PRESSURE AND PRESSURE DERIVATIVE ANALYSIS FOR ASYMMETRY FINITE-CONDUCTIVITY FRACTURED VERTICAL WELLS

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ABSTRACT

Many researchers have developed equations to characterize hydraulic fractures assuming they are symmetrical with respect to the well, since symmetrical fractures are less likely to occur. Therefore, since there is no direct analytical methodology that allows an adequate interpretation using the pressure derivative function to determine the fracture asymmetry, the position of the well with respect to the fracture, fracture conductivity and half-fracture length. For this reason, the *TDS* methodology that uses characteristic lines and points found in the pressure and derivative log-log graphs is presented here to develop analytical equations used to determine in a simple, practical and exact way the aforementioned parameters. The technique was satisfactorily verified with synthetic problems.

Keywords: Fracture Conductivity, Transient Pressure Analysis, TDS Technique, Fractured Wells.

ANALISIS DE PRESIÓN Y DERIVADA DE PRESIÓN PARA POZOS FRACTURADOS ASIMÉTRICAMENTE CON FRACTURA DE CONDUCTIVIDAD FINITA

RESUMEN

Muchos investigadores han desarrollado ecuaciones para caracterizar fracturas hidráulicas asumiendo que éstas son simétricas con respecto al pozo puesto que las fracturas simétricas son menos probable que ocurran. Por lo tanto, puesto que no existe una metodología analítica directa que permita una adecuada interpretación utilizando la derivada de presión para determinar la asimetría de la fractura, la posición del pozo con respecto a la fractura, la conductividad de fractura y la longitud media de la misma. Por ello, aquí se presenta la metodología *TDS* que utiliza líneas y puntos característicos hallados en los gráficos log-log de presión y derivada para desarrollar ecuaciones analíticas usadas para determinar en forma simple, práctica y exacta los parámetros anteriormente mencionados. La técnica se verificó satisfactoriamente con problemas sintéticos.

Palabras clave: Conductividad de fractura, análisis de pruebas de presión, Técnica TDS, Pozos fracturados.

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INTRODUCTION

The first fractured wells began in 1860 and explosive materials such as nitroglycerin were used. Subsequently began to use acids, leaving aside such materials, and finally in 1947 is studied the possibility of using water and only until 1952 in the Soviet Union appears the first well fractured hydraulically. This technique makes it possible to increase the hydrocarbon extraction from reservoirs with low permeability, although lately it has been used in more permeable formations, and has been so important that in year 2015, approximately, 60% of the extraction wells in use used this technique.

Most of the published work on the behavior of the pressure transient in fractured wells considers that the fracture is symmetrical with respect to the axis of the well. However, it has been shown that this may be the less likely case in reality, hence the importance of studying the asymmetry of fractures in vertical wells and how this influences pressure behavior.

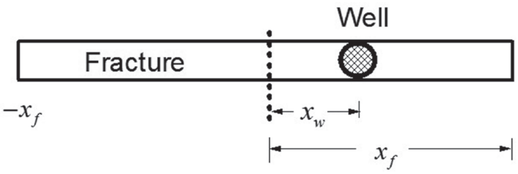
Cinco–Ley, Samaniego and Dominguez (1978) developed a mathematical model to study the behavior of the pressure transient in a fractured vertical well with finite conductivity. Also Narasimhan and Palen (1979) briefly discussed the influence of fracture asymmetry on the behavior of well pressure under a constant rate of production. Later, Bennet, Rosato, Reynolds and Raghavan (1983) studied this problem and defined the conditions under which the asymmetry would have a negligible influence on the well response. The problem was solved numerically in these studies. However, no practical means have been provided for evaluating fracture parameters, such as asymmetry, among others, since most of the solutions use type-curve matching, Rodriguez, Cinco-Ley and Samaniego (1992) and Resurreicao and Fernando (1991), which is a basically a trial-and-error procedure involving uncertainty and tedious work.

Basically the purpose of this work is to develop a practical interpretation technique for asymmetric fractures observing and studying the behavior of pseudolinear and radial flow regimes by observations on the pressure and pressure derivative plot. This methodology of interpretation is an extension of the *TDS* (Tiab's Direct Synthesis) Technique, Tiab (1995). This technique has been widely used for several cases of fractured wells. The most important works on fractured wells using *TDS* technique were given by Tiab (1994) and Tiab, Azzougen, Escobar and Berumen (1999). A recent work on pseudolinear flow in fractured wells was presented by Escobar, Gonzalez, Hernandez and Hernandez (2016). Escobar, Zhao and Zhang (2014b) provided *TDS* Technique for hydraulically-fractured wells in bi-zonal gas reservoirs. Escobar, Castro and Mosquera (2014c) provided a rate-transient analysis methodology for fractured wells. Escobar, Montenegro and Bernal (2014d) worked on shale reservoirs under transient-rate analysis and later Bernal, Escobar & Ghisays-Ruiz (2014a) extended this work to pressure transient analysis. Escobar, Ghisays-Ruiz and Bonilla (2014d) provided a new elliptical flow regime model for fractured wells. Zhao, Escobar, Hernandez and Zhang (2016) developed an interpretation technique for fractured wells in gas composite reservoirs and the works of Tiab and Bettam (2007) and Escobar, Zhao and Fahes (2015) focus on fractured wells in naturally-fractured formations.

MATHEMATICAL FORMULATION

Mathematical model

The mathematical model proposed by Rodriguez, et al (1992) is given below:



b) Symmetrically fractured well, $a = 0$

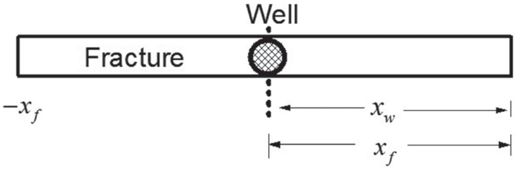


Figure 1. Schematic representation of fracture symmetry, after Rodriguez, et al. (1992).

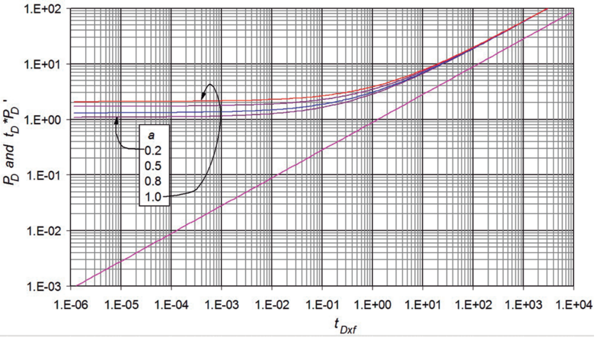


Figure 2. Dimensionless pressure and pressure derivative behavior for a vertical fractured well with low fracture conductivity, $C_{fD} = 1$

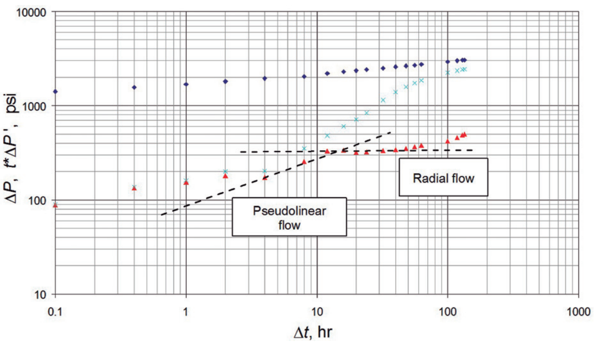


Figure 3. Pressure and pressure derivative against time for an asymmetrically fractured well. Information from Bostic, Agarwal and Carter (1980).

$$(PD)_{PLF} = \sqrt{\pi (t_{Dxf})_{PLF}} + \frac{\pi}{3}\frac{(1+3a^2)}{C_{fD}} \tag{1}$$

Which pressure derivative was analytically taken:

$$(t_D * P_D')_{PLF} = 0.5\sqrt{\pi (t_{Dxf})_{PLF}} \tag{2}$$

Suffix *PLF* stands for pseudolinear flow. The asymmetry factor "*a*" is a dimensionless parameter defined as the ratio of well position, x_w, with the half-fracture length, x_f. The asymmetry factor varies from zero, in the case of a symmetrical fracture, to one, in the case of a well located at the tip of the fracture. See Figure 1. The dimensionless pressure and pressure derivative behavior obtained from Equations (1) and (2) are shown in Figure 2. The impact of the asymmetry is observed there. As suggested by equation (2), the asymmetry does not affect the pressure derivative curve; then, a single curve is obtained for all cases. Such curve has a slope of ½ as suggested by Equation (2). A typical case is presented by Bostic, et al (1980) in Figure 3 but because of lacking of information (gas gravity and wellbore radius) the problem was not solved here.

DIMENSIONLESS PARAMETERS

The dimensionless time, pressure and pressure derivative normally used in transient-pressure analysis are given as:

$$t_D = \frac{0.0002637kt}{\phi\mu c_t x_f^2} \tag{3}$$

$$P_D = \frac{kh\Delta P}{141.2q\mu B} \tag{4}$$

$$t_D * P_D' = \frac{kh(t*\Delta P')}{141.2q\mu B} \tag{5}$$

And the dimensionless fracture conductivity, Cinco-Ley, et al (1978), is given by:

$$C_{fD} = \frac{k_f w_f}{k x_f} \tag{6}$$

3. TDS TECHNIQUE FOR OIL WELLS

Replacing Equations (3) and (5) in Equation (2) and solving for the half-fracture length, x_f, gives:

$$x_f = \frac{2.032\,qB}{h(t*\Delta P)_{PLF}}\sqrt{\frac{t_{PLF}\mu}{k\phi c_t}} \tag{7}$$

Division of Equation (1) by (2) and replacement of Equations (3) to (5) on the resulting expression leads to solve for the fracture asymmetry factor, *a*, so that:

$$a^2 = 1.8^2\left[\frac{0.02878\sqrt{\dfrac{t_{PLF}}{\phi\mu c_t k}}\dfrac{k_f w_f}{x_f^2}}{\pi}\left(\frac{\Delta P_{PLF}}{2(t*\Delta P')_{PLF}} - 1\right) - \frac{1}{3}\right] \tag{8}$$

Equation (8) includes a correction factor introduced after the application of this equation.

Permeability and skin factors can be estimated from, Tiab (1995);

$$k = \frac{70.6q\mu B}{h(t*\Delta P')_r} \tag{9}$$

$$s = 0.5\left(\frac{\Delta P_r}{(t*\Delta P')_r} - \ln\left[\frac{kt_r}{\phi\mu c_t r_w^2}\right] + 7.43\right) \tag{10}$$

Once skin factor and the half-fractured length are known, the fractured conductivity can be estimated from a correlation presented by Tiab (2003).

$$s = 0.5\left(\frac{\Delta P_r}{(t*\Delta P')_r} - \ln\left[\frac{kt_r}{\phi\mu c_t r_w^2}\right] + 7.43\right) \tag{11}$$

$$k_f w_f = \frac{3.31739k}{e^s/r_w - 1.92173/x_f} \tag{12}$$

4. TDS TECHNIQUE FOR GAS WELLS

The dimensionless time for gas with rigorous time and pseudotime, Agarwal (1979), are:

$$t_D = \frac{0.0002637kt}{\phi(\mu c_t)_i x_f^2} \tag{13}$$

$$t_{Da}=\left(\frac{0.0002637k}{\phi x_f^2}\right)t_a(P) \tag{14}$$

And the pseudopressure and pseudopressure derivative are given by:

$$m(P)_D=\frac{hk\left(m(P_i)-m(P)\right)}{1422.52q_{sc}T} \tag{15}$$

$$t_{Da}*m(P)'_D=\frac{kh\left(t*\Delta m(P)'\right)}{1422.52q_{sc}T} \tag{16}$$

With these dimensionless quantities Equations (7) and (8) become:

$$x_f=\frac{20.472q_{sc}T}{h[t*\Delta m(P)']_{PLF}}\sqrt{\frac{t_{PLF}}{k\phi(\mu c_t)_i}} \tag{17}$$

$$x_f=\frac{20.472q_{sc}T}{h[t*\Delta m(P)']_{PLF}}\sqrt{\frac{t_a(P)_{PLF}}{k\phi}} \tag{18}$$

$$a^2=1.8^2\left[\frac{0.02878\sqrt{\frac{t_{PLF}}{k\phi(\mu c_t)_i}}\frac{k_f w_f}{x_f^2}}{\pi}\left(\frac{\Delta m(P)_{PLF}}{2[t*\Delta m(P)']_{PLF}}-1\right)-\frac{1}{3}\right] \tag{19}$$

$$a^2=1.8^2\left[\frac{0.02878\sqrt{\frac{t_a(P)_{PLF}}{k\phi}}\frac{k_f w_f}{x_f^2}}{\pi}\left(\frac{\Delta m(P)_{PLF}}{2[t*\Delta m(P)']_{PLF}}-1\right)-\frac{1}{3}\right] \tag{20}$$

The permeability and skin factor are found from, Nunez, Tiab and Escobar (2003) and Escobar, Lopez and Cantillo (2007):

$$k=\frac{711.26qT}{h(t*\Delta m(P)')_r} \tag{21}$$

$$s'=0.5\left\{\frac{\Delta m(P)_r}{[t*\Delta m(P)']_r}-\ln\left(\frac{kt_r}{\phi\mu c_t r_w^2}\right)+7.43\right\} \tag{22}$$

$$s'=0.5\left\{\frac{\Delta m(P)_r}{[t*\Delta m(P)']_r}-\ln\left(\frac{kt_a(P)_r}{\phi r_w^2}\right)+7.43\right\} \tag{23}$$

SYNTHETIC EXAMPLES

OIL EXAMPLE

A pressure test was simulated for an oil reservoir with a hydraulically-fractured vertical well having finite conductivity. The input data is given in Table 1 and simulated results are presented in Table 2 and Figure 4. It is requested to estimate permeability, asymmetry, half-fracture length and fracture conductivity.

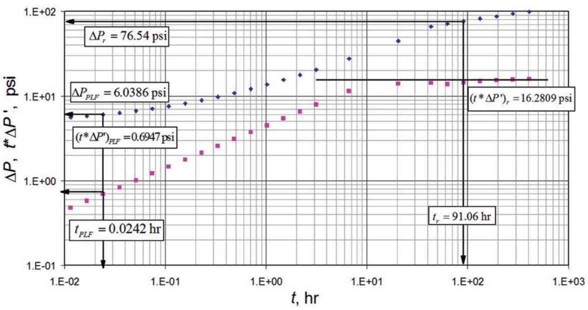


Figure 4. Pressure and pressure derivative against time log-log plot for oil example.

Table 1. Well, reservoir and fluid data for the worked examples.

Parameter	Oil Example	Gas Example
q	430 BPD	500 Mscf/D
B	1.12 bbl/STB	0.0107 bbl/SCF
μ (cp)	2.3	0.0107
h (ft)	80	50
x_w (ft)	120	90
x_f (ft)	400	500
ϕ	0.18	0.07
c_t (1/psi)	1x10^{-5}	2x10^{-6}
k (md)	60	0.01
T, °R		720
C_{fD}	8	10

Table 2. Pressure and pressure derivative data for oil example.

t, hr	Δ*P*, psi	*t**Δ*P*’, psi	*t*, hr	Δ*P*, psi	*t**Δ*P*’, psi
0.012	5.60	0.48	1.02	13.67	4.51
0.017	5.80	0.58	1.49	15.53	5.44
0.024	6.04	0.69	2.16	17.77	6.56
0.035	6.32	0.84	3.14	20.46	7.91
0.051	6.67	1.01	6.64	27.64	11.50
0.074	7.08	1.22	20.39	44.95	13.95
0.11	7.59	1.47	43.09	66.25	14.23
0.16	8.19	1.77	62.64	71.23	13.81
0.23	8.92	2.13	91.07	76.53	14.52
0.33	9.80	2.57	132.39	82.07	15.04
0.48	10.86	3.10	192.47	87.78	15.41
0.70	12.13	3.74	279.81	93.61	15.67
			406.78	99.52	15.86

Solution. The below information was read from Figure 4.

$t_r = 91.06$ hr $(t*\Delta P')_r = 16.28$ psi $\Delta P_r = 76.54$ psi
$t_{PLF}=0.0242$ hr $(t*\Delta P')_{PLF}=0.695$psi $\Delta P_{PLF}=6.038$psi
Find permeability by means of Equation (9);

$$k=\frac{70.6\,q\mu B}{h(t*\Delta P')_r}=\frac{70.6(430)(1.12)(2.3)}{(80)(16.2809)}=60.04\text{ md}$$

Use Equation (7) to find the half-fracture length:

$$x_f=\frac{2.032\,qB}{h(t*\Delta P)_{PLF}}\sqrt{\frac{t_{PLF}\mu}{k\phi c_t}}=\frac{2.032(430)(1.12)}{(80)(0.6947)}\sqrt{\frac{(0.0242)(2.3)}{(60.04)(0.18)(0.00001)}}=399.78$$

Estimate fracture conductivity with Equation (6):

$$k_f w_f = C_{fD} k x_f = (8)(60.04)(399.78) = 191189.4$$

Finally, find asymmetry with Equation (8):

$$a^2=1.8^2\left[\frac{0.02878\sqrt{\dfrac{0.0242}{(0.18)(2.3)(1\times10^{-5})(60.04)}}\;\dfrac{191894.4}{399.78^2}}{\pi}\left(\frac{6.0386}{2*0.6947}-1\right)-\frac{1}{3}\right]$$

$a = 0.3$

The estimation of x_f, a, and x_w has an error of 0.06 %, 0 % and 0.08 %, respectively, with respect to the input data used to run the simulation.

GAS EXAMPLE

A pseudopressure test was simulated for a gas reservoir drained by a hydraulically-fractured finite-conductivity vertical well. The input data is given in Table 1 and simulated results are presented in Table 3 and Figure 5. Find permeability, asymmetry, half-fracture length and fracture conductivity for this test.

Solution. The following data were read from Figure 5.

$[t*\Delta m(P')]_r = 512114869$ psi^2/cp $t_{PLF} = 0.04107$ hr
$[t*\Delta m(P')]_{PLF} = 15020549.4$ psi^2/cp
$[\Delta m(P)]_{PLF} = 1.41\text{x}10^8$ psi^2/cp

Find permeability with Equation (21):

$$k=\frac{711.26\,qT}{h\,(t*\Delta m(P)')_r}=\frac{711.26(500)(720)}{(50)(512118356)}=0.01\text{ md}$$

Find the half-fracture length with Equation (17):

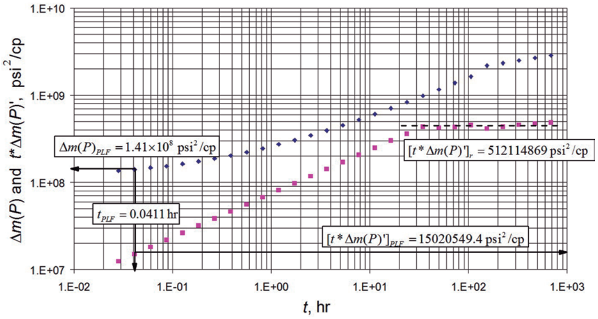


Figure 5. Pseudopressure and pseudopressure derivative against time log-log plot for gas example.

Table 3. Pseudopressure and pseudopressure derivative data for gas example.

t, hr	$\Delta m(P)$, psi^2/cp	$t*\Delta m(P')$, psi^2/cp	t, hr	$\Delta m(P)$, psi^2/cp	$t*\Delta m(P')$, psi^2/cp
0.028	1.36E+08	12457641.2	5.32	4.53E+08	170976262
0.041	1.41E+08	15020549.4	7.74	5.23E+08	206151177
0.060	1.47E+08	18110724.3	11.25	6.08E+08	248562620
0.087	1.54E+08	21836640.2	16.35	7.10E+08	299699362
0.126	1.63E+08	26329088.1	23.77	8.33E+08	361356456
0.183	1.74E+08	31745766.5	34.56	9.82E+08	435698253
0.267	1.87E+08	38276817.2	50.24	1.16E+09	422912933
0.388	2.03E+08	46151499.7	73.04	1.38E+09	428568437
0.564	2.22E+08	55646239.2	106.18	1.64E+09	456458589
0.819	2.45E+08	67094329.7	154.36	2.18E+09	413422131
1.19	2.73E+08	80897633.7	224.41	2.34E+09	434154181
1.73	3.06E+08	97540688.8	326.24	2.51E+09	456556408
2.52	3.46E+08	117607717	474.28	2.68E+09	472665728
3.66	3.94E+08	141803130	689.50	2.86E+09	484225857

$$x_f=\frac{20.472\,q_{sc}T}{h\,(t*\Delta m(P)')_{PLF}}\sqrt{\frac{t_{PLF}}{k\phi(c\mu_t)_i}}=\frac{20.472(500)(720)}{(50)(15020549.4)}\sqrt{\frac{(0.041)}{(0.01)(0.07)(0.0113)(2\times10^{-6})}}=500\text{ ft}$$

Find fracture conductivity with Equation (6)

$$k_f w_f = C_{fD} k x_f = (10)(0.01)(500) = 50\text{ md-ft}$$

Determine the asymmetry with Equation (19):

$$a^2=1.8^2\left[\frac{0.02878\sqrt{\dfrac{0.041071102}{(0.01)(0.07)(0.0113)(2E-6)}}\;\dfrac{50}{500^2}}{\pi}\left(\frac{1.41\times10^8}{2(15020549.4)}-1\right)-\frac{1}{3}\right]$$

$a = 0.19$

The estimation of x_f, a, and x_w has an error of 0 %, 5.3 % and 5.3 %, respectively, with respect to the input data used to run the simulation.

ANALYSIS OF RESULTS

All the obtained results match quite well with the input values used for running the simulations. In the gas example the asymmetry factor value was 0.18 compared with 0.19 from the computations. Although, the difference looks so small, the absolute error is 5.3 % which stills is valid in pressure transient analysis. Notice that with actual data probably the fracture conductivity is unknown. If so, it can be estimated with Equation (12). The oil example provided better results compared to the gas example which may be due to the fact that the gas uses the pseudopressure function which is an artificial function that may cause the error to be slightly higher.

CONCLUSION

Equations for vertical wells in oil and gas reservoirs were developed following the philosophy of the *TDS* Technique to characterize such asymmetrically fractured wells parameters as half-fracture length, well position and asymmetry factor. The deviation error obtained from the exercise is very low.

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NOMENCLATURE

a	Asymmetry factor
B	Volume factor, for oil the units are bbl/STB, for gas the units are bbl/SCF
c_t	Total compressibility, 1/psi
C_{fD}	Dimensionless fracture conductivity
h	Formation thickness, ft
k	Permeability, md
$k_f w_f$	Fracture conductivity, md-ft
q	Oil flow rate, BPD
q_{sc}	Gas flow rate, Mscf/D
r_w	Well radius, ft
P_D	Dimensionless pressure
t	Time, hr
t_D	Dimensionless time base on well radius
t_{DA}	Dimensionless time base on area
$t_D{*}P_D'$	Dimensionless pressure derivative
$t{*}\Delta P'$	Pressure derivative, psi
ΔP	Pressure change, psi
x_f	Half-fracture length, ft
x_w	Well position along the fracture, ft

Suffixes

D	Dimensionless
Dxf	Dimensionless based on half-fracture length
PLF	Pseudolinear
r	Radial
w	Well

GREEK

Δ	Change
ϕ	Porosity, fraction
μ	Viscosity, cp

SI METRIC CONVERSION FACTOR

bbl x 1.589 873	E-01 = m^3
cp x 1.0*	E-03 = Pa-s
ft x 3.048*	E-01 = m
ft^2 x 9.290 304*	E-02 = m^2
psi x 6.894 757	E+00 = kPa

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