American Journal of Engineering Research (AJER) 2015

American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-4, Issue-12, pp-134-142
www.ajer.org
Research Paper Open Access

# Deconvolution and Interpretation of Well Test Data 'Masked' By Wellbore Storage in A Build Up Test

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**ABSTRACT**: When a well test contains a series of different flow rates, or a continuously varying flow rate, the combination of the pressure transients due to varying flow rate is called convolution. while deconvolution means removing a distorting effect upon the variable of interest. This paper is on the study of an analytical technique that can be used to explicitly deconvolve wellbore storage distorted well test data using pressure data and the flow rate. Then to determine the reservoir properties from this deconvolved well test data by using the conventional well test interpretation methods. Also the comparison of the material balance deconvolution method results with the β-deconvlolution method result were carried out and then used to determine which method was a better deconvolution tool**.** The results showed that the material balance deconvolution technique performed very well with minor discrepancies and gave better estimation of the reservoir parameters.

**Keywords:** Buildup Test, β-deconvlolution, Wellbore Storage Effect, Material Balance deconvolution,

## I. INTRODUCTION

Well testing can be said to be the only technique that examines a significant portion of the reservoir under dynamic conditions in order to determine its production capability and reservoir properties. It has long been recognized that wellbore storage (after flow) can impede pressure transient test analysis thus several methods have been suggested for determining the effects of afterflow when well known semi-logarithmic techniques cannot be used for transient test analysis. Often times, during well testing, the test may not be carried out for a very long time so as to acquire sufficient information that can be used to interpret the result in the usual conventional method available in literatures, hence, the need to make use of the early time region (ETR) data, for the interpretation. In such situation, we then have to try to make the data as reliable as possible by eliminating wellbore storage effect from the data.

Ramey H.T(1970) concluded that annulus unloading and wellbore storage are important physical effect that often controls the behavior of early pressure data taken during a well test. Van Everdingen and Hurst.. (1953) reported that wellbore storage effects include a "skin effect" or a region of altered permeability adjacent to the wellbore and that in many cases the production flow rate can be approximated using equation. Kuchuk F.J, (1985) applied "β deconvolution" for the analysis of wellbore storage distorted pressure transient data and formulated the β-deconvolution equation that helps to computes the undistorted pressure drop function directly from the wellbore storage affected data. Bourdet et al (1989) showed that the most recently documented pressure derivative approach has combined the most powerful aspects of the two previously distinct methods into a single stage interpretative plot Roumboustsos and Stewart (1985) developed convolution and deconvolution methods based on the ideas proposed by kuchuk. Kuchuk presented a generalized rate-convolution and deconvolution methods. He obtained deconvolved pressure values from the Riemann sum and from exponential wellbore flow-rate case. Igbokoyi, A.O (2007) used the deconvolution approach and the resulting Duhamels integral formulation to develop a model that successfully interpreted short-time pressure data distorted by wellbore storage and skin in a buildup test.

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## II. MATERIAL BALANCE DECONVOLUTION

Material balance deconvolution is a practical approach for the analysis of pressure transient data distorted by wellbore storage effects, The general form of material balance deconvolution provide for the pressure drawdown case in terms of the material balance time function and the rate normalized pressure drop function. The material balance time function and the rate-normalized pressure drop function is given by the equations 1and 2

$$t_{mb} = \frac{N_p}{q}$$ ______(1)

$$\frac{\Delta p}{q} = \frac{(p_i - p_{wf})}{q}$$ ______(2)

From the first principle, applying material balance to a well with wellbore storage, the following equations are stated,

$$q_{sf} = q + \frac{24C_s}{B}\frac{dP_w}{dt}$$ ______(3)

For buildup, the flow rate at the surface q = 0,
so we have:

$$q_{sf} = \frac{24C_s}{B}\frac{dP_w}{dt}$$ ______(4)

Then for a normalization of the sandface flow rate, $q_{ref}$

$$\frac{q_{sf}}{q_{ref}} = \frac{24C_s}{q_{ref}B}\frac{dP_w}{dt}$$ ______ (5)

But for this case, we can say that $\frac{q_{sf}}{q_{ref}} = q_{wbs}$ . ______(6)

Then the equation 5 becomes:

$$\frac{dp_w}{dt} = q_{wbs} * \frac{q_{ref}B}{24C_s}$$ ______(7)

But $C_s = C_{wb} * V_{wb}$ ______(7a)

From equation (7),

A plot of $\frac{dp_w}{dt}$ against $q_{wbs}$ gives the slope $m_{wbs}$ ,

which can be express as:

$$m_{wbs} = \frac{qB}{24C_s}$$ ______(8)

Substituting equation (8) into equation (6)

$$q_{wbs} = \frac{1}{m_{wbs}}\frac{d}{d\Delta t}(\Delta p_{ws})$$ ______(9)

For a buildup test, the pressure drop is measured against pressure at time t =0,
thus the pressure drop is given as:

$$\Delta P_{ws} = p_{ws} - p_{wf}(\Delta t = 0)$$ ______(10)

NOTE:

$$\left(\frac{d(\Delta P_{ws})}{d(\Delta t)}\right)_n = \frac{(\Delta P_{ws})_{\Delta t_{n+1}} - (\Delta P_{ws})_{\Delta t_{n-1}}}{\Delta t_{n+1} - \Delta t_{n-1}}$$ ______(11)

Integrating the equation :

$$N_p = \int q_{sf}\,dt = \frac{24C_s}{B}\int \frac{dp_w}{dt}dt \tag{12}$$

$$N_p = \frac{24C_s}{B} * P_w \tag{13}$$

Now, to normalize the above equation, we divide all through by reference rate $q_{ref}$.

$$\frac{N_p}{q_{ref}} = \frac{24C_s}{q_{ref}B} * P_w \tag{14}$$

$$N = \frac{1}{m_{wbs}} * P_w \tag{15}$$

Applying the above equation for the case of a buildup test we have:

$$N = \frac{1}{m_{wbs}} * \Delta P_{ws} \tag{16}$$

Applying material balance to the time:

$$\Delta t = \Delta t_{wbs} + N \tag{17}$$

$$\Delta t_{wbs} = \Delta t - \frac{1}{m_{wbs}}\Delta p_{wbs} \tag{18}$$

Also, the rate due to wellbore storage in a buildup test is given as:

$$q_{ref} = q_{BU} + q_{sf} \tag{19}$$

$$q^* = 1 - \frac{q_{sf}}{q_{ref}} \tag{20}$$

$$q^* = 1 - q_{wbs} \tag{21}$$

The wellbore storage-based, material balance time function is expressed as:

$$\Delta t_{mb} = \frac{N}{1 - q_{wbs}} \tag{22}$$

Substituting equation (11) and (16) into (22)
Then the wellbore storage based rate-normalized pressure drop function becomes

$$\Delta p_s = \frac{1}{1 - \frac{1}{m_{wbs}}\frac{d}{d\Delta t}(\Delta p_{wbs})}(\Delta p_{wbs}) \cdots \tag{23}$$

Plot of rate-normalized pressure function versus the material balance time function shows that the material balance time function does correct the erroneous shift in the semi log straight-line obtained by rate normalization.

**β- DECONVOLUTION FORMULATION**

Van Everdingen and Hurst (1953) introduced an exponential model for the sandface rate during the wellbore storage distortion period of a pressure transient test. The exponential formulation of the flowrate function is given as:

$$q_D(t_D) = 1 - e^{-\beta t_D} \ldots \tag{24}$$

Equation (23) is based on the empirical observations made by Van Everdingen and Hurst.

Recalling the Duhamel’s convolution principle equation:

$$P_{WD} = \int_0^{t_D} q'_D(\tau)\, p_{SD}(t_D - \tau)\, d\tau \qquad (25)$$

Laplace transform of integration function is given as follows: If

$$g(t) = \int_0^t f(\tau)\, d\tau \qquad (26)$$

Then

$$L(g)(z) = \frac{1}{z} L(f)(z) \qquad (27)$$

Where z is the Laplace space function.
Therefore, applying Laplace transformation to equation (24):

$$\bar{P}_{wD}(Z) = Z'\bar{q}_D(Z)\bar{P}_{SD}(Z) \qquad (28)$$

NOTE: $z' = \frac{1}{z}$

Rearranging for the equivalent constant rate pressure drop function, $\bar{P}_{SD}$ we obtain The Laplace transform of the rate profile, equation (15) is: Substituting equation (19) into equation (18), we obtain:

$$\bar{P}_{SD}(Z) = \bar{P}_{WD}(Z)(1 + \frac{Z}{\beta}) \qquad (29)$$

Taking the inverse Laplace transformation of this result yields the “beta” deconvolution formula:

$$\beta = \frac{1}{P(t_D) - P_{WD}} \frac{dP_{WD}(t_D)}{dt_D} \qquad (30)$$

To alleviate the issue of the exponential sandface flowrate, equation (18) to solve for the β-term.
Solving equation (18) for the β-term, we have:

Multiplying through by the $C_D$ – term, we have:

$$\beta C_D = \frac{1}{P_{sD}(t_D) - P_{wD}(t_D)} C_D \frac{dP_{wD}(t_D)}{dt_D} \ldots \qquad (31)$$

Recalling the definition of the wellbore storage model, we have:

$$q_D(t_D) = 1 - C_D \frac{dp_{wD}(t_D)}{dt_D} \ldots \qquad (32)$$

Assuming wellbore storage domination (i.e $q_D \approx 0$) at early times then equation (32) becomes:

$$C_D \frac{dp_{wD}(t_D)}{dt_D} \approx 1 \quad \text{(Early time)} \qquad (33)$$

Integrating by separating the variables in equation (23) above, we have:

$$P_{wD} \approx \frac{t_D}{C_D} \quad \text{(Early time).} \qquad (34)$$

Substituting Equation (33) and (34) into equation (31); we obtain:

$$\beta C_D = \frac{1}{P_{sD}(t_D) - \frac{t_D}{C_D}} \quad \text{(Early time)}\ldots \qquad (35)$$

Equation (35) has shown that one can “correlate” the $\beta C_D$ -product with $\frac{t_D}{C_D}$ -this observation becomes the basis for the use of these plotting functions to compare the β-deconvolution relations. The “master” plot of the β-deconvolution function for the case of a single well in an infinite-acting homogenous reservoir is derived using equation (20).

## III. DERIVATION OF THE COEFFICIENT FOR β-DECONVOLUTION

From Van Everdingen and Hurst exponential rate model, we have:

$$q_D = 1 - e^{-\beta(t_D)t_D} \qquad \text{(36)}$$

Taking the time derivative of equation (36), we have

$$q'_D = \frac{dq_D}{dt_D} = b(t_D)e^{-\beta(t_D)t_D} \qquad \text{(37)}$$

Where the $b(t_D)$ -term is defined as:

$$b(t_D) = \beta(t_D) + \beta'(t_D)t_D \qquad \text{(28)}$$

taking the time derivative, $q'_D(t_D) = \frac{dq_D}{dt_D} = -C_D \frac{d^2 p_{wD}}{dt^2} = -C_D\, p''_{wD} \cdots$ (39)

Equating equations (27) and (28) gives:

$$C_D\, p''_{wD}(t_D) = C_D \frac{d^2 p_{wD}}{dt_D^2} = -b(t_D)e^{-\beta(t_D)t_D} \ldots \qquad \text{(40)}$$

Equating equation (21) and (25), we have:

$$e^{-\beta(t_D)t_D} = C_D \frac{dp_{wD}}{dt_D} = C_D\, p'_{wD}(t_D) \qquad \text{(41)}$$

Combining equation (28) and (29) and solving for $b(t_D)$

$$b(t_D) = -\frac{1}{t_D}\frac{p''_{wD}}{p'_{wD}} = \beta(t_D) + \beta'(t_D)t_D \qquad \text{(42)}$$

Where the $p''_{wD}$ and $p'_{wD}$ terms are defined as:

$$P_{wDd} = t_D \frac{dp_{wD}}{dt_D} \qquad \text{(43)}$$

$$P_{wDdd} = t^2_D \frac{d^2 p_{wD}}{dt^2_D} \qquad \text{(44)}$$

Equation (41) can be used to determine β($t_D$) and β'($t_D$) — a graphical representation of the equation, where the intercept and slope values are β($t_D$) and β'($t_D$) respectively.

The value of β($t_D$) and β'($t_D$) can be approximated by numerical methods such as least square — which is the functional approach adopted here

## IV. DISCUSSION AND RESULT:

A single-phase and single-rate pressure buildup test was conducted on a case study oil well- Xl. using the following reservoir parameters: $B_O$ = 1.224 rb/stb, h = 55ft, ϕ = 0.06, $r_w$ = 0.21ft, $C_t$ =17.5 x $10^{-6}$ $Psi^{-1}$, $\mu_o$ = 0.65 cp, $\rho_o$ =53.5 lbm/$ft^3$, $q_f$ = 250stb/day, $t_p$=13,630 hours.

The material balance deconvolution technique performs extremely well, with minor discrepancies at the start of the data set. At the beginning of the data set deconvolved, the material balance shows an abnormal curve or deviation from the normal trend, thus, not a better tool for deconvolving during this time period. However, after the very early time period, the material balance deconvolution method performs very well like every other deconvolution method and gives a better estimation of the reservoir parameters than any other deconvolution technique. The 'beta' deconvolution method was also a good deconvolution method as shown in Figure 3 It has an advantage over the material balance during the very early time period and after which it is not a better deconvolution method than the material balance method as shown in Figure 4. However it gives an estimate of the reservoir parameters during the periods dominated by the wellbore storage effects, though not as accurate as the material balance method. Nevertheless, both can yield reservoir parameters at any time, provided the production rate varies exponentially during the shut-in period.

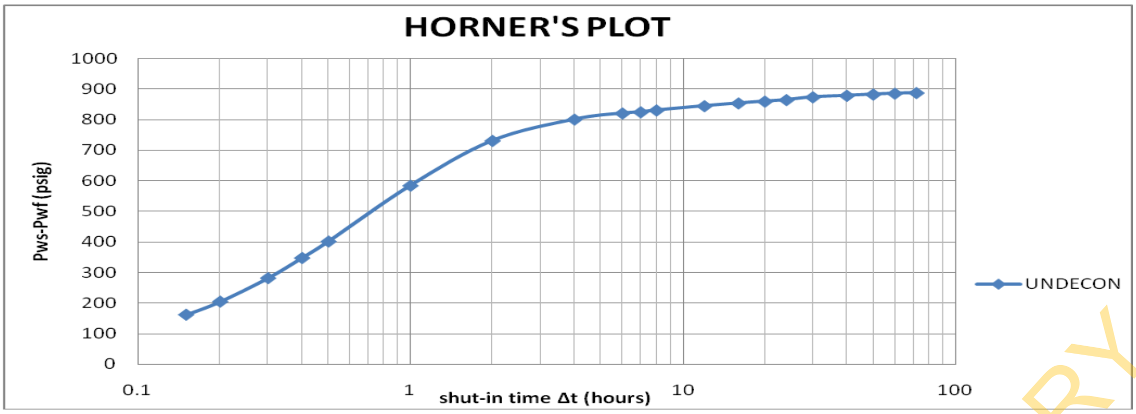

Figure 1: Horner's plot for the case study well-XI.

**Table1 : Pressure buildup data from the case study well-XI**

| S/N | $\Delta t$ | $P_{ws}$ |
|---|---|---|
| 1 | 0 | 3519 |
| 2 | 0.15 | 3680 |
| 3 | 0.2 | 3723 |
| 4 | 0.3 | 3800 |
| 5 | 0.4 | 3866 |
| 6 | 0.5 | 3920 |
| 7 | 1 | 4103 |
| 8 | 2 | 4250 |
| 9 | 4 | 4320 |
| 10 | 6 | 4340 |
| 11 | 7 | 4344 |
| 12 | 8 | 4350 |
| 13 | 12 | 4364 |
| 14 | 16 | 4373 |
| 15 | 20 | 4379 |
| 16 | 24 | 4384 |
| 17 | 30 | 4393 |
| 18 | 40 | 4398 |
| 19 | 50 | 4402 |
| 20 | 60 | 4405 |
| 21 | 72 | 4407 |

**Table 2: Shut-in time and undeconvolved Pressure data**

| S/N | $\Delta t$ | $P_{ws}$ | $\Delta P_{ws}$ |
|---|---|---|---|
| 1. | 0 | 3519 | 0 |
| 2 | 0.15 | 3680 | 161 |
| 3 | 0.2 | 3723 | 204 |
| 4 | 0.3 | 3800 | 281 |
| 5 | 0.4 | 3866 | 347 |
| 6 | 0.5 | 3920 | 401 |
| 7 | 1 | 4103 | 584 |
| 8 | 2 | 4250 | 731 |
| 9 | 4 | 4320 | 801 |
| 10 | 6 | 4340 | 821 |
| 11 | 7 | 4344 | 825 |
| 12 | 8 | 4350 | 831 |
| 13 | 12 | 4364 | 845 |

| | | | |
|---|---|---|---|
| 14 | 16 | 4373 | 854 |
| 15 | 20 | 4379 | 860 |
| 16 | 24 | 4384 | 865 |
| 17 | 30 | 4393 | 874 |
| 18 | 40 | 4398 | 879 |
| 19 | 50 | 4402 | 883 |
| 20 | 60 | 4405 | 886 |
| 21 | 72 | 4407 | 888 |

**Table 3: Material data deconvolution data**

| S/N | $P_{ws}(psig)$ | $P_{ws}(psia)$ | $\Delta t(hours)$ | $\Delta p_{ws}$ | $\frac{1}{m_{wbs}}\Delta p_{ws}$ | $\Delta t-\frac{1}{m_{wbs}}\Delta p_{ws}$ | $\frac{d}{d\Delta t}[\Delta p_{ws}]$ | $\frac{1}{m_{wbs}}\frac{d}{d\Delta t}[\Delta p_{ws}]$ | $1-\frac{1}{m_{wbs}}\frac{d}{d\Delta t}[\Delta p_{ws}]$ | $t_{mbs}$ | $p_{mbs}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3519 | 3534 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 2 | 3680 | 3695 | 0.15 | 161 | 0.1607 | -0.0107 | 509.250 | 0.509 | 0.491 | -0.022 | 327.458 |
| 3 | 3723 | 3738 | 0.2 | 204 | 0.2037 | -0.0037 | 400.000 | 0.400 | 0.600 | -0.006 | 339.500 |
| 4 | 3800 | 3815 | 0.3 | 281 | 0.2807 | 0.0193 | 357.500 | 0.358 | 0.643 | 0.030 | 436.887 |
| 5 | 3866 | 3881 | 0.4 | 347 | 0.3467 | 0.0533 | 300.000 | 0.300 | 0.700 | 0.076 | 495.286 |
| 6 | 3920 | 3935 | 0.5 | 401 | 0.4007 | 0.0993 | 197.500 | 0.198 | 0.803 | 0.124 | 499.315 |
| 7 | 4103 | 4118 | 1 | 584 | 0.5837 | 0.4163 | 110.000 | 0.110 | 0.890 | 0.468 | 655.843 |
| 8 | 4250 | 4265 | 2 | 731 | 0.7307 | 1.2693 | 36.167 | 0.036 | 0.964 | 1.317 | 758.119 |
| 9 | 4320 | 4335 | 4 | 801 | 0.8007 | 3.1993 | 11.250 | 0.011 | 0.989 | 3.236 | 809.810 |
| 10 | 4340 | 4355 | 6 | 821 | 0.8207 | 5.1793 | 4.000 | 0.004 | 0.996 | 5.200 | 823.996 |
| 11 | 4344 | 4359 | 7 | 825 | 0.8247 | 6.1753 | 2.500 | 0.003 | 0.998 | 6.191 | 826.767 |
| 12 | 4350 | 4365 | 8 | 831 | 0.8307 | 7.1693 | 2.000 | 0.002 | 0.998 | 7.184 | 832.365 |
| 13 | 4364 | 4379 | 12 | 845 | 0.8447 | 11.1553 | 1.438 | 0.001 | 0.999 | 11.171 | 845.916 |
| 14 | 4373 | 4388 | 16 | 854 | 0.8537 | 15.1463 | 0.938 | 0.001 | 0.999 | 15.161 | 854.501 |
| 15 | 4379 | 4394 | 20 | 860 | 0.8597 | 19.1403 | 0.688 | 0.001 | 0.999 | 19.153 | 860.291 |
| 16 | 4384 | 4399 | 24 | 865 | 0.8647 | 23.1353 | 0.700 | 0.001 | 0.999 | 23.152 | 865.306 |
| 17 | 4393 | 4408 | 30 | 874 | 0.8737 | 29.1263 | 0.438 | 0.000 | 1.000 | 29.139 | 874.082 |
| 18 | 4398 | 4413 | 40 | 879 | 0.8787 | 39.1213 | 0.225 | 0.000 | 1.000 | 39.130 | 878.898 |
| 19 | 4402 | 4417 | 50 | 883 | 0.8827 | 49.1173 | 0.175 | 0.000 | 1.000 | 49.126 | 882.854 |
| 20 | 4405 | 4420 | 60 | 886 | 0.8857 | 59.1143 | 0.114 | 0.000 | 1.000 | 59.121 | 885.801 |
| 21 | 4407 | 4422 | 72 | 888 | 0.8877 | 71.1123 | 7.381 | 0.007 | 0.993 | 71.641 | 894.301 |

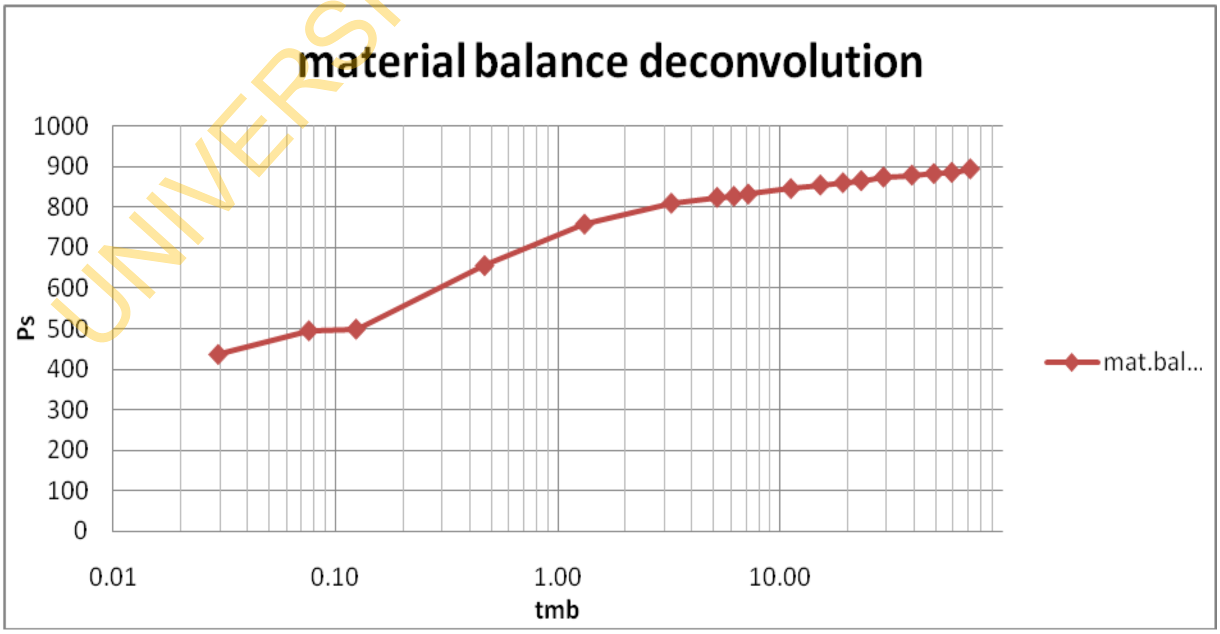

Figure 2: Material balance  deconvolved data

Table 4: Beta deconvolution data

| $S/N$ | $\Delta t$ | $P_{ws}$ | $\Delta P_{ws}$ | $P_D$ | $t_D$ | $\frac{\partial P_D}{\partial t_D}$ | $\frac{1}{\beta}\frac{\partial P_D}{\partial t_D}$ | $P_{SD}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 3519 | 0 | 0 | 0 | 0 |  | 0 |
| 2 | 0.15 | 3680 | 161 | 2.605118 | 0.110518 | 11.2003 | 0.00053 | 338.7342 |
| 3 | 0.2 | 3723 | 204 | 3.300895 | 0.147357 | 8.78455 | 0.000554 | 429.1883 |
| 4 | 0.3 | 3800 | 281 | 4.54682 | 0.221036 | 7.851191 | 0.000742 | 591.1832 |
| 5 | 0.4 | 3866 | 347 | 5.614757 | 0.294715 | 6.588412 | 0.000831 | 730.0264 |
| 6 | 0.5 | 3920 | 401 | 6.488523 | 0.368394 | 4.337371 | 0.000684 | 843.5969 |
| 7 | 1 | 4103 | 584 | 9.44962 | 0.736787 | 2.415751 | 0.000761 | 1134.046 |
| 8 | 2 | 4250 | 731 | 11.82821 | 1.473574 | 0.79427 | 0.000501 | 1419.445 |
| 9 | 4 | 4320 | 801 | 12.96087 | 2.947148 | 0.247065 | 0.000311 | 1555.341 |
| 10 | 6 | 4340 | 821 | 13.28448 | 4.420722 | 0.087845 | 0.000166 | 1594.158 |
| 11 | 7 | 4344 | 825 | 13.34921 | 5.157509 | 0.054903 | 0.000121 | 1601.919 |
| 12 | 8 | 4350 | 831 | 13.44629 | 5.894296 | 0.043923 | 0.000111 | 1613.568 |
| 13 | 12 | 4364 | 845 | 13.67282 | 8.841444 | 0.031569 | 0.000119 | 1640.753 |
| 14 | 16 | 4373 | 854 | 13.81845 | 11.78859 | 0.020589 | 0.000104 | 1658.227 |
| 15 | 20 | 4379 | 860 | 13.91554 | 14.73574 | 0.015098 | 9.52E-05 | 1669.876 |
| 16 | 24 | 4384 | 865 | 13.99644 | 17.68289 | 0.015373 | 0.000116 | 1679.587 |
| 17 | 30 | 4393 | 874 | 14.14207 | 22.10361 | 0.009608 | 9.09E-05 | 1697.059 |
| 18 | 40 | 4398 | 879 | 14.22297 | 29.47148 | 0.004941 | 6.23E-05 | 1706.764 |
| 19 | 50 | 4402 | 883 | 14.2877 | 36.83935 | 0.003843 | 6.06E-05 | 1714.531 |
| 20 | 60 | 4405 | 886 | 14.33624 | 44.20722 | 0.002496 | 4.72E-05 | 1720.354 |
| 21 | 72 | 4407 | 888 | 14.3686 | 53.04867 | 0.162148 | 0.00368 | 1724.674 |

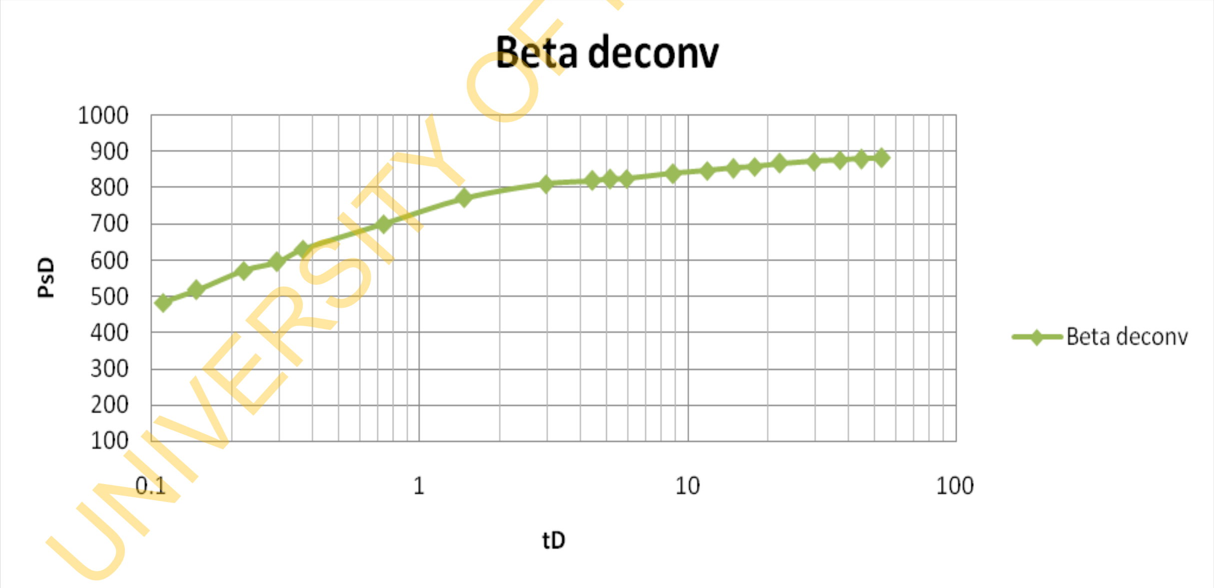

Figure 3: β-deconvolved data

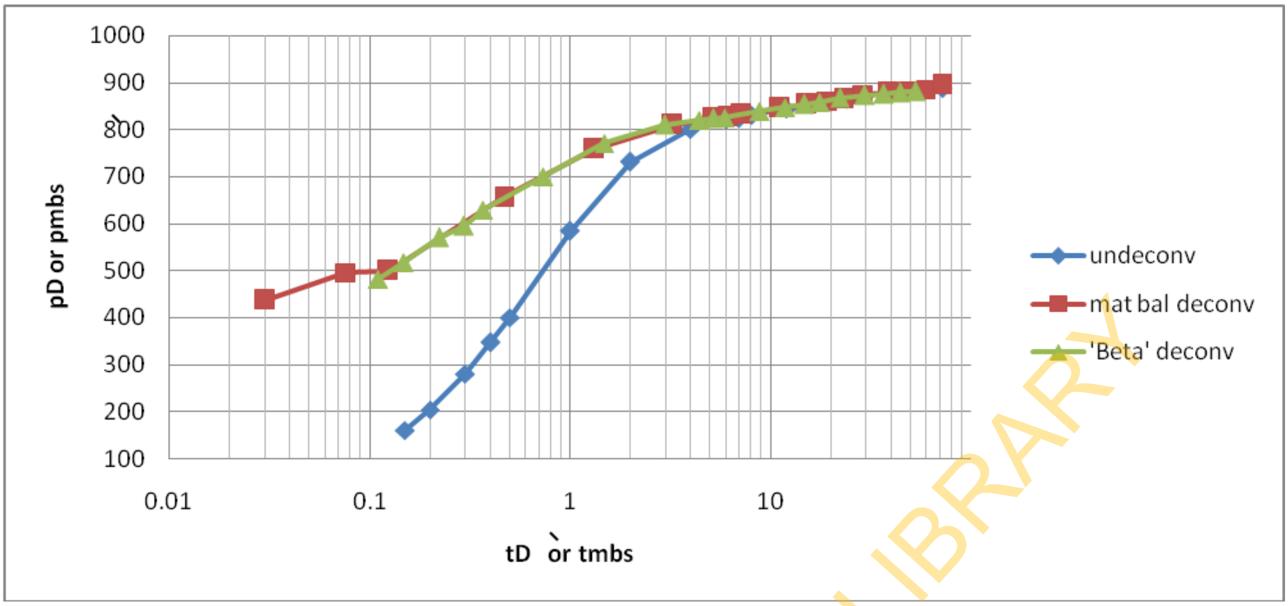

**Figure 4: Comparison of the deconvolved and undeconvolved data**

**Table 5. Comparing the Undeconvolution and Deconvoluted Results**

| PARAMETER | UNDECONVOLUTED | DECONVOLUTED | |
|---|---|---|---|
| | (MTR) | MATERIAL BAL | BETA' |
| m(psi/cycle) | 70 | 110 | 200 |
| K(mD) | 8.4 | 5.4 | 3.9 |
| S | 5.87 | 4.2 | 2.7 |

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