Wireline Formation Testers Analysis with Deconvolution

By

Joelle Mitri

A report submitted in partial fulfillment of the requirements for the award of the degree of Master of Science in Petroleum Engineering

September 2013
DECLARATION OF OWN WORK

I declare that this thesis *Wireline Formation Testers Analysis with Deconvolution* is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature:

Name of student: Joelle Mitri

Names of supervisors: Prof. Alain C. Gringarten and Lekan Aluko (Petro-vision)
ACKNOWLEDGEMENT

To my parents and sisters, for their continuous and invariable support of my endeavors, in literally all four corners of the world.

To my boyfriend, for his impatience, a constant reminder of what life is really about.

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A Sincere Thank you,

Joelle
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Wireline Formation Testers Analysis with Deconvolution

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Abstract

Wireline Formation Testers (WFTs) technology evolved considerably over the last 50 years following the developments in exploration frontiers. Deeper waters and increasingly more challenging environments drove the rising demand for complete and efficient reservoir characterisation. From the introduction of the Formation Tester in 1955 providing one sample per descent, to the Repeat Formation Tester (RFT*) in 1975, and the Modular Formation Dynamics Tester (MDT*) in 1991, WFT toolstrings today can combine up to 30 different modules and provide days of continuous reservoir evaluation.

This was coupled with the development of Crystal Quartz Gauges (CQG*) with improved accuracy and dynamic response, as well as reliable Tough Logging Conditions (TLC*). TLC conveyance technology enables these tools to be run on drill pipe while still connected to the wireline, therefore eliminating the weight limitation and reducing the fishing risk. On deep water operations, development/marginal wells and in environmentally sensitive areas, cost and flaring constraints may render a well testing operation uneconomic or impossible. With much diversity and reliability, WFT services namely, Interval Pressure-Transient Tests (IPTTs), emerged as substitutes to conventional well testing under these conditions. IPTTs combine a dual-packer module, isolating a one-meter interval of formation, with traditionally one or two vertical observation probes. This resulting transient behaviour matches that of a limited-entry well.

This study looks into the analysis of both synthetic and real pressure transient data obtained from IPTTs, using the latest Well Test Analysis (WTA) tool: Deconvolution. Deconvolution transforms the pressure and variable-rate history of a given well into a constant-rate drawdown with a duration equivalent to that of the entire test. This increased depth of investigation may reveal or confirm critical boundary conditions that are otherwise not detected when interpreting individual flow periods. Another powerful advantage of deconvolution is its ability to correct for erroneous rates which heavily compromise conventional WTA techniques such as the superposition function. Although deconvolution was introduced in the literature as early as 1949, its application only came recently after a reliable algorithm was implemented by von Shcroeter, Hollaender, and Gringarten in 2001.

In principle, deconvolution can be equally applied to IPTTs; however, the openhole conditions which govern a WFT operation challenge this undertaking: They involve withdrawal of drilling mud trapped in the interval, clean-up of near-wellbore invasion and ultimately sampling of native reservoir fluid. The Duhamel integral underlying the theory of deconvolution, pertains to a linear system which is therefore not entirely satisfied by IPTTs. Through forward modeling, interpretation and sensitivity runs, it is found that invasion exhibits skin-like effects in early-time transients as well as inconsistent late-time behaviors on the deconvolved derivative. Excluding cleanup and contaminated flow periods eliminates this inconsistency but fails to reconstruct the correct pressure history.

Introduction

WFT operations require careful planning and execution as well as a complete understanding of client objectives and borehole conditions. MDT* is a versatile family of tools: probes, packers, pumps, downhole fluid analyzers, sample chambers; robust yet precise engineering designed to meet a wide spectrum of formation and fluid properties. Dual-packers, also known as straddle-packers, provide a flow area a thousand times larger than that of a standard probe, which allows for higher flow rates and reduced drawdowns. They were mainly designed to test thin laminated beds, unconsolidated formations, low permeability formations and fluids at bubble point pressures; additional applications include stress testing and mini-frac. In homogenous layers equally, they provide dynamically-controlled pressure tests, and are combined with vertical probes to deliver interference tests that allow for the direct measurement of vertical and horizontal permeabilities.

IPTTs theory and interpretation are well-established in the literature and are continually explored and revisited as new
technologies emerge; additional accounts can be found in Zimmerman et al. (1990); Goode et al. (1991, 1992); Pop et al. (1993); Ayaz et al. (1996). Applications of IPTTs also include layer productivity estimation prior to completion (Da Prat et al. 1999) and multiphase flow properties derivation by combining resistivity measurements of invasion with IPTTT process (Zeybek et al. 2001). Understanding the invasion and cleanup processes is not only critical to WFT operations but to the overall productivity of the well.

Dynamic mud invasion occurs during the drilling process, it continues after the mud cake has been formed and drilling stopped in a process referred to as filtration or static invasion. Shortly after drilling the formation, the mud cake develops as a result of the suspension of mud particles in the pore space, which leads to further accumulation of solids on the inner wall of the well. Devoid of solvents, filtrate continues to invade the formation at rates proportional to the permeability of the mud cake. This results in formation damage in the invaded zone, reducing permeability, porosity and in some cases altering wettability (Shuang 1990). It has been reported in the literature that relying uniquely on uninvaded formation and fluid properties to analyze WFT data can incur an error of 100% and lead to underestimating permeability by a factor of 3.6 (Goode et al. 1996).

The invasion process depends on many factors namely: pressure differential between the hydrostatic and formation pressures, shear rate, mud solid content, mud type, formation permeability, absolute temperature and time sequential. As a result, modeling invasion is a very complicated task; it is governed by dynamic flow as well as capillary pressures and gravity effects. However, the process itself is not of prime importance to our study but the resulting reservoir conditions prior to WFT and their effect on pressure transients. To model the effect of invasion, several studies assumed negligible capillary pressures and gravity effects as well as negligible formation damage, reducing it to a miscible or immiscible flow (Phelps et al. 1984; Hammond 1991; Zeybek et. al 2001). Goode et al. (1996) developed an analytical model of a two-region problem, the invaded and uninvaded regions, with different vertical and horizontal mobilities and compressibilities. The study investigates the effect of this invasion on the sink, horizontal and vertical probes in a Multi-probe WFT, assuming a sharp invasion front and a piston-like displacement in a single homogenous layer. Gök et al. (2003) developed this model to include dual-packer as well as multi-probe WFT in single and multilayer systems. However, the basic assumption has been that the invasion front is static during the WFT which is not the case on dual-packer operations where cleanup is expected and fluid contamination is monitored in real-time. Alpak et al. (2006) and Malik et al. (2007) used compositional simulators to model the cleanup process and match their simulations to real Gas-Oil Ratio (GOR) and probe transient data.

In this study, we neglect gravity and capillary effects and we model a two-phase flow process in a two-zone radial composite model representing invaded and non-invaded zones. We investigate the effect of Water-Based Mud (WBM) invasion of an oil reservoir flowing above the bubble point pressure, by varying anisotropy, the radius of invasion, viscosity and compressibility of the invading fluid and monitoring transient pressures at the dual-packer and observation probe in a single finite homogenous layer. Finally, the transient data is analyzed using the latest WTA technique: Deconvolution.

Deconvolution was first introduced in the literature by van Everdingen and Hurst (1949) as an adaptation of the Duhamel Principle of heat conduction, but it wasn’t until 2001 that the first robust algorithm was implemented by von Schroeter et al. (2001). This algorithm present several advancements over existing Spectral and Time-Domain methods and was characterized by: a novel encoding of the solution, regularization by curvature to maintain a degree of smoothness in the result, a total least-squares formulation to account for errors in pressure and rate data, and confidence intervals and error estimates for the results. Since, many improvements and applications were suggested to the algorithm and continuous efforts made to encourage reservoir engineers to make use of this powerful technique (von Schroeter et al. 2004; Levitan 2005; Levitan et. al 2006; Gringarten 2006, 2010). Recently, a modification of this algorithm was presented by Pimonov et al. (2009); it enables the user to define different error estimates to different parts of the data as mitigation to unreliable pressure and rate data as well as inconsistencies with the reservoir model. Onur et al. (2011) presented a modification to the latter for multiwell-interference tests and IPTTs by replacing the rate signal with the observation probe signal thus eliminating the errors and uncertainty associated with the flow-rate.

Using generated synthetic and real data sets we investigate the reliability and viability of the deconvolution under different invasion conditions using the algorithm developed by von Schroeter et al. (2004).

Model Design and Verification

The IPTT response we aim to reproduce is that of a dual-packer/probe configuration. The inflatable packers isolate an interval of 3.2ft (0.98m) in the standard configuration that can be extended to 5.2, 8.2 or 11.2ft (1.58, 2.5 or 3.41m) (Schlumberger 2002, 2011). Fig. 1 represents the schematic of this configuration and defines the model parameters h, b, z, r, D, used throughout the paper.

The IPTT model is implemented, using the commercial simulator Eclipse® 100 in fully-implicit blackoil mode (Schlumberger Information Solutions 2010), to examine the effects of varying formation and invasion parameters on the transient data. A 3-D radial grid (r,θ,z) represents a 10-meter thick homogenous layer and extends 500 m away from a vertical
well. A well diameter of 8.5in (0.216m) is set throughout the study. The distance away from the borehole is chosen such that the pressure disturbance does not reach the boundary for the duration of the test.

- With the inner and outer radii of the grid defined, 50 layers make up the radial dimension \( r \) following a geometric series; this ensures the near wellbore area is well defined.

At the observation probe, for an 8.5" hole, 30 divisions with \( d\theta=12^\circ \), result in a cell dimension of 1" equivalent to the diameter of the probe; while the dual packer is azimuthally symmetric. It was found however, that with 8 azimuthal divisions and \( d\theta=45^\circ \), the signal at the probe is equally reproduced and additional computational efficiency is achieved.

- In the \( z \) direction, the grid consists of 107 layers; the dual-packer interval is equally divided into 36 layers while the probe occupies a single layer, one inch in thickness. The remaining layers increase logarithmically away from the interval and probe sections. A cross-section of the grid is shown in Fig. 2.

Table 1 summarizes the main rock and fluid properties of the model. Since we are measuring and interpreting downhole pressures and rates, the total depth of the well and the absolute depth of the model are of no consequence.

On the following tests, the model is run over a 2.4hr constant-rate drawdown period followed by a buildup of equal duration. The time steps vary logarithmically and a flow rate of 5m\(^3\)/day is set throughout. The elements of the final model are built and tested systematically starting with a homogenous limited-entry well, to radial composite and finally invaded radial composite.

**Limited-entry well with C & S, homogenous, infinite lateral extent**

In a limited entry test such as the IPTT with the dual-packers positioned in the middle of the layer, the early-time flow regime is spherical (-1/2 slope); once the upper and lower boundaries of the layer are reached, radial flow stabilization is established. The model transients at the dual-packer and observation probe are matched using Saphir (Kappa Engineering 2012), for \( k_v=50 \text{md} \) and \( k_h=100 \text{md} \), as shown in Fig. 3.

**Table 1 Formation and Fluid Properties, homogenous case**

<table>
<thead>
<tr>
<th>Uninvaded Zone Properties</th>
<th>( \varphi )</th>
<th>0.18</th>
</tr>
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<tbody>
<tr>
<td>( \mu_o ) (cp)</td>
<td>1.142</td>
<td></td>
</tr>
<tr>
<td>( k_h ) (md)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>( k_v ) (md)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>( c_t ) (bar(^{-1}))</td>
<td>1.27E+4</td>
<td></td>
</tr>
<tr>
<td>( S_{sw} )</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>( S_{or} )</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 Schematic of the dual-packers/probe configuration (not drawn to scale)

Figure 2 Cross-section: 3-D Radial grid \((r,\theta,z)\)

Figure 3 Dual-packer (PA) and Observation probe (PS) pressures and derivatives, \( k_v=100 \text{md} \).
Fig. 4a and Fig. 4b demonstrate the effect of varying the \( k_v/k_h \) ratio on the dual-packer and observation probe responses respectively. As the vertical permeability decreases, the radial flow stabilization is delayed; the time it takes pressure disturbance to reach the vertical boundaries increases.

Limited-entry well with C & S, radial composite, infinite lateral extent

We model the invaded and non-invaded zones as co-centric zones around the wellbore with different properties. For a fixed radius of damaged formation \( r_i \), we vary the permeability ‘damage’, which is the ratio of \( k_{hi} \) to \( k_{hu} \). The assumption is that the drilling and invasion process has altered the vertical and horizontal permeabilities equally and so the \( k_v/k_h \) ratios are constant. This is demonstrated in Fig. 5a and Fig. 5b on the dual-packer and observation probe responses respectively. The effect of the formation damage is the alteration of the spherical flow \(-1/2\) slope into a step change; the greater the damage, the larger the step on the derivative response.

As shown in Fig.6a and Fig.6b, the early time response matches the invaded zone properties (homogenous model with invasion zone properties) while the late time behavior is that of the uninvaded zone (match of a homogenous model with uninvaded zone properties). The match comparison was done using Interpret (Paradigm 2010).
For the same invaded and uninvaded zone permeabilities, we vary the radius of the damaged formation; the results are shown in Fig. 7a and Fig. 7b for the dual-packer and obs. probe respectively. The literature suggests that ideally we wouldn’t expect the radius of invasion to extend beyond 48” (Hammond 1991, Phelps 1984, Gök 2003) (values greater than that are for illustration purposes). It is interesting to see as will be pointed out later, that while the dual-packer response shows greater variation, in the early times, to the extent of formation damage, the observation probe exhibits little change; the shallow depths, D< 0.79”, 4.16” and 23.5”, meet at the spherical flow -\frac{1}{2} slope. The permeabilities used to demonstrate this example were: \(k_{r,1} = 5\) md, \(k_{r,2} = 50\) md, \(k_{r,3} = 1.5\) md and \(k_{r,4} = 15\) md.

![Log-Log plot: p-p@dt=0 and derivative [psi] vs dt [hr]](image)

**Figure 7** Effect of varying the radius of invasion on dual-packer (a, left) and obs. probe (b, right) responses, Radial Composite

Limited-entry well with C & S, radial composite (with filtrate invasion), infinite lateral extent

We now investigate the radial composite model with formation damage and presence of mud filtrate. Previous studies assumed sharp and constant invasion fronts corresponding to the formation damage zones. We take a more realistic approach by first simulating the invasion as a water injection process varying the time of invasion. The resulting gradual saturation profiles are then used to initialize the model. As a result, it is not less obvious as to where the extent of the damaged formation should be; here we adopt two methods and explore the difference. In the first, we choose the radius of invasion and formation damage at the point where water saturation is 50%. The second approach uses a narrower front and assumes a radius of invasion and damage at 65% water saturation, which corresponds to 1-S_w. For disambiguation, we will now refer to the radius formation damage radius as \(r_i\) and to that of filtrate invasion as \(r_d\); \(D_i\) and \(D_d\) are the distances measured from the wellbore wall as per Fig. 1.

The invasion front is not assumed to be stationary and so, given the same drawdown duration, the breakthrough of native fluid will vary considerably; this will be illustrated when we vary native and invasion fluid parameters next. For the same values of permeabilities as in figures 7a and 7b, we illustrate the effect of varying the invasion radius with filtrate invasion. We illustrate the first method whereby the formation damage extends to the limit of 50% filtrate saturation in Fig. 8a and Fig. 8b for the dual-packer and obs. probe respectively. The second method is illustrated in Fig. 9a and Fig. 9b.

![Log-Log plot: p-p@dt=0 and derivative [psi] vs dt [hr]](image)

**Figure 8** Effect of varying the radius of invasion on dual-packer (a, left) and obs. probe (b, right) responses, Radial Composite with filtrate invasion

![Log-Log plot: p-p@dt=0 and derivative [psi] vs dt [hr]](image)

**Figure 9** Effect of varying the radius of invasion on dual-packer (a, left) and obs. probe (b, right) responses, Radial Composite with filtrate invasion

Comment [ACG4]: I am not sure I understand the difference. Is this a three-region radial composite?

Comment [ACG5]: Do you mean “not” or “less”?

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Wireline Formation Testers Analysis with Deconvolution

Figure 9 Effect of varying the radius of invasion on dual-packer (a, left) and obs. probe (b, right) responses, Composite with filtrate invasion, Narrow formation damage.

Figure 10 Comparing three cases: 14GK, Formation damage, 13D, Formation Damage and Invasion, 13DF Narrow Formation Damage, filtrate invasion

Putting all the model parameters together in comparison we note from Fig.10a (the dual-packer response) that the two cases with similar formation damage model namely 14GK and 13D, have similar shape, the difference being that the invasion acts like a skin in early time. Reducing the damaged formation zone (as in 13DF case) changed the radial composite model and led to overall a higher oil production from the simulated run. The same was run on a model with higher permeabilities, the same behavior was observed but the cleanup was slower. At the observation probe, the difference is minimal as shown in Fig.10b suggesting the observation probe is less affected by invasion.

Applying deconvolution to the dual-packer and probe transients from case 13DF reveals a late time inconsistency on the dual-packer signal and a poor reconstructed pressure while the result of deconvolution at the probe was satisfactory (Figs. 11a, 11b, 11c, 11d).

Deconvolution of synthetic data

We simulate a sampling WFT sampling consisting of the following schedule of drawdowns (DDs) and build-ups (BU's):

<table>
<thead>
<tr>
<th>Duration (hrs)</th>
<th>Rate (Rm3/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26</td>
<td>3.55</td>
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<tr>
<td>0.17</td>
<td>0</td>
</tr>
<tr>
<td>3.80</td>
<td>3.15</td>
</tr>
<tr>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>5.80</td>
<td>1.32</td>
</tr>
<tr>
<td>0.55</td>
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<tr>
<td>0.79</td>
<td>3.46</td>
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<td>0.32</td>
<td>5.3</td>
</tr>
<tr>
<td>1.05</td>
<td>0</td>
</tr>
</tbody>
</table>

Comment [ACG7]: Difficult to distinguish 14GK from 13DF. Change the colors

Comment [ACG8]: Not identified on the figure

Comment [ACG9]: The correct nomenclature is “skin effect” or “skin factor”

Comment [ACG10]: Which deconvolution software did you use? What did you deconvolve, the DD and the BU or just the BU?

Comment [ACG11]: This seems to be due to an erroneous simulated pressure at the beginning. The simulated pressure goes down and up at the beginning. This is not physical and should be checked.

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Comment [ACG12]: This is not a typical schedule for a sampling MDT. Usually, there is a pre-test at the beginning and another one at the end
First we apply deconvolution in the presence of a damaged formation but in the absence of invasion fluid for easier comparison with the final model. Fig. 12 shows the deconvolved derivative which is consistent with the individual BUs. Next we initialize our model with filtrate invasion, \( r_i = 61'' \), the resulting BUs are shown in Fig. 13. Although the build-ups will eventually converge at late times, early times show that invasion acts like a skin effect. Build-up#1 is the most affected because the previous clean-up was not sufficient. Fig. 14 illustrates the result of Deconvolution of build-ups 2-3-4 which exhibits an inconsistent late time behavior. Nu, Lambda and Pi were varied. Fig. 15 shows a slightly better match still with a hump after varying Pi. Increasing the smoothness or increasing Pi doesn’t correct this hump, it only rotates it. This also confirms that the second clean-up was no effective either. Deconvolution of Build-ups 3&4 is shown in Fig. 16 gave a satisfactory result. However, this result does not reconstruct successfully the Drawdown responses or the build-ups that were affected by invasion and not included in the Deconvolution as shown in Figs. 17 and 18. It behaves like the well was never invaded. A similar behavior was reported in Levitan (2005, Fig. 5) when deconvolving flow periods with changing wellbore storage.

Comment [ACG13]: Show!
Comment [ACG14]: Don’t use the future tense
Comment [ACG15]: Have you tried to deconvolve one BU at a time, and all the data (DDs and BUs)?
Comment [ACG16]: Do not use capital letters for this and similar words
Comment [ACG17]: The figures show a lack of match at the beginning which is clearly associated with erroneous simulated pressures.
Comment [ACG18]: My recollection is that the deconvolved derivative is not correct at early times is skin effects or wellbore coefficients are different in different flow periods. This is of little concern as we do have the actual derivative data at early times. We are mainly interested in late time derivative beyond what is available in the individual flow periods.
Figure 13 CASE B: Log-Log plot of BU 1,2,3,4. Radial composite model initialized with invasion of 61” (dual packer response).

Figure 14 CASE B: Radial composite model initialized with invasion of 61”, BUs 2-3-4. Pi=4855.14 psia (as found by Deconvolution).

Figure 15 CASE B: Radial composite model initialized with invasion of 61”, BUs 2-3-4. Forced Pi to Pi=4855.67 psia.
Discussion and Conclusion

In this study we investigated water invasion in an oil interval flowing at pressures above the bubble point. The reduction in permeability of the invaded zone due to bridging and solids was modeled as a radial composite system and verified. Radius of invasion, mobility ratio and diffusivity were varied between the invaded and non-invaded zones. It was found that the dual-packer response is more affected by invasion in early times than the response seen at the observation probe.

A job was simulated with various rates and cleanup and build-up periods and deconvolution applied systematically on the pressure signal of the dual-packer. As expected, invasion imposed a non-linear system and deconvolution applied on the entire dataset yielded erroneous results and the effect was seen on early as well as late times.

The length of the cleanup period is clearly the most important factor in getting the most out of subsequent flow periods with deconvolution. Smaller permeabilities result in faster cleanup with greater drawdown. In a real well situation, the quality of the mudcake also plays a big role in recharging the invasion and effective cleanup (supercharging).

Applying deconvolution on this inconsistent data set yielded a consistent deconvolved derivative when applying it on buildups after sufficient cleanup has been made; that means after the effect of invasion has been reduced or eliminated.

As a result, the reconstructed pressure has no memory of invasion and does not match the actual signal.

As a way forward, having showed the more consistent data quality at the probe, it would be interesting to apply the algorithm by replacing rates with the signal at the observation probe.
Wireline Formation Testers Analysis with Deconvolution

Figure 18 Reconstruction of Deconvolution with Build-ups 2-3&4 (Above). Close-up on Build-ups 2-3&4 (Below)

Nomenclature

\[ D_1 = \text{Distance from middle of dual-packer interval to probe, } L, \text{ m (ft)} \]
\[ D_i = \text{Extent of invasion measured from the borehole wall, } L, \text{ in} \]
\[ D_f = \text{Extent of formation damage measured from the borehole wall, } L, \text{ in} \]
\[ h = \text{Thickness of homogenous layer, } L, \text{ m} \]
\[ h_w = \text{Thickness of the dual-packer interval, } L, \text{ m (ft)} \]
\[ k = \text{Permeability, } L^2, \text{ md} \]
\[ M = \text{Mobility ratio, ratio} \]
\[ p = \text{Pressure m/Lt}^2, \text{ psia} \]
\[ r_i = \text{Radius of invasion measured from the center of the wellbore, } L, \text{ in} \]
\[ r_f = \text{Radius of formation damage measured from the center of the wellbore, } L, \text{ in} \]
\[ t = \text{Time, t, hours} \]
\[ z_w = \text{Distance from middle of dual-packer interval to bottom boundary, } L, \text{ m(ft)} \]
\[ \mu = \text{mobility, } L^3/t, \text{ md/cp} \]
\[ d\theta = \text{Angle of grid azimuthal division, angle, deg} \]
\[ \mu_o = \text{Oil viscosity, m/Lt, cp} \]
\[ \mu_w = \text{Water viscosity, m/Lt, cp} \]
\[ \mu_f = \text{Fluid viscosity, m/Lt, cp} \]
\[ \phi = \text{porosity, } L^3/L^3, \text{ fraction} \]

Subscripts

\[ h = \text{Horizontal} \]
\[ i = \text{Invaded Zone} \]
\[ u = \text{Uninvaded Zone} \]
\[ v = \text{Vertical} \]
References


APPENDICES

A- APPENDIX: MILESTONES

<table>
<thead>
<tr>
<th>Paper No</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>71574-MS</td>
<td>2001</td>
<td>Deconvolution of Well Test Data as a Nonlinear Total Least Squares Problem</td>
<td>Thomas von Schroeter, Florian Hollaender, Alain C. Gringarten</td>
<td>First introduction of a new method that demonstrates Deconvolution as a separable nonlinear Total Least Squares (TLS) problem. A modified error model accounts for errors in both pressure and rate data. This method enables to deconvolve smooth, interpretable response functions from data with errors of up to 10% in rates.</td>
</tr>
<tr>
<td>77688-PA</td>
<td>2004</td>
<td>Deconvolution of Well Test Data as a Nonlinear Total Least Squares Problem</td>
<td>Thomas von Schroeter, Florian Hollaender, Alain C. Gringarten</td>
<td>Regularization of smoothness was modified. It introduced bias and confidence intervals of signal.</td>
</tr>
<tr>
<td>84290-PA</td>
<td>2005</td>
<td>Practical Application of Pressure/Rate Deconvolution to Analysis of Real Well Tests</td>
<td>Michael M. Levitan</td>
<td>Von Schroeter et al’s algorithm fails when used with inconsistent data. The paper presents enhancement to the existing deconvolution algorithm that allows it to be used reliably with real test data.</td>
</tr>
<tr>
<td>23030-PA</td>
<td>1996</td>
<td>Influence of an Invaded Zone on a Multiprobe Formation Tester</td>
<td>Peter A. Goode R.K. Michael Thamblyatham</td>
<td>Developed an analytical model of a two-region problem, the invaded and uninvaded regions, with different vertical and horizontal mobilities and compressibilities. The study investigates the effect of this invasion on the sink, horizontal and vertical probes in a Multi-probe WFT, assuming a sharp invasion front and a piston-like displacement in a single homogenous layer.</td>
</tr>
<tr>
<td>SPE-84093-PA</td>
<td>2006</td>
<td>Effect of an Invaded Zone on Pressure-Transient Data From Multiprobe and Packer-Probe Wireline Formation Testers</td>
<td>Ihsan M. Gok, SPE, and Mustafa Onur, SPE, Istanbul Technical U.; Peter S. Hegeman, SPE, and Fikri J. Kuchuk, SPE, Schlumberger</td>
<td>Discusses the effects of the invasion on Pressure transient data (Probe and Dual Packer) and sets out to model it using composite zones concentric with the reservoir in order to estimate both invaded and non-invaded properties.</td>
</tr>
<tr>
<td>90680-PA</td>
<td>2006</td>
<td>Practical Considerations for Pressure-Rate Deconvolution of Well-Test Data</td>
<td>Michael M. Levitan, Gary E. Crawford, Andrew Hardwick</td>
<td>Paper presents how to recover the initial reservoir pressure from well test data by use of Deconvolution. It also introduces the application of Deconvolution sequentially to individual build-ups.</td>
</tr>
<tr>
<td>SPE-123982-MS</td>
<td>2010</td>
<td>A New Pressure Rate Deconvolution Algorithm to Analyze Wireline Formation Tester and Well-Test Data</td>
<td>Evgeny Pimonov and Cosan Ayan, Schlumberger; Mustafa Onur, Istanbul Technical University; and Fikri Kuchuk, Schlumberger</td>
<td>A modification to the algorithm of von Schroeter et al is presented. It enables the user to define different error estimates to different parts of the data as mitigation to unreliable pressure and rate data as well as inconsistencies with the reservoir model.</td>
</tr>
<tr>
<td>SPE-149567-PA</td>
<td>2011</td>
<td>Pressure-Pressure Deconvolution Analysis of Multiwell-Interference and Interval-Pressure-Transient Tests</td>
<td>M. Onur, Istanbul Technical University; and C. Ayan and F.J. Kuchuk, Schlumberger</td>
<td>Onur et al. (2011) presented a modification to the Pimonov 2009 algorithm for multiwell-interference tests and IPTTs by replacing the rate signal with the observation probe signal thus eliminating the errors and uncertainty associated with the flow-rate.</td>
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</table>
B- APPENDIX: CRITICAL LITERATURE REVIEW

SPE: 71574-MS (2001)
Deconvolution of well test data as a nonlinear Total Least Squares problem

Authors: Thomas von Schroeter, Florian Hollaender, Alain C. Gringarten

Contribution to the understanding of deconvolution:
This algorithm presented several advancements over existing Spectral and Time-Domain methods and was characterized by: a novel encoding of the solution, regularization by curvature to maintain a degree of smoothness in the result, a total least-squares formulation to account for errors in pressure and rate data.

Objective of the paper:
- To introduce a robust deconvolution algorithm

Methodology used:
- Novel method of encoding the solution to eliminate the need for sign constraint. The algorithm calculates the natural logarithm of the derivative instead of the derivative itself.
- Minimization of an error measure function $E$ by minimizing its three error sources: error in pressure ($\varepsilon$), error in rates ($\delta$) and smoothness term ($Dz$).

Conclusion reached:
- If $\lambda$ and $\nu$ should are selected carefully this algorithm was proved to be robust in deconvolving simulated and real test data, allowing for errors in the measurement, up to 10%.
- The result is a unit rate drawdown signal with a duration equivalent to that of the entire test.

Comments:
- Needs to be applied carefully and with knowledge due to the subjective input of the user.
“Deconvolution of well test data as a nonlinear Total Least Squares problem”

Authors: Thomas von Schroeter, Florian Hollaender, Alain C. Gringarten

Contribution to the understanding of deconvolution:
- This paper presents a method to output estimates for bias and confidence intervals of the parameters

Objective of the paper:
- Demonstration of improvements of deconvolution algorithm presented in SPE paper 71574-MS.
- Reinforces the algorithm developed in 2001 by applying deconvolution to extensive data.

Methodology used:
- In contrast to previous SPE paper 71574, assumption is made that the initial reservoir pressure is known
- The original error weight ($ν$) is multiplied by a factor N/m in order to balance the effect of different sample sizes on the pressure drop and derivative

Conclusion reached:
- Eliminated the oscillations previously encountered by adding the regularization by curvature. It prevents the flattening of the derivative while keeping it smooth.
- Deconvolution can be applied to independent flow periods.
- Deconvolution handles error and pressure errors very well.
- The selection criteria of error weight ($ν$) and regularization parameter ($λ$) remains as a very subjective one.

Comments:
- Care must be exercised when increasing the regularization parameter. Result constantly monitored and compared with original data.
SPE: 84290-PA (2005)  
“Practical application of pressure-rate deconvolution to analysis of real well tests”  
Authors: Michael M. Levitan

Contribution to the understanding of deconvolution:
- The paper states that the algorithm developed by von Schroeter et al. 2001 works well on consistent sets of pressure and rate data. However, the algorithm fails when applied on inconsistent data set.
- Inconsistency is given by skin factor or wellbore storage changing with time.

Objective of the paper:
- Evaluate the application and limitations of the von Schroeter algorithm
- Demonstrates some enhancements to the original algorithm for it to be applied reliably with inconsistent data sets

Methodology used:
- Demonstrates the application and limitations of the deconvolution algorithm using several inconsistent data sets.

Conclusion reached:
- For Inconsistent data sets, deconvolution produces correct results when applied to individual flow periods
- The pressure data from a single flow period do not contain enough information to identify initial reservoir pressure and to correct rates. Comparison of the deconvolved derivative from several flow periods is necessary to identify initial reservoir pressure and model parameters.