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PRESSURE AND PRESSURE DERIVATIVE ANALYSIS FOR PSEUDOPLASTIC FLUIDS IN VERTICAL FRACTURED WELLS

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ABSTRACT

Petroleum engineers often deal with Non-Newtonian fluids in many activities of the oil industry. Some of these fluids are used as fracturing, EOR and drilling mud fluids. If one of these fluids is used to fracture a well and a post-fracture test is run, afterwards, the interpretation cannot be conducted with the conventional models. A pseudoplastic model has to be used. The oil literature presents only one work on well test analysis for fractured wells with non-Newtonian fluids. The application was specific for fall-off testing and the interpretation for determination of the half-fractured length is conducted using both the conventional straight-line method and type-curve matching. However, applications of the pressure derivative for this type of systems have not been performed yet. This paper presents a methodology using the pressure and pressure derivative log-log plot for interpretation of pressure transient tests in infinite-conductivity vertically fractured wells with a pseudoplastic fluid. The interpretation was extended to estimate the half-fracture length and the well drainage area. It was successfully tested on field and synthetic data.

Keywords: Non-Newtonian, dilatant, pseudoplastic, reservoir area, fractures length.

1. INTRODUCTION

Pseudoplastic fluids obey the power law. The flow index behavior, *n*, for them is smaller than the unity. Most of the fluids in the oil industry possess a pseudoplastic behavior. The pressure derivative during radial flow regime of a pseudoplastic fluid is a straight line which increases its slope as the flow index behavior decreases.

Ikoku has been the most outstanding researcher on the field of well test analysis of non-Newtonian fluids. His contributions comprise many analytical solutions for flow of foam and other non-Newtonian fluids through porous materials as can be seen in Ikoku (1978), Ikoku (1979), Ikoku and Ramey (1979a) and Ikoku and Ramey (1979b).

Application of the pressure derivative to non-Newtonian fluids was first used by Vongvuthipornchai and Raghavan (1987a) and extension of the *TDS* technique for such fluids was presented initially by Katime-Meindl and Tiab (2001). Escobar, Martinez and Montealegre (2010) presented a *TDS* technique, Tiab (1993), to radial composite reservoirs with a Non-Newtonian/Newtonian interface for pseudoplastic and dilatants systems, respectively.

Vongvuthipornchai and Raghavan (1987b) presented the only work on fractured well for power-law fluids. They used a dimensionless pressure solution provided by Odeh and Yang (1979) to generate a type-curve matching and conventional methodology for well test interpretation. The solution given Odeh and Yang (1979) is also used in this work to generate pressure and pressure derivative behavior for fracture wells with non-Newtonian fluids. As for the case of Newtonian fluids the pressure and pressure derivative also displays a half-slope straight line in both curves. Extension of the *TDS* technique was used to determine half-fracture length and well-drainage area.

2. MATHEMATICAL FORMULATION

The dimensionless quantities introduced by Ikoku and Ramey (1979) are:

$$P_{DNN} = \frac{\Delta P}{141.2\left(96681.605\right)^{1-n}\left(\frac{qB}{h}\right)^{n}\frac{\mu_{eff}\, r_w^{1-n}}{k}} \quad (1)$$

$$t_{DNN} = \frac{t}{G r_w^{3-n}} \quad (2)$$

$$t_{Dxf} = \frac{t}{G x_f^{3-n}} \quad (3)$$

$$t_{DA} = \frac{t}{G\left(\pi r_e^{3-n}\right)} \quad (4)$$

$$r_D = \frac{r}{r_w} \quad (5)$$

In which;

$$G = \frac{3792.188 n\phi c_t \mu_{eff}}{k}\left(96681.605\frac{h}{qB}\right)^{1-n} \quad (6)$$

and,

$$\mu_{eff} = \left(\frac{H}{12}\right)\left(9+\frac{3}{n}\right)^{n}\left(1.59344\times10^{-12} k\phi\right)^{(1-n)/2} \quad (7)$$

Where suffix *N* indicates Newtonian and suffix *NN* indicates non-Newtonian. Escobar *et al*. (2010) presented more practical expressions for the determination of both permeability and skin factor:

$$\frac{k}{\mu_{eff}} = \left[70.6\left(96681.605\right)^{(1-\alpha)(1-n)} \left(\frac{0.0002637 t_r}{n\phi c_t} \right)^{\alpha} \left(\frac{qB}{h} \right)^{n-\alpha(n-1)} \left(\frac{1}{\left(t*\Delta P'\right)_r} \right) \right]^{\frac{1}{1-\alpha}} \tag{8}$$

$$s = \frac{1}{2}\left[\begin{array}{l} \left[\dfrac{0.0002637 k t_r}{n\phi\mu_{eff} c_t r_w^{3-n}} \left(96681.605 \dfrac{h}{qB} \right)^{n-1} \right]^{\alpha} \left(\dfrac{\Delta P}{\left(t*\Delta P\right)} \right)_r - \\ \ln\left(\dfrac{k t_r}{n\phi\mu_{eff} c_t r_w^{3-n}} \left(96681.605 \dfrac{h}{qB} \right)^{n-1} \right) + 7.43 \end{array} \right] \tag{9}$$

Where α is the slope of the pressure derivative curve and is defined by:

$$\alpha = \frac{1-n}{3-n} \tag{10}$$

being *n* the flow behavior index which may be found from the slope of the pressure derivative curve during radial flow regime. The dimensionless pressure derivative during radial-flow regime is governed by:

$$\left(t_D * P_D{}'\right)_{rNN} = 0.5 t_{DNN}^{\alpha} \tag{11}$$

Odeh and Yang (1979) linearized the partial-differential equation for the problem of a well intercepted by a vertical fracture. Their dimensionless pressure solution is given below:

$$P_D\left(t_D\right) = \frac{(3-n)^{2\nu} t_D^{\nu}}{\left(1-n\right)\Gamma(1-\nu)} - \frac{1}{1-n} \tag{12}$$

Where $\nu = (1-n)/(3-n)$

Vongvuthipornchai and Raghavan (1987b) presented two interpretation methodologies: type-curve matching and conventional straight-line for characterization of fall-off tests in vertically hydraulic wells with a pseudoplastic fluid. They indicated that at early times, a well-defined straight line with slope equal to 0.5 on log-log coordinates will be evident, then,

$$P_D = \left(\frac{\pi}{2}\right)^{\frac{n-1}{2}} \sqrt{\pi\, t_{Dxf}} \tag{13}$$

$$t_{Dxf} = \frac{0.0002637 kt}{\phi c_t \mu_{eff} x_f^2} \tag{14}$$

Equation (12) is used here to develop pressure and pressure derivative curves for vertically infinite-conductivity fractured wells. An example of a curve for *n* = 0.5 is given in Figure-1. Notice that the slope of the pressure derivative during radial flow regime is greater than zero. Zero value of the pressure derivative corresponds the case for *n* = 1 (Newtonian). It is important to observe that during the formation linear flow to the fracture the slope of the pressure and pressure derivative is yet 0.5 as for the Newtonian case. The pressure derivative governing equation is:

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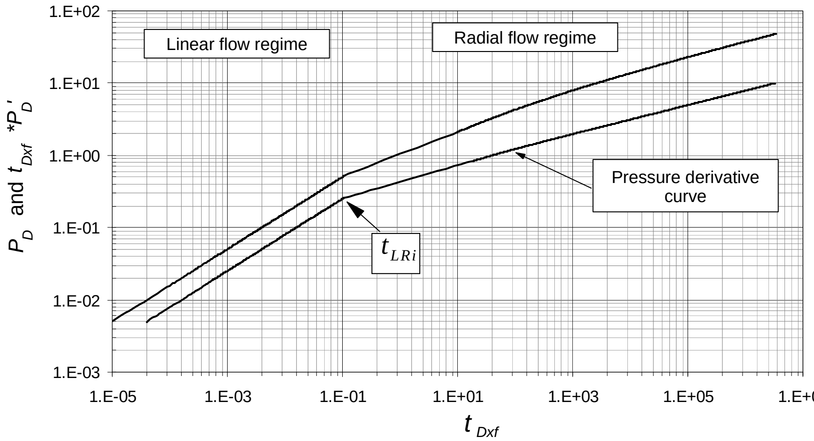

Figure-1. Dimensionless pressure and pressure derivative behavior for a vertical infinite-conductivity fractured well with a non-Newtonian pseudoplastic fluid with $n = 0.5$.

$$t_{Dxf} * P_D' = 0.5\left(\frac{\pi}{2}\right)^{\frac{n-1}{2}}\sqrt{\pi t_{Dxf}} \quad (15)$$

By using the intersect point of the pressure derivative during linear flow regime, Equation (15), with the radial flow regime governing equation, Equation (11), called t_{LRi}, an expression to obtain the half-fracture length is presented:

$$x_f = \left[0.028783\frac{(1.570796)^{\frac{n-1}{2}}}{\left(\frac{0.0002637kt_{LRi}}{\phi c_t\mu_{eff}}\right)^{\alpha}}\sqrt{\frac{t_{LRi}k}{\phi c_t\mu_{eff}}}\right]^{\left(\frac{3-n}{1+n}\right)} \quad (16)$$

Escobar, Vega and Bonilla (2012) showed that the late-time pressure derivative plot during pseudosteady-state the expression governing the late-time pseudosteady-state flow regime is:

$$t_D * P_D' = 2\pi t_{DA} \quad (17)$$

The point of intersection of the pressure derivatives during linear flow and pseudosteady-state (not shown here), called t_{LPi}, allows to obtain the well drainage area. In other words, equating Equations (15) and (17) and solving for the well-drainage area leads to the following expression:

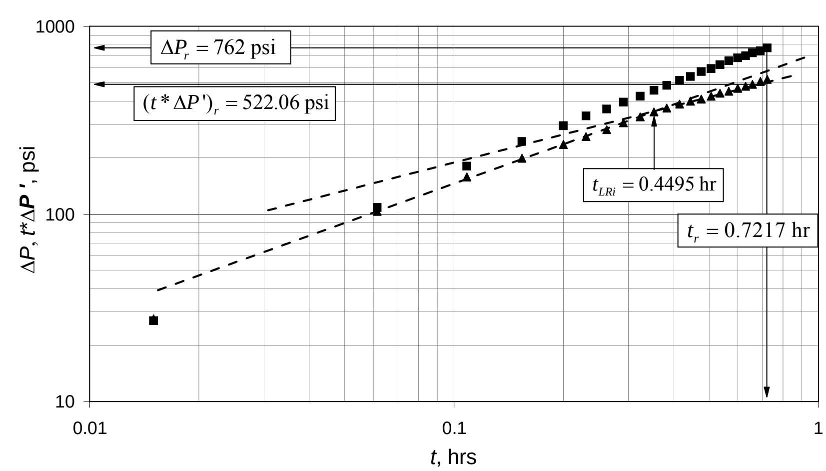

Figure-2. Pressure and pressure derivative for field example.

$$A = \pi \left[\frac{t_{LPi}}{0.0625 \left(\frac{\pi}{2} \right)^{n-1} G} \right]^{2/(3-n)} \qquad (18)$$

3. EXAMPLES

3.1. Field example

Fan (1998) presented a pressure test of a test conducted in a hydraulic fractured well with the information given below. Pressure and pressure derivative data for this test is reported in Figure-2.

n = 0.4	h = 70 ft	k = 0.65 md	q = 507.5 BPD
ϕ = 10 %	B = 1 rb/STB	μ_{eff} = 0.00065 cp	c_t = 0.00001 psi^{-1}
r_w = 0.26 ft	H = 20 cp*s^{n-1}		

Solution

The following information was read from the pressure and pressure derivative plot, Figure-2,

t_{LRi} = 0.4495 hr t_r =0.7217 hr ΔP_r = 762 psi $(t^*\Delta P')_r$ = 522.06 psi

Using Equation (10), a value of 0.23 is found for α. Reservoir permeability, skin factor, half-fracture length were estimated with Equations (8), (9) and (16). Their respective values are 0.65 md, 2.4 and 771 ft. Reservoir permeability and half-fracture length are re-estimated by simulating the test providing values of 0.65 md and 776 ft, respectively; therefore, the absolute errors for these calculations are less 0.06 % and 0.5 %.

3.2. Synthetic example

Figure-3 presents the pressure and pressure derivative data for a simulated test of a 250-ft long hydraulic fracture. Other information is given below:

n = 0.5	h = 30 ft	k = 150 md	q = 500 BPD
ϕ = 25 %	B = 1.15 rb/STB	μ_{eff} = 10 cp	c_t = 0.000005 psi^{-1}
r_w = 0.5 ft	H = 11144.07 cp*s^{n-1}		

Solution

From Figure-3, the following information was read:

t_{LRi} = 3.81 hr t_r = 30 hr ΔP_r = 257000 psi $(t^*\Delta P')_r$ =98400 psi

Equation (10) provided an α value of 0.2. Then, a skin factor of 3.73 was estimated with Equation (9) and a half-fracture length of 250.02 was found with Equation (16). In this case the absolute error was of 0.08 %.

4. COMMENTS ON THE RESULTS

The results obtained from the worked examples provide very low deviation errors which confirm that the developed methodology works very well for characterizing hydraulic fractured wells in reservoirs containing non Newtonian power-law fluids.

CONCLUSIONS

An estimation of the half-fracture length from pressure transient analysis using the pressure and pressure derivative log-log plot for reservoirs bearing power-law non-Newtonian fluids is presented for the first time and successfully tested with synthetic and field examples.

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Nomenclature

B	Volumetric factor, RB/STB
c_t	System total compressibility, 1/psi
C	Wellbore storage, bbl/psi
C_{fD}	Dimensionless fracture conductivity
h	Formation thickness, ft
H	Consistency (Power-law parameter), cp*s^{n-1}
G	Group defined by equation 3
G	Minimum pressure gradient, Psi/ft
G_D	Dimensionless pressure gradient
k	Permeability, md
k	Flow consistency parameter
m	Slope
n	Flow behavior index (power-law parameter)
P	Pressure, psi
q	Flow/injection rate, STB/D
t	Time, hr
r	Radius, ft
$t^*\Delta P'$	Pressure derivative, psi
$t_D^*P_D'$	Dimensionless pressure derivative

Greeks

Δ	Change, drop
ϕ	Porosity, fraction
μ	Viscosity, cp
μ_{eff}	Effective viscosity for power-law fluids, cp*(s/ft)$^{n-1}$

Suffices

app	Apparent
D	Dimensionless

DA	Dimensionless based on area
eff	Effective
i	Initial
LPi	Intersect of linear and pseudosteady-state lines
LPi	Intersect of linear and linear lines
NN	Non-Newtonian
R	Radial (any point on radial flow)
W	Wellbore

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