VOL. 8, NO. 9, SEPTEMBER 2013 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

©2006-2013 Asian Research Publishing Network (ARPN). All rights reserved.

www.arpnjournals.com

INJECTION AND FALL-OFF TESTS TRANSIENT ANALYSIS OF NON-NEWTONIAN FLUIDS

Freddy Humberto Escobar, Johanna Marcela Ascencio and Daniel Felipe Real
Universidad Surcolombiana/CENIGAA, Avenida Pastrana, Cra 1, Neiva, Huila, Colombia
E-Mail: fescobar@usco.edu.co

ABSTRACT

The use of non-Newtonian fluids is not new in the oil industry. Some of their qualities have been used as completion and stimulation fluids, fracturing operations and enhanced oil recovery projects. Besides, most heavy oils obey a non-Newtonian behavior. Therefore, it is important to have available a practical well test interpretation methodology for testing wells through which non-Newtonian fluids have been injected. Conventional analysis has been used for well test interpretation of injected non-Newtonian fluids. The main drawback of conventional analysis resides in properly identification of the points through which certain flow regime goes. This is not the case for the pressure derivative. Needless to say that an adequate analysis of these data will help obtaining a maximum oil recovery since it depends on a better reservoir characterization, then, a more practical and accurate methodology is required. Once the behavior of non-Newtonian injection fluids was obtained for different flow behavior indexes appropriate equations of the *TDS* technique were used along with conventional analysis for interpretation well test data. Both methodologies were used and successfully tested with synthetic and field examples.

Keywords: power-law fluids, non-Newtonian, transient-pressure analysis, flow behavior index, consistency, *TDS* technique.

1. INTRODUCTION

It appears to be that Van Pollen and Jargon (1969) were the first researchers who studied the transient pressure behavior of Non-Newtonian fluid flow in oil formations. They conducted a numerical study under steady and unsteady state conditions and represented the non-Newtonian behavior by varying the viscosity as a function of the position. Odeh and Yang (1979) derived a partial differential equation to describe flow of Non-Newtonian flow through porous media. They provided a methodology for interpretation of injection tests. In the same year, McDonald (1979) presented a numerical study using the model proposed by Odeh and Yang (1979) and found that the grid had to be finer in non-Newtonian fluids than those used in black oil. It is the authors' opinnion that Ikoku and Ramey (1978), Ikoku and Ramey (1979) and Ikoku and Ramey (1980) have contributed the most to the field of transient pressure analysis of Non-Newtomni Power-law fluids. Ikoku and Ramey (1979) developed a new mathematical model for describing non-Newtonian fluid flow through isotropic and homogeneous porous materials assuming power-law and slightly compressible fluid. Their partial differential equation governs such non-Newtonian agents used in secondary and tertiary oil recovery projects as polymeric, miscellar and surfactant solutions. Also, Ikoku and Ramey (1978) transformed their model into a linear form by using the predictor-corrector method proposed by Douglas-Jones. Additionally, Ikoku and Ramey (1980) extended their original theory to finite reservoirs including skin and wellbore storage effects. The reservoir was assumed to have a circular shape and both, steady and pseudosteady state situations were considered. Ikoku (1979) applied new techniques for fall-of tests in power-law flow. He used linear superposition to develop an analytical solution. Huh and Snow (1985) considering both the distribution and rheology of the fluid concluded that conventional techniques cannot be applied for interpretation of tests run in reservoirs containing non-Newtonian fluids. They found out that polymer injection presents two problems: (1) because of the fluid rheology, viscosity is a function of fluid velocity and (2) polymer distribution is non-uniform in the reservoir.

Lund and Ikoku (1981) conducted a study of Newtonian/Non-Newtonian behavior which may be presented when a non-Newtonian fluid is injected into a reservoir containing a Newtonian fluid such as black oil. They treated the problem as a composite reservoir. Okpobiri and Ikoku (1982) analyzed fall-off pressure tests in composite Newtonian/Non-Newtonian. However, they considered that the non-Newtonian fluid is dilatant. Vongvuthipornchai and Raghavan (1987) introduced for the first time the pressure derivative function to pressure tests in non-Newtonian fluids and included a new expression to estimate the effective wellbore. Olarewaju (1992) presented the unique study of non-Newtonion fluid flow through naturally fractured (double porosity) formations. They presented an analytical solution for infinite transient pressure behavior is such reservoirs including skin and wellbore storage.

Later on, Katime-Meindl and Tiab (2001) applied the *TDS* (Tiab´s Direct Synthesis) methodology for interpretation of pressure tests conducted in infinite reservoirs with non-Newtonian fluids. They also included the effect of a close and an open linear boundary. Igbokoyi and Tiab (2007) applied type-curve matching for the interpretation of pressure tests for non-Newtonian fluids in infinite systems including skin and wellbore storage effects. Escobar *et al.* (2011) used the model proposed by Olarewaju (1992) to extend the *TDS* technique for interpretation pressure tests in double porosity reservoirs.

Escobar *et al.* (2010) and Martínez *et al.* (2011) applied the *TDS* methodology to radial composite reservoirs with non-newtonian/Newtonian interphase. The works were performed for pseudoplastic and dilatant non-Newtonain fluids, respectively. Also, Escobar *et al.* (2012a) and Escobar *et al.* (2012b) used the *TDS* technique for characterizing fractured wells and determining reservoir area, respectively. Recently, Escobar (2012) presented the state-of-the-art on pressure transient analysis for non-Newtonian fluids which include both conventional straight-line and *TDS* interpretation techniques. He gives special emphasis to the pressure derivative function application to homogeneous and heterogeneous porous rocks.

2. MATHEMATICAL FORMULATION

Ikoku (1979) presented an analytical dimensionless solution for the pressure fall-off behavior of non-Newtonian fluids for the case of a well under constant injection rate in an infinite reservoir. Skin and wellbore storage effects are excluded.

$$P_{DNNs}=\frac{(3-n)^{(2[1-n])/(3-n)}}{(1-n)\Gamma\left(\dfrac{2}{3-n}\right)}\left[\left[t_f+\Delta t\right]_{DNN}^{\frac{1-n}{3-n}}-\left[\Delta t\right]_{DNN}^{\frac{1-n}{3-n}}\right] \tag{1}$$

The dimensionless quantities are defined as:

$$P_{DNN}=\frac{\Delta P}{141.2\left(96681.605\right)^{1-n}\left(\dfrac{qB}{h}\right)^{n}\dfrac{\mu_{eff}r_w^{1-n}}{k}} \tag{2}$$

$$t_{DNN}=\frac{t}{Gr_w^{3-n}} \tag{3}$$

$$G=\frac{3792.188n\phi c_t\mu_{eff}}{k}\left(96681.605\frac{h}{qB}\right)^{1-n} \tag{4}$$

and,

$$\mu_{eff}=\left(\frac{H}{12}\right)\left(9+\frac{3}{n}\right)^{n}\left(1.59344\times10^{-12}k\phi\right)^{(1-n)/2} \tag{5}$$

Figure-1 is obtained from Equation (1). The pressure behavior is very similar to that of a producer well. Therefore, the equations presented by Escobar *et al.* (2010) for the determination of permeability and skin using the *TDS* technique, Tiab (1995), apply here:

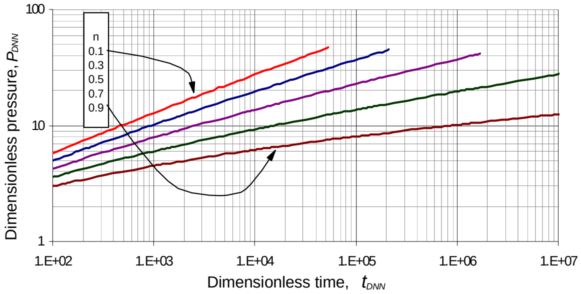

Figure-1. Dimensionless fall-off pressure for a non-Newtonian fluid in an infinite reservoir.

$$k=\left[\begin{array}{l}70.6\left(96681.605\right)^{(1-\alpha)(1-n)}\left(\dfrac{0.0002637t_r}{n\phi c_t}\right)^{\alpha}\\ \left(\dfrac{qB}{h}\right)^{n-\alpha(n-1)}\left(\dfrac{1}{(t*\Delta P')_r}\right)\end{array}\right]^{\frac{1}{1-\alpha}} \tag{6}$$

Another expression for permeability:

$$k=\left\{\begin{array}{l}\left[\begin{array}{l}70.6\left(96681.605\right)^{(1-\alpha)(1-n)}\left(\dfrac{0.0002637t_r}{n\phi c_t}\right)^{\alpha}\left(\dfrac{qB}{h}\right)^{n-\alpha(n-1)}\\ \left(\dfrac{r_w^{\ \alpha(n-3)+(1-n)}}{(t*\Delta P')_r}\right)\end{array}\right]^{\frac{1}{1-\alpha}}\\ \left[\left(\dfrac{H}{12}\right)\left(9+\dfrac{3}{n}\right)^{n}\left(1.59344\times10^{-12}\phi\right)^{\left(\frac{1-n}{2}\right)}\right]\end{array}\right\}^{\frac{2}{1+n}} \tag{7}$$

Being α the slope of the pressure derivative curve, defined by:

$$\alpha=\frac{1-n}{3-n} \tag{8}$$

The skin factor is estimated by:

$$s=\frac{1}{2}\left(\frac{(\Delta P)_{rNN}}{(t*\Delta P')_{rNN}}-\frac{1}{\alpha}\right)\left(\frac{t_{rNN}}{G\,r_w^{3-n}}\right)^{\alpha} \tag{9}$$

Ikoku and Ramey (1979) presented the expressions for the determination of permeability, skin factor and investigation radius by means of the straight-line conventional analysis. A plot of either ΔP o P_{wf} vs. $t^{1-n/3-n}$ yields a straight line during radial flow regime which slope, m_{NN}, is given by:

$$m_{NN}=\frac{\left(\dfrac{q}{2\pi h}\right)^{\frac{1+n}{3-n}}\left(\dfrac{\mu_{eff}}{k}\right)^{\frac{2}{3-n}}}{(1-n)\Gamma\left(\dfrac{2}{3-n}\right)\left[\dfrac{n\phi c_t}{(3-n)^2}\right]^{\frac{1-n}{3-n}}} \tag{10}$$

©2006-2013 Asian Research Publishing Network (ARPN). All rights reserved.

At time t = 0 sec, the intercept is,

$$\Delta P_o = \left(\frac{q}{2\pi h}\right)^n \frac{\mu_{eff} r_w^{1-n}}{k_r(n-1)} \tag{11}$$

At time t = 0 sec, $\Delta P = \Delta P_o$, then the skin factor can be estimated from:

$$s = \left(\frac{\Delta P_o}{r_w^{1-n}}\right)\left(\frac{2\pi h}{q}\right)^n\left(\frac{k_r}{\mu_{eff}}\right) + \left(\frac{1}{1-n}\right) \tag{12}$$

The radius of investigation is found from:

$$r_{inv} = \left[\Gamma\left(\frac{2}{3-n}\right)\right]^{\frac{1}{n-1}}\left[\frac{(3-n)^2 t}{G}\right]^{\frac{1}{3-n}} \tag{13}$$

If the consistency index, H, is known, permeability can be solved from Equation (9), as follows:

$$k = \left(\frac{q}{2\pi h}\right)\left\{\frac{\left[(1-n)\Gamma\left(\frac{2}{3-n}\right)\right]^{n-3}}{\frac{\left[\frac{H}{12}\left(9+\frac{3}{n}\right)^n (150)^{\frac{1-n}{2}}\right]^2 (3-n)^{2(1-n)}}{(nc_t)^{1-n}(m_{NN})^{3-n}}}\right\}^{\frac{1}{1+n}} \tag{14}$$

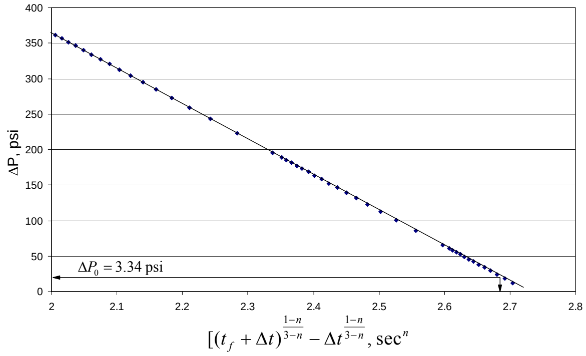

Figure-2. Shut-in well pressure drop vs. $[(t_f+\Delta t)^{0.1304} - \Delta t^{0.1304}]$ plot for synthetic example.

3. EXAMPLES

3.1. Synthetic example

Figure-2 presents data for a synthetic fall-off simulated with the below given information after an injection period of 10300 sec. It is required to determine permeability and skin.

q = 300 cm^3/sec ϕ = 0.18 r_w = 20 cm
μ = 15 cp c_t = 1.5x10^{-6} psi^{-1} h = 6000 cm
n = 0.7 k = 700 md

Solution by conventional analysis

As additional information is given that ΔP_0 = 3.34 psi = 23000 Pa at a time t = 0 sec. Additionally, H = 2.5 x 10^{-02} Pa.seg^n. The effective viscosity is 0.000313 Pa.sec$^{0.7}$.m$^{0.3}$ estimated from Equation (5). Then, a slope m_{NN} = 94400 Pa/sec$^{0.7}$ is found from Equation 9 and a permeability of 6.91x10^{-13} m^2 = 700 md is calculated using Equation (12). Finally, a skin factor of 4.86 is found with Equation (11).

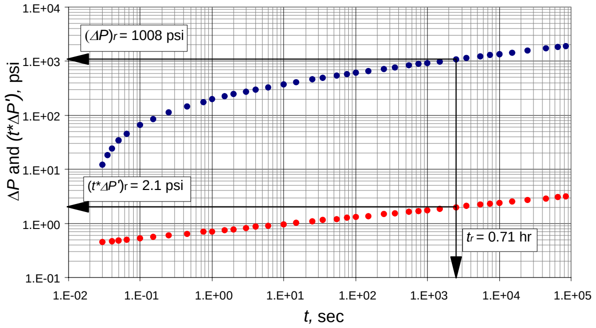

Figure-3. Pressure and pressure derivative plot for synthetic example.

Solution by the *TDS* technique

Assuming a volume factor of 1 bbl/STB and taking an arbitrary time of t = 0.71 hr *at* which ΔP = 1008 psi and $(t^*\Delta P')$ = 2.1 psi were read from Figure-3, permeability of 698.44 md and skin factor of 4.73 were determined using Equations (6) and (8), respectively. A value of α = 0.13 is also found from Equation (7).

3.2. Field example

Estimate reservoir permeability and skin factor for an example provided by Ikoku (1979) of a pressure test run into a water flooded reservoir which was subject to polymer flooding. Figure-4 provides the pressure drop vs. $[(t_f+\Delta t)^{0.224} - \Delta t^{0.224}]$ plot. First, 24000 bls (3815.7 m^3) of water were injected, followed by 19000 bbl (3020.8 m^3) of polymer solution. Other important data are provided below:

q = 0.0001381 m^3/sec ϕ = 0.228
r_w = 24.1 cm λ_{eff} = 8.694x10^{-9} m$^{1.423}$/Pa.sec
c_t = 7.567x10^{-6} psi^{-1} h = 5182 cm
n = 0.423 t_f = 292500 sec
H = 0.065 Pa.sec$^{0.423}$ B = 1 bbl/STB

Solution by conventional analysis

A ΔP_0 value of -1500 Kpa and m_{NN} of 74100 Pa/sec$^{0.224}$ are found from Figure-3. From Equation 9 the permeability resulted to be 34.4 md and the skin factor of -9.8 is found with Equation (11).

©2006-2013 Asian Research Publishing Network (ARPN). All rights reserved.

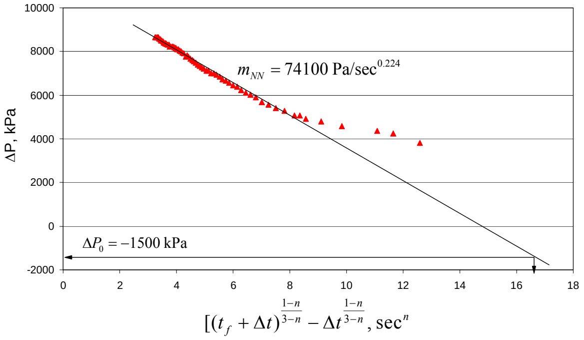

Figure-4. Shut-in well pressure vs. $[(t_f+\Delta t)^{0.224} - \Delta t^{0.224}]$ plot for field example.

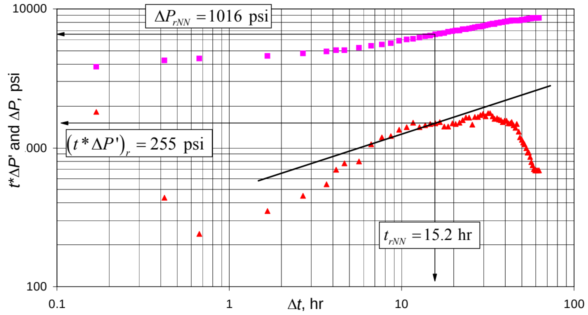

Figure-5. Pressure and pressure derivative plot for field example.

Solution by the *TDS* technique

The slope of the pressure derivative curve during radial flow resulted to be 0.224 psi/hr from which a flow behavior index, *n*, of 0.427 was estimated. This value is very close to the one given in the test of 0.423. From the pressure derivative plot the following information was read:

$t = 15.2$ hr $\quad \Delta P = 1016$ psi $\quad (t^*\Delta P') = 255\ psi$

A formation permeability value of 39.44 md was obtained using Equations (6). An effective viscosity of 0.01385 cp was found with Equation (5) and the *G* parameter resulted to be 4.4814×10^{-4} from Equation (4). Finally, Equation (8) allows determining a skin factor of -11.9.

4. COMMENTS OF THE RESULTS

From the worked examples was found a close agreement between the results obtained by the straight-line conventional and the *TDS* technique which confirm the accuracy and practicality of the last methodology for handling either injection or fall-off tests.

5. CONCLUSIONS

The *TDS* technique was successfully extended to injection and fall-off tests of non-Newtonian pseudoplastic fluids. The equations were tested by its application to field and synthetic examples and compared to results from the straight-line conventional analysis.

Nomenclature

For conventional analysis SI units are used. For TDS technique field units are used.

B	Volumetric factor
c_t	System total compressibility
H	Consistency, Pa.sec^n
k	Permeability
m	Slope
n	Flow behavior index
P	Pressure
q	Flow rate
t	Time, hr
r_{inv}	Radius of investigation
r_w	Wellbore radius
$t^*\Delta P'$	Pressure derivative
ΔP	Pressure drop

Greeks

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

Suffices

D	Dimensionless
eff	Effective
NN	Non Newtonian
rNN	Arbitrary point during radial Non-Newtonian fluid
0	Zero value

ACKNOWLEDGEMENTS

The authors gratefully thank the Most Holy Trinity and the Virgin Mary mother of God for all the blessing received during their lives.

REFERENCES

Escobar F.H. 2012. Transient Pressure and Pressure Derivative Analysis for Non-Newtonian Fluids. Chapter 7-New Technologies in the Oil and Gas Industry. ISBN 978-953-51-0825-2, In Tech, October. p.31.

Escobar F.H., Martinez J.A. and Montealegre-M, M. 2010. Pressure and Pressure Derivative Analysis for a Well in a Radial Composite Reservoir with a Non-Newtonian/Newtonian Interface. Paper sent to CT and F to request publication. 4(1): 33-42. December.

Escobar F.H., Zambrano A.P, Giraldo D.V. and Cantillo J.H. 2011. Pressure and Pressure Derivative Analysis for Non-Newtonian Pseudoplastic Fluids in Double-Porosity Formations. CT and F. 5(3): 47-59. June.

©2006-2013 Asian Research Publishing Network (ARPN). All rights reserved.

Escobar F.H., Bonilla D.F. and Ciceri Y,Y. 2012 [a]. Pressure and Pressure Derivative Analysis for Pseudoplastic Fluids in Vertical Fractured wells. Journal of Engineering and Applied Sciences. ISSN 1819-6608. 7(8). August.

Escobar F.H., Vega L.J. and Bonilla L.F. 2012 [b]. Determination of Well Drainage Area for Power-Law Fluids by Transient Pressure Analysis. CT and F. 5(1): 45-55. December.

Igbokoyi A. and Tiab D. 2007. New Type Curves for the Analysis of Pressure Transient Data Dominated by Skin and Wellbore Storage: Non-Newtonian Fluid. Paper SPE 106997 presented at the SPE Production and Operations Symposium, Oklahoma, 31 March - 3 April.

Ikoku C. U. 1979. Practical Application of Non-Newtonian Transient Flow Analysis. Paper SPE 8351 presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas-NV, September. pp. 23-26.

Ikoku C. U. and Ramey H. J. Jr. 1979. Numerical Solution of the Nonlinear Non-Newtonian Partial Differential Equation. Paper SPE 7661. American Institute of Mining, Metallurgical, and Petroleum Engineers, 1978.

Ikoku C.U. and Ramey H.J. Jr. 1979. Transient Flow of Non-Newtonian Power-Law Fluids in Porous Media. Paper SPE 7139 presented at the SPE-AIME 48th California Regional Meeting, San Francisco, April 12-14, 1978. Revised manuscript received, January 22.

Ikoku C. U. and Ramey H. J. Jr. 1980. Wellbore Storage and Skin Effects during the Transient Flow of Non-Newtonian Power-Law Fluids in Porous Media. paper SPE 7449 presented at the SPE 53rd Annual Fall Technical Conference and Exhibition, Houston, October 1-4, 1978. Society of Petroleum Engineers of Aime, February.

Ikoku C.U. 1982. Well Test Analysis for Enhanced Oil Recovery Projects. ASME Journal of Energy Resources Technology, June 1.

Katime-Meindl I. and Tiab D. 2001. Analysis of Pressure Transient Test of Non-Newtonian Fluids in Infinite Reservoir and in the Presence of a Single Linear Boundary by the Direct Synthesis Technique. Paper SPE 71587 prepared for presentation at the SPE Annual Technical Conference and Exhibition, New Orleans-Louisiana, 30 September-3 October.

Lund O. and Ikoku C.U. 1981. Pressure Transient Behavior of Non-Newtonian/Newtonian Fluid Composite Reservoirs. Paper SPE 9401 presented at the SPE 55th Annual Technical Conference and Exhibition, Dallas, September 21-24, 1980. Revised manuscript received, January 12.

Martinez J.A., Escobar F.H. and Montealegre-M M. 2011. Vertical Well Pressure and Pressure Derivative Analysis for Bingham Fluids in a Homogeneous Reservoirs. Dyna, Year 78, Nro. 166, pp. 21-28. Dyna.

McDonald A.E. 1979. Approximate Solutions for Flow of Non-Newtonian Power-Law Fluids Through Porous Media. Paper SPE 7690 presented at the SPE Fifth Symposium on Reservoir Simulation, Denver, February 1-2.

Odeh A.S. and Yang H.T. 1979. Flow of Non-Newtonian Power-Law Fluids through Porous Media. Paper SPE 7150 presented at the SPE-AIME 48th Annual California Regional Meeting, San Francisco, April 12-14, 1978. Revised manuscript received, January 31.

Okpobiri G.A. and Ikoku. C.U. 1983. Pressure Transient Behavior of Dilatant Non-Newtonian/Newtonian Fluid Composite Reservoirs. Paper SPE 12307 presented at the Eastern Regional Meeting held in Champion, Pennsylvania, November 9-11.

Olarewaju J.S. 1992. A Reservoir Model of Non-Newtonian Fluid Flow. paper SPE 25301. Society of Petroleum Engineers.

Tiab D. 1993. Analysis of pressure and pressure derivative without type-curve matching: 1- skin and wellbore storage. Journal of Petroleum Science and Engineering. 12: 171-181.

Van Poollen H.K. and Jargon J.R. 1969. Steady-State and Unsteady-State Flow of Non-Newtonian Fluids through Porous Media. Paper SPE 1567 presented at SPE 41st Annual Fall Meeting, Dallas-Texas, October 2-5, 1966. Revised manuscript received, January 10.

Vongvuthipornchai S. and Raghavan R. 1987. Well test analysis of Data Dominated by Storage and Skin: Non-Newtonian Power-Law Fluids. Paper SPE 14454 presented at the SPE Annual Technical Conference and Exhibition, Las Vegas, September 22-25, 1985. Revised manuscript received, January 23.