = 2792 psi) obtained from Figure 3 were applied into *Equations 12* and *Equation13* to yield an estimation of Y_E = 249,6 ft and s_{DL} = 4,9, respectively. Also, from Figure 4 values of m_{LF} = 1968,4 psi/h^{0,5} and b_{DLF} = 4921 psi were read to be applied into *Equation 16* to estimate a Y_E value of 242 ft and *Equation 18* was used to estimate a s_L of -8,6. A summary of the results are given in Table 2. We observe a very good agreement between the calculated and the input Y_E value.

Field example

Escobar *et al*. (2004) presented an example of a pressure drawdown test run in a well in a channelized reservoir in the Eastern Planes basin in Colombia. Reservoir and well parameters are given in the third

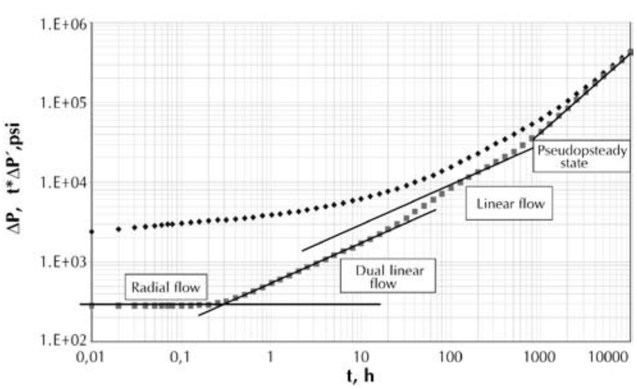

Figure 2. Pressure and pressure derivative for simulated example

Table 1. Reservoir, well and fluid parameters

	SIMULATED EXAMPLE	FIELD EXAMPLE
Parameter	Value	
μ, cp	3	3,5
B, rb/STB	1,35	1,07
c_t, 1/psi	,.5E-6	9E-6
ø, %	20	24
r_w, ft	0,4	0,51
k, md	100	Not given
h, ft	30	14
q, BPD	3000	1400
X_E, ft	6000	Not given
Y_E, ft	250	Not given
b_x, ft	1000	Not given
P_i, psi		1326,28

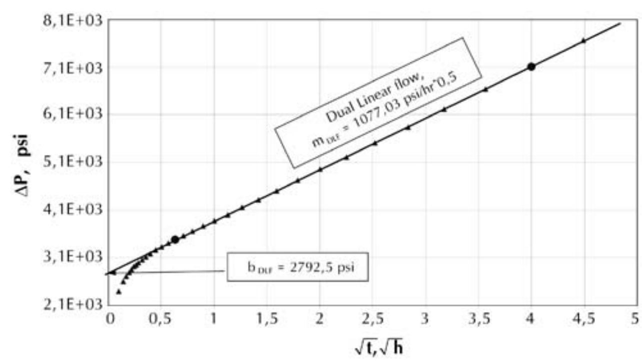

Figure 3. Pressure change vs. square root of time for the simulated example during dual linear flow regime

Table 2. Summary of results for the simulated example

PARAMETER	SIMULATED	THIS WORK
Y_E, from dual linear flow, ft	250	249,6
Y_E, from linear flow, ft		242,03
s_{DL}	Not given*	4,9
s_L	Not given*	-8,6

* Simulator uses the image method (superposition) then neither linear nor dual linear skins are used.

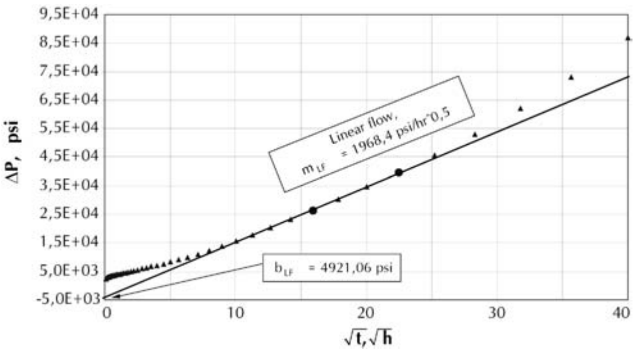

Figure 4. Pressure change vs. square root of time for the simulated example during single linear flow regime

column of Table 1 and pressure and pressure derivative data are given in Figure 5.

As shown in Figure 5, radial, dual linear, parabolic flows and steady state are observed. Escobar *et al*. (2004) reported a permeability of 441 md and a mechanical skin factor of -4,9 determined using the TDS technique, Tiab (1993). As shown in Figure 6, the semilog slope is found to be 140 psi/cycle and P_{1h} = 1158 psi. The conventional equation to estimate the mechanical skin factor is given by Earlougher (1977):

$$s_r = 1{,}1513\left[\frac{P_{1h} - P_i}{m} - \log\left(\frac{k}{\phi\mu c_t r_w^2}\right) - 3{,}23\right] \tag{24}$$

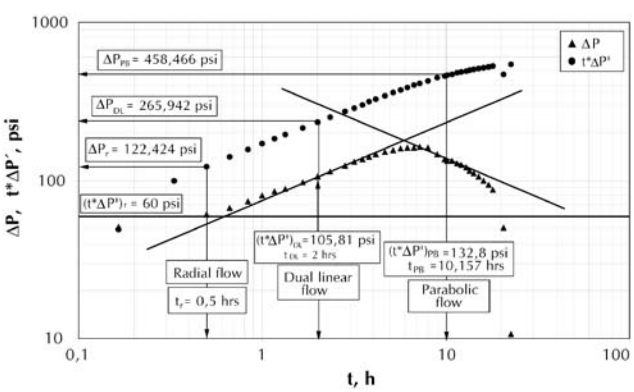

Figure 5. Pressure and pressure derivative for field example

Using *Equation 24* the mechanical skin factor, s, is -4,6. From Figure 7, the slope during dual linear flow regime was 150,82 psi/h^{0,5} and an intercept value of 19,4 psi was also determined. A reservoir width, Y_E of 350 ft was determined using *Equation 12*. The dual linear skin factor, s_{DL}, estimated with *Equation 13* was 0,17.

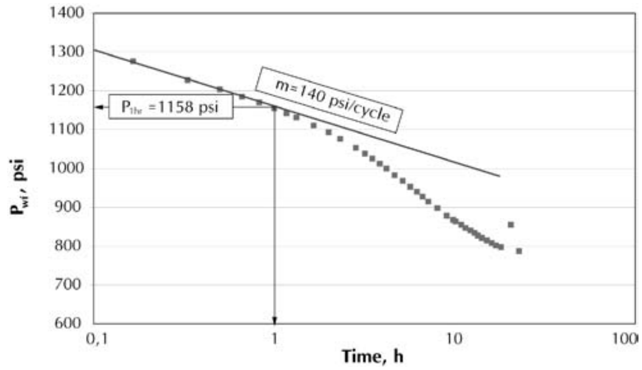

Figure 6. Semilog plot of well-flowing pressure vs. time for the field example

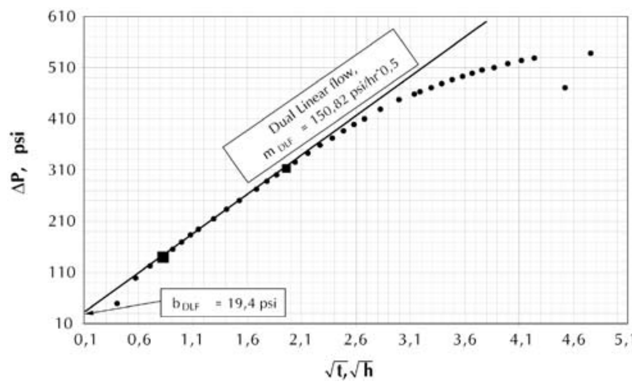

Figure 7. Pressure change vs. square root of time for the field example during dual linear flow regime

From Figure 8, the slope during parabolic flow was determined to be -851,6 psi*h^{0,5} and the intercept was 731 psi. The well position along the x-direction, b_x, was estimated with *Equation 21* to be 277 ft and the parabolic skin factor found from *Equation 22* was 6,1. The following results were obtained by simulation using a commercial and well-known well test interpretation software:

k = 416 md

s = -5,1

Well distance to the north = 85 ft

Well distance to the constant-pressure

Table 3. Summary of results for the field example

PARAMETER	COMMERCIAL SOFTWARE	THIS STUDY	ESCOBAR *et al*. (2004)
Y_E, from dual linear flow, ft	506	350	532 and 368
b_x, from parabolic flow, ft	279	277,4	284, 186, and 284
X_E, from dual linear flow, ft	621	N.C.	628, 637 and 637
s	-5,1	-4,6	-4,9
s_{DL}	N.C.	0,2	0,4
s_{PB}	N.C.	6,1	6,1
s_t	N.C.	1,7	1,6

boundary = 278 ft

Well distance to the no-flow boundary = 343 ft

Well distance to the south = 421 ft

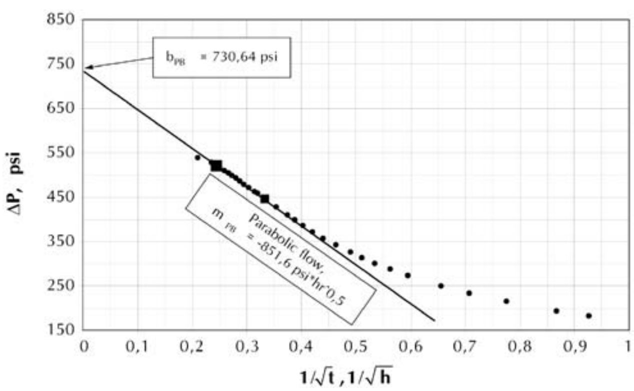

Figure 8. Pressure change vs. the inverse of the square root of time for the field example during dual parabolic flow regime

From the above data $Y_E = 85 + 421 = 506$ ft, $b_x = 2785$ ft and $X_E = 279 + 343 = 621$ ft. Escobar *et al*. (2004) did not report the parabolic skin factor, however, it will be estimated using their *Equation 9*, as follows:

$$s_{PB} = \left(\frac{\Delta P_{PB}}{(t * \Delta P')_{PB}} + 2 \right) \left(\frac{123{,}16 b_x^2}{Y_E} \right) \sqrt{\frac{\phi \mu c_t}{k t_{PB}}} \quad (25)$$

The following information was read from the pressure and pressure derivative plot shown in Figure 4:

t_{PB} = 10,157 h

$(t^*\Delta P')_{PB}$ = 132,873 psi

ΔP_{PB} = 458,466 psi

Using b_x = 277, k = 441 md and Y_E = 350 ft a s_{PB} = 6,1 was calculated from *Equation 25*. Table 3 summarizes the results for this example. Notice there that the only unmatched value is reservoir witdh obtained from simulation. The remaining estimations are in close agreement. Needless to say, how well the estimated total skin factor agrees with the one obtained from the *TDS* technique.

ANALYSIS OF RESULTS

As expected, reliable results (Table 3) were obtained from the application of the developed set of equations to the worked examples. For the numerical example we observe that the reservoir width value, Y_E, obtained from *Equation 12* agrees almost perfectly with the value used to run the simulation. The value of reservoir width from *Equation 16* has a relative small error of 3,2 % compared to the original value. We can state that there is a good agreement between the two values. No discussion can be established regarding the kin factor since there is no point of comparison; commercial simulators use space superposition to generate the pressure curves.

As far as the field problem is concerned, we observe a good matching between the values obtained from the equations presented in this study and those results obtained from both TDS technique and commercial software. See Table 3. The value of reservoir width obtained from numerical simulation (commercial software) does not agree well with the results of this study. However, the matching of the simulated and field data were not the best, therefore, the difference may be due to it.

CONCLUSIONS

- New relationships to characterize the single linear flow regime for the conventional method of well test interpretation have been presented for estimation of reservoir width and linear skin factor. Also, equations for conventional analysis during parabolic flow regime for the determination of the well position along the x-direction and the parabolic skin factor are presented. The equations were tested and verified by their application to numerical examples and compared to results obtained from simulation and the *TDS* technique.

- Since most of simulators use superposition (the image method) for estimating the pressure behavior of a well inside a rectangular system, they do not estimate neither linear, nor dual, nor parabolic skin factors, therefore, comparison of those parameters was referred to the *TDS* technique.

- Even though, the traditional conventional analysis is a very powerful and respected tool, the *TDS* technique can provide, in a much more practical way, more parameters from the same test.

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