DECONVOLUTION IN WELL TESTING

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ABSTRACT

Well testing refers to the collection of data and measurement, and the verification of the reservoir’s ability to produce. Pressure transient analysis (PTA) is the interpretation methodology and usually begins with the examination of the rate and downhole pressure test data on different derivative, superposition, or Cartesian Plots. From these plots, a united and more recognizable picture can be built which will enable us to understand the main features of the test transient pressure behavior and to characterize well and reservoir parameters. This traditional and conventional well testing approach is still being used. However, a new well testing tool called Deconvolution was starting to receive much attention, and has been emerging as a new tool of analyzing test data in the form of constant rate drawdown response. In other words, it transforms variable rate and pressure data into initial constant rate pressure response equal to the duration of the entire test. Pressure rate deconvolution is not a replacement of conventional techniques but a useful addition to the well test analysis. The results will provide us with additional insights of the reservoir. In this paper, a brief introduction of conventional well test interpretation will be presented, followed by several cases concerning the use of deconvolution, where its limitations will be demonstrated and its results will be interpreted. Some recommendations on how to avoid some unwanted results will be stated as well.

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Dedicated to the memory of my grandfather, Pierre Abou Jaoude, who always believed in my ability to be successful in my academic years. You are gone but your belief in me has made this journey possible, and I am sure that you are always watching over me from above.

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Nomenclature

BOPD: Barrels of oil per day

Psi: Pounds per square inches

mD: Milli-Darcy

tp: Production time

ΔP_{DD}: Variation in pressure drawdown

Pwf: Bottom hole pressure

Pi: Initial pressure

bbl: Barrels

stbbl: Stock tank barrels

cP: centi- Poise

q: Oil or Gas rate

B: Formation volume factor

μ: Viscosity

K: Permeability

h: Net Pay

PI: Productivity index

Re: Drainage radius

Rw: Wellbore radius

S: Skin

PSS: Pseudo-Steady State

Φ: Porosity

IARF: Infinite Acting Radial Flow

PBU: Pressure Build-Up

Conversion table

Variable	**Oilfield Unit**	**SI Unit**	**Conversion (Multiply SI Unit)**
Volume	bbl	m^3	6.29
Compressibility	psi^{-1}	Pa^{-1}	6897
Length	ft	m	3.28
Permeability	mD	m^2	1.01×10^{15}
Pressure	psi	Pa	1.45×10^{-4}
Rate (oil)	BOPD	m^3/s	5.434×10^5
Rate (gas)	Mscf/d	m^3/s	3049
Viscosity	cP	Pa-s	1000

Introduction

Well testing refers to the gathering of data and measurements while flowing fluids from the well, into the reservoir, and out through the well and into the surface, and is usually carried out at all stages from exploration to field development[1]. Well testing is a really important key to determine whether a formation is able to produce hydrocarbons, and to estimate the amount of production, which in turn will be useful for determining whether we will have an extra return on capital invested in the project[2]. The main objectives in well testing is to be able to design a well test program, to interpret the results of well test analysis, and to use modern software to conduct the interpretation[3]. Evaluation of pressure transient behaviors starts with the interrogation of test data on different analysis plots like the derivative plots and superposition plots. Each plot is examined and read in a different way, and provides us with a different view of pressure transient behavior[4]. After collecting data and adding the results, a much bigger and clearer picture of our final reservoir shape and the properties of the fluids will be obtained[4]. This traditional pressure transient analysis, also known as build up test, relies on the use of downhole pressure measurements from permanent or retrievable gauges with a fixed flow rate[4]. This conventional well testing method is still being used nowadays, but something new was recently being introduced.

In the past decade, a method called Deconvolution was starting to receive much attention, and has been emerging as a new tool of analyzing test data in the form of constant rate drawdown response using specific pressure rate algorithms. It isn't considered a new method; it is the same as the derivative method but enables us to process pressure and rate data to obtain additional information on the pressure to be interpreted[5]. Deconvolution converts a multi-rate pressure response into a single rate pressure response, equal to the duration of the entire test, and directly yields the corresponding pressure derivative normalized to a unit rate[5]. Hence, the deconvolved response is defined on longer time interval, and gives us additional features and insights that could not be observed with conventional analysis approach[4]. The reconstructed response combines wellbore storage and skin effects. However, the calculation of the deconvolved response is complex. Most of the times, it can be non-unique depending on the available data, where it can give different number of responses which it thinks are true, but actually are not the optimal solution. Also, the process is sensitive to different types of data like the initial pressure. As a result, engineers using this tool encounter so many limitations, and sometimes feel doubtful about its reliability[4]. There is no guarantee that deconvolution will provide us with a meaningful result. Many factors should be taken into account, and should be studied carefully, in order for this method to be successful and give accurate results.

In this paper, a brief introduction to well testing will be presented at first, followed by some literature about the advantages of deconvolution, as well as its limitations. Furthermore, various uses of deconvolution in long and short test durations will be stated, where its problems will be tackled, and practical considerations and recommendations on how to resolve deconvolution problems in order to produce correct results will be discussed. Several number of cases will be demonstrated.

Introduction to Well Testing

"Well testing is related to recording pressure measurements near the productive interval, the fabrication of the basis for transient well test analysis, and the primarily use for determining rock properties of the reservoir and build limits of the formation" [6]. Furthermore, it allows us to predict if the project will be economically feasible or not, through predicting production amount. While testing exploration wells, the data collected is analyzed and used to determine an estimation of reservoir limits and volume, in addition to well permeability and skin effects[1]. Fluid samples are also taken to determine properties of hydrocarbons inside the reservoir. For testing producing wells, usually the most important data obtained are the estimation of formation pressure of the reservoir (also known as static initial pressure), verification of formation permeability and skin, as well as the prediction of the behavior or interactions between reservoir rock and fluids[1]. Operators use these data to determine the most efficient way for the extraction process[2]. There are several types of well test like[7]:

- Mini-DST, to find formation pressure, mobility and to have fluid samples
- Drill stem test or DST, to find formation pressure, permeability, skin, and to have fluid samples
- Standard production test, in which our main objectives are to find permeability, reservoir boundaries, skin, well deliverability and others
- Limit Test, in which we investigate reservoir boundaries
- Interference Test, to study communication between layers

1. Well Performance

When we flow a well or inject at a certain rate, pressure changes will be created in the reservoir and in the well itself. It is important to measure the performance of that well (producing or injecting), especially the Inflow Performance Relationship (IPR), which describes the capacity of the reservoir to yield up fluids as they move to the wellbore through the rock, as well as the Vertical Flow Performance (VFP), which describes the capacity of the wellbore to give up fluids (inside the well up to the surface) [8]. A change in rate can be created by opening or closing the choke at the surface, which will lead to the movement of the VFP curves and the change in operating point, as seen in the figure below:

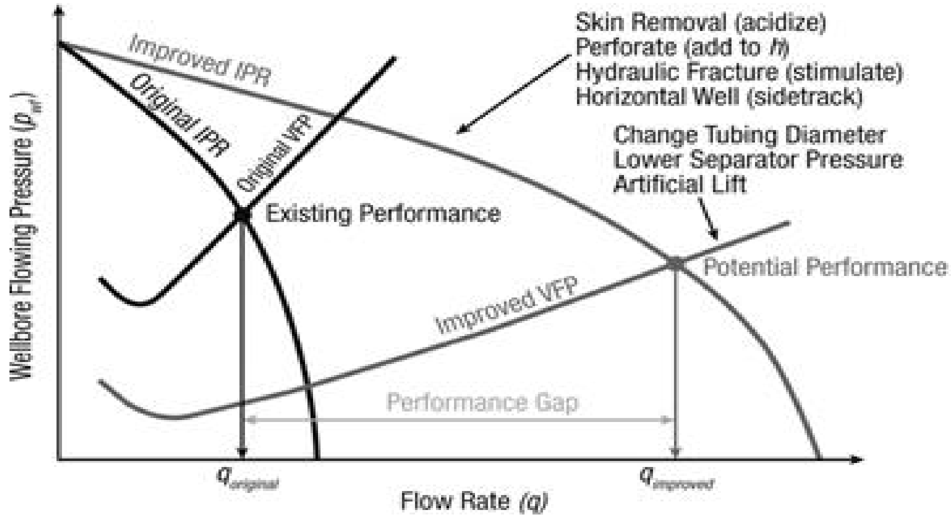

Figure 1: Well Performance showing IPR and VFP[9]

The factors that influences the IPR curves are[8]:

- Reservoir static Pressure
- Bottom hole flowing pressure
- Rock Properties
- Fluid Properties
- Wellbore Damage (skin)
- Well Geometry

These factors are related to each other by the Darcy law, for a steady state radial oil flow in the reservoir, which is[8]:

$$PI = \frac{Qo}{\Delta P} = 0.00708 \frac{k\ h}{\mu\ Bo\ (\ln(\frac{Re}{Rw}) + S)} \text{ --EQN 1}$$

Where PI is the Productivity index and Δp is the difference between static pressure and bottom flowing pressure. The units are in Oilfield system.

The initial and boundary conditions when we have steady state radial flow are:

$$\frac{\partial P}{\partial t} = 0\ for\ \forall \mathrm{r}, \forall \mathrm{t}$$

P = Pe = constant for r=re

As for the factors influencing the VFP curve[8]:

- Production Flow rate
- Pipe Length
- Tubing internal diameter
- Average density fluid inside pipe
- Average viscosity inside pipe

- Gas oil Ratio (GOR)
- Water Oil Ratio (WOR)

2. Pressure Transient Analysis

"Pressure Transient Analysis (PTA), is the analysis of pressure change over time, and relies on the use of downhole pressure measurements from permanent or retrievable gauges"[10]. This well testing approach improved in the last 2 decades due to the introduction of high accuracy and resolution pressure gauges, the storming of computer automated optimization procedures, and the building and development of reservoir models[11]. During well testing, a limited amount of fluid is allowed to flow from the formation at a given rate, where the pressure drawdown or pressure decrease is measured with respect to time. After the production period, the well is shut in and pressure build up occurs and is monitored, where the reservoir tries to reach equilibrium. Figure 2 shows the variation in pressures, corresponding to a specific rate, and we can notice that as the rate changes, a different pressure drawdown response will take place[11]. These changes in pressure will provide us with many useful information concerning the shape and the productivity of the reservoir[10]. The log-log pressure derivative technique is usually used for the interpretation of these pressure changes, which will lead to a better understanding of the reservoir properties. Figure 3 represents the change in bottom hole pressure as a function of time, corresponding to a constant rate. As stabilization time is reached, which represents the time when the pressure propagation reaches the reservoir boundaries, it is realized that the pressure with respect to time continues either in a steady state (water aquifer is strong), or in a pseudo-steady state, where the reservoir will be depleted, and which signifies a weak aquifer[12]. Figure 4 represents a log-log plot, where we have a normal pressure change with its corresponding derivative[12]. In this plot, we realize a linear flow with a half slope at late time of the curve, which signifies that the reservoir type corresponds to a channel. We can also see a unit slope, which signifies depletion.

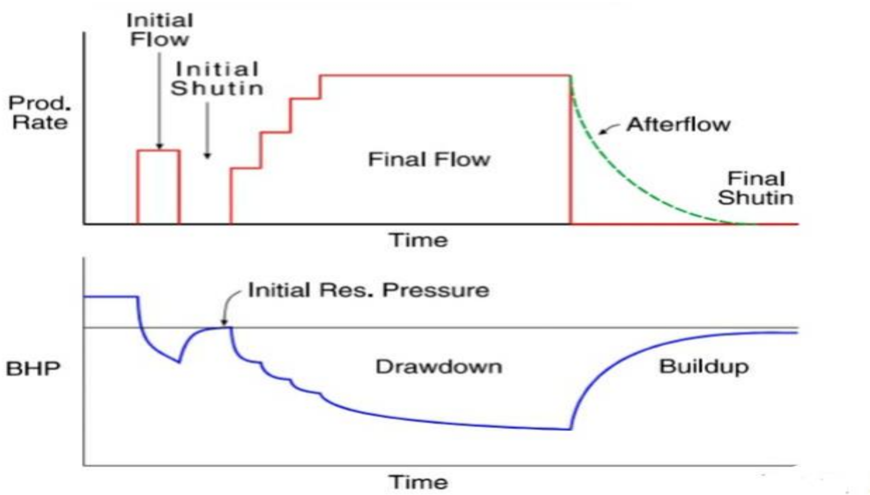

Figure 2: Pressure change with respect to time corresponding to specific rates[11]

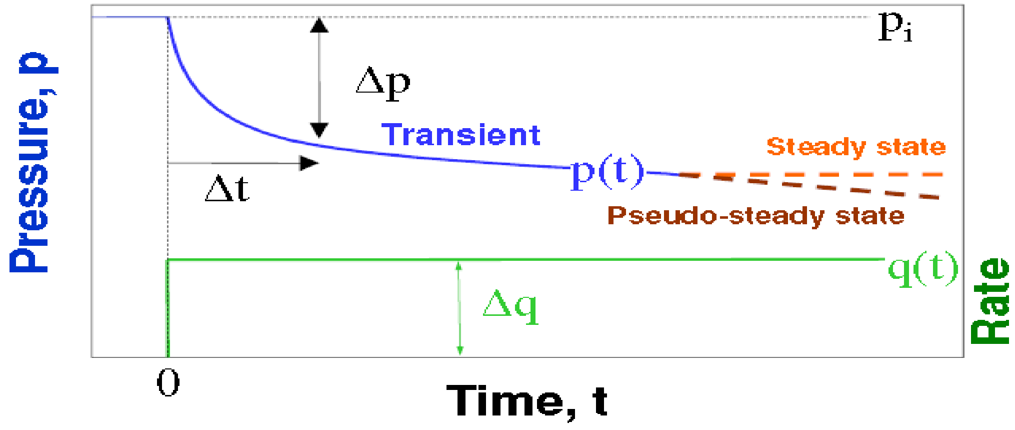

Figure 3:Pressure with respect to time for a certain constant rate with 2 different late time options[12]

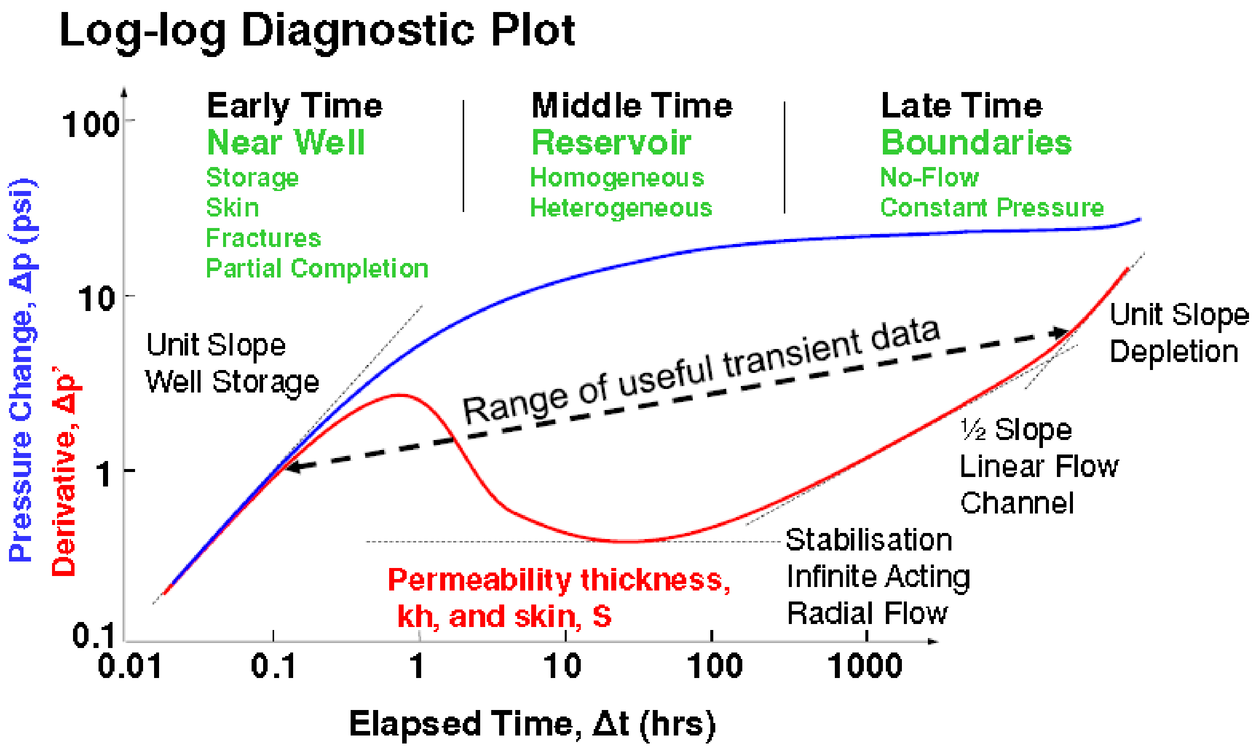

Figure 4: Log-log plot showing normal and derivative pressure curves, in addition to different well test models and different reservoir types[12]

3. Well test models

The well test model identification is divided into three parts: early times, middle times, and late times[7]. The early time models represent the wellbore and near the wellbore, and include several models like Wellbore Storage and skin, infinite or finite conductivity vertical fracture, partial penetration or horizontal well[7]. The middle time models represent the reservoir, and include homogenous (also called infinite acting radial flow (IARF)), double porosity, dual permeability, radial composite and linear composite[7]. Late times models represent the reservoir boundaries. Boundaries can either be no flow boundaries (pseudo-steady state), or constant pressure boundaries (steady state) [7]. The different well test models could be observed in Figure 4. The radial flow, which occurs in the middle time region before the occurrence of a boundary, is the flow regime which helps us determine the permeability and total apparent skin. This flow period is mainly known as infinite acting radial flow, and is characterized by the following equation for oil[7]:

$$\Delta P = \frac{162.6\ q\ B\ \mu}{k\ h}\ [\log(\frac{k\ t}{\varphi\ \mu\ ct\ rw^2}) - 3.23 + 0.869s] \text{ --------------------------------------- EQN 2}$$

Where q is the oil rate at Stock tank conditions in BOPD, B is the formation volume factor of the oil in bbl/stbbl, μ is the viscosity in cP, k is the permeability in mD, h is net pay-zone in feet, rw is the well radius in feet, ct is the total compressibility in psi^{-1}, t is the time in seconds. The units are the ones of the oilfield system. The symbols and units can be checked in the nomenclature section. The direction of radial flow is perpendicular to the axis of the well. It usually takes a day or more for outer boundaries to affect well-test results, and this depends on whether the boundaries, such as faults, are close to the wellbore. As for early time, the most occurring phenomena which will be encountered in the cases later in this paper, is the Wellbore storage effect, in which it happens when the well is opened or shut in. Both the pressure and the derivative curve will follow a unit slope at first until the pressure disturbance reaches the wellbore, where the derivative will produce a hump shape curve. Wellbore storage effects usually happens if the clean-up wasn't perfectly done, and if the well is deep, where the pressure will take time to propagate through the well. In addition to that, having high compressibility of fluids like gas, which will lead to expansion inside the wellbore, will also produce wellbore storage effects. The shape of the hump will vanish as soon as the wellbore effects are negligible. Figure 5 demonstrates the difference between having a high dimensionless wellbore storage coefficient and skin (C_De^{2s}) and having a low one[7]. A comparison of wellbore storage effect between two different cases with different permeabilities will be demonstrated later during the body of the paper.

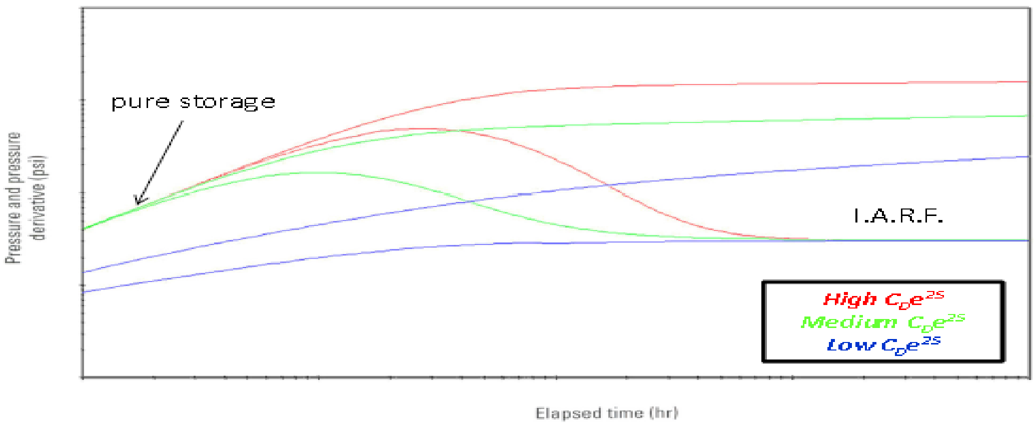

Figure 5:Wellbore Storage effect[7]

4. Superposition in Time

Since a well will produce at varying rates, the superposition in time concept should be taken into account, and is valid when the solutions to the diffusivity equation are linear[13]. The multi-rate sequence is broken up into a set of single rates, where the rate used for each step is the difference between the current rate and the previous rate[14]. Usually the superposition functions differ according to the flow regime occurring. The equation which describes the superposition in time principle is the following[13]:

$P(t) = Pi - \sum_{i=1}^{N} \Delta P_{DD}[(q_i - q_{i-1}),(t - t_{i-1})]$ -- EQN 3

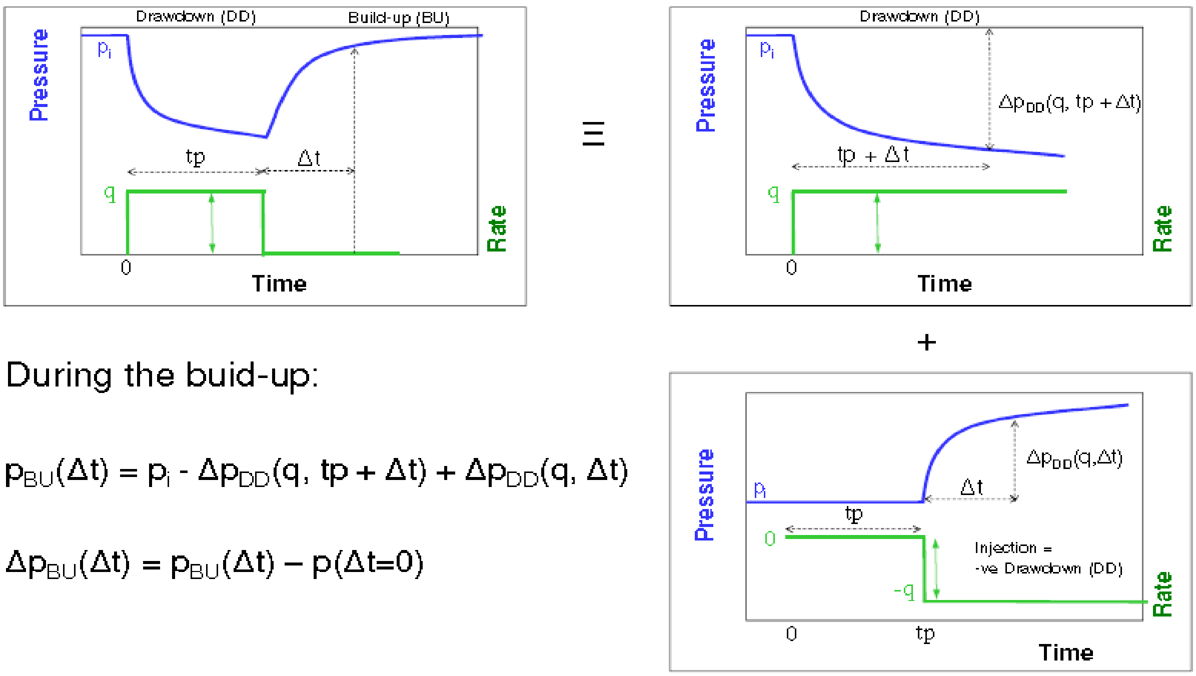

Figure 6: Superposition in Time for the build-up case with one constant rate[12]

Figure 6 shows the process of superposition in time for a build-up equation following a single rate. Thus, in order to come up with the build-up equation, the superposition principle is used. We imagine that after time t_p, we still have a continuous flowrate (which corresponds to a continuous pressure drawdown), which is added to another case of which we imagine that we have an injection with negative rate after tp (where the pressure curve increases), and the summation of both will give us the final form, and will lead to the development of the build-up equation[12]. As a result, every pressure drop that takes place is due to the difference of the rates that exist, as shown in Figure 7, which demonstrates the superposition in time with two rates.

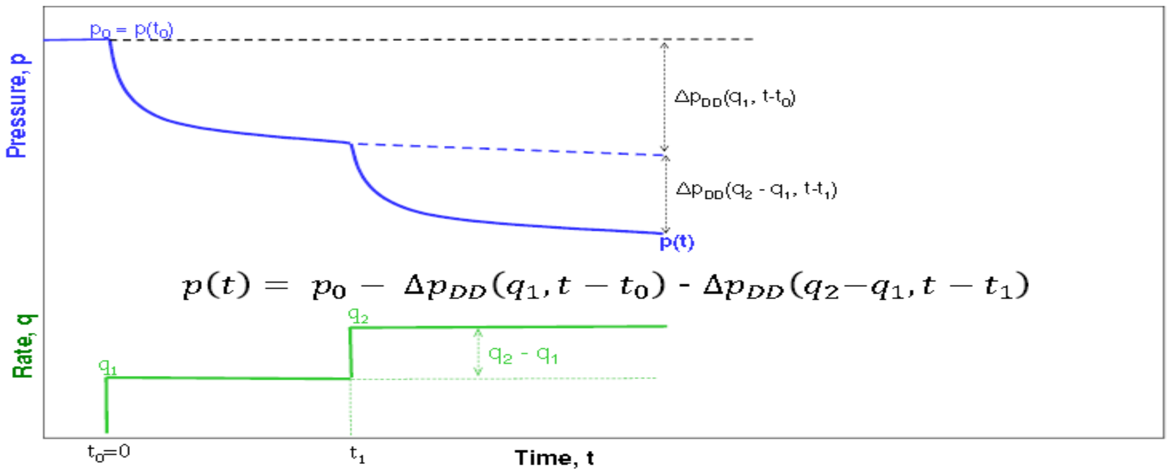

Figure 7: Superposition in Time for two rates[12]

Pressure-Rate Deconvolution Benefits and Limitations

Deconvolution has become the driving tool in well test analysis in the last decade. It transforms variable rate and pressure data into initial constant rate pressure response equal to the duration of the entire test[15]. Figure 8 demonstrates how this idea about how deconvolution works. The well flowing pressure is given by the convolution integral, also known as Duhamel's principle or superposition principle, which is[15]:

$$Pi - Pwf\ (t) = \int_0^t q(\tau)\,\frac{dpu\ (t-\tau)}{dt}\ d\tau \text{ -- EQN 4}$$

with P_i being the initial pressure, $P_{wf}(t)$ being the well flowing pressure at bottom-hole conditions, q(t) being the sand-face well rate and pu(t) being the well pressure response due to constant unit rate production. Deconvolution is a pure mathematical process, that usually works by iterations using superposition[16]. It uses a single rate pressure drawdown response as an initial guess and superpose it with historical rate data, and generates a pressure response with respect to time. If this generated pressure signal matches the actual pressure data that we have (with minimum difference in error), then it is a good deconvolution, and the deconvolved response signifies a good and accurate shape[16], as shown in Figure 9.

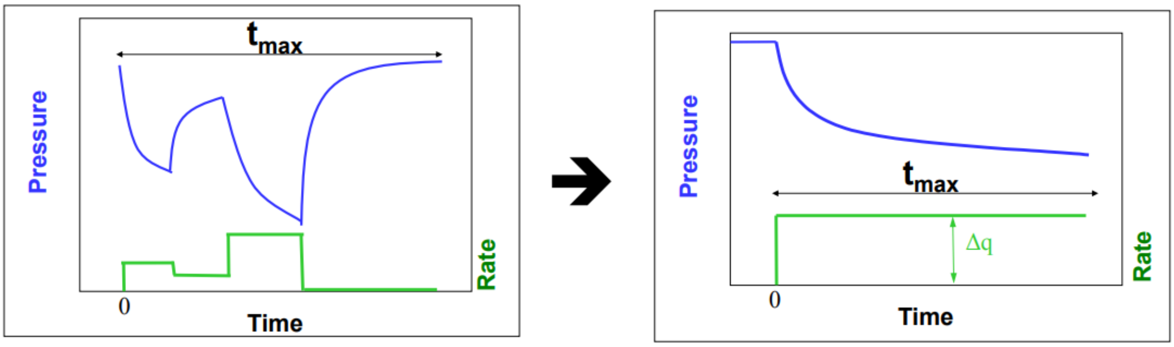

Figure 8: Deconvolution Principle[12]

Normally, the pressure data gathered during flow periods are not used for the deconvolution process because of their poor quality[4]. On the other hand, pressure build up data is the part that we rely on more. The deconvolved derivative, which is free of distortions (errors) that are usually caused by the conventional derivative calculation algorithm, is defined over a longer interval than the original build up pressure duration (Figures 10 and 11); therefore it enables us to[15]:

- acquire additional insights
- differentiate and recognize different flow regimes over time, especially the radial flow regime in the horizontal plane
- identify and detect presence of boundaries
- obtain technical evidence for increasing minimum collected volume

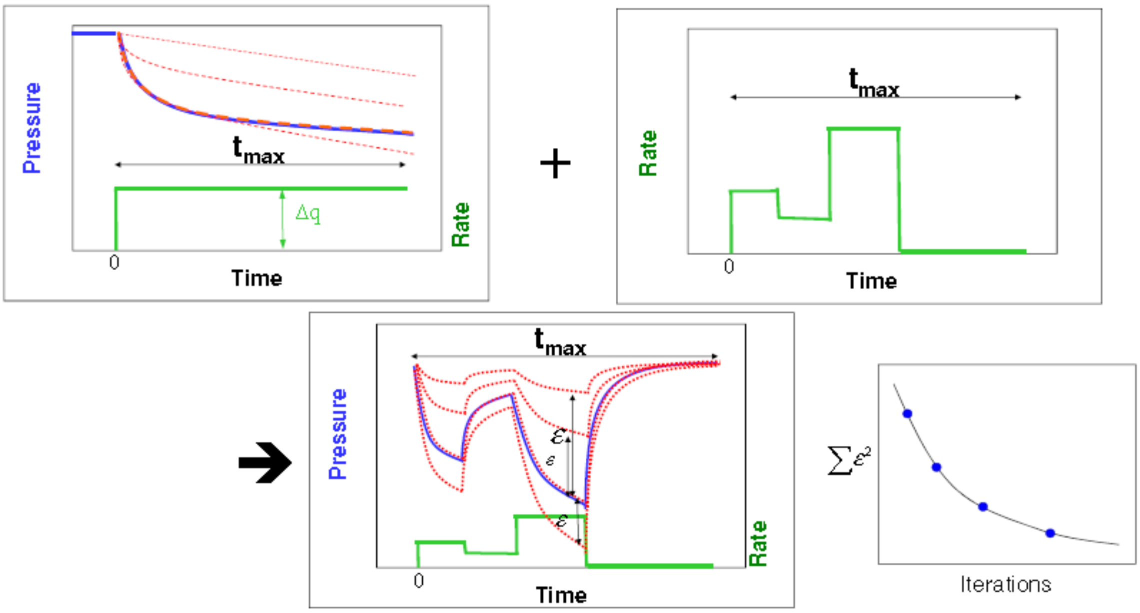

Figure 9:Deconvolution Process through Superposition[12]

Moreover, deconvolution also helps us to refine initial pressure, which can be inserted as an input, or can be unknown and provided as an output[4]. Thus, deconvolution reduce uncertainties concerning the reservoir. If an assumption was taken that the reservoir only contains either oil and gas with irreducible water saturation, and that the well produces single phase fluid, then the minimum tested stock tank oil initially in place (STOIP) or the minimum tested gas initially in place (GIIP) can be calculated, according to these following equation[13] :

$$STOIP_{mintested} = \frac{a2}{a1a3} \frac{(1-Sw)}{Ct} q \frac{\Delta tmax}{\Delta p\prime max} \text{ --- EQN 5}$$

$$GIIP_{tested} = \frac{(1-Sw)}{Ct} q \frac{\Delta tmax}{\Delta nm(p)\prime max} \text{ --- EQN 6}$$

Where a1, a2, and a3 are unit coefficients which vary with respect to the units used (either SI, Darcy, Metric or Oilfield units). In case of Oilfield units[13], a1= 0.007082, a2= 0.0002637, a3= 0.8936

Concerning reservoir pore volume, there exists an equation able to calculate this value at a unit slope straight line in late time after reaching PSS, which is related to the reconstruction of the drawdown response by deconvolution, and the equation is[13]:

$$PV_{\text{min tested}} = = \frac{a2}{a1a3} \frac{qB}{Ct} \frac{\Delta tmax}{\Delta p\prime max} \text{ --- EQN 7}$$

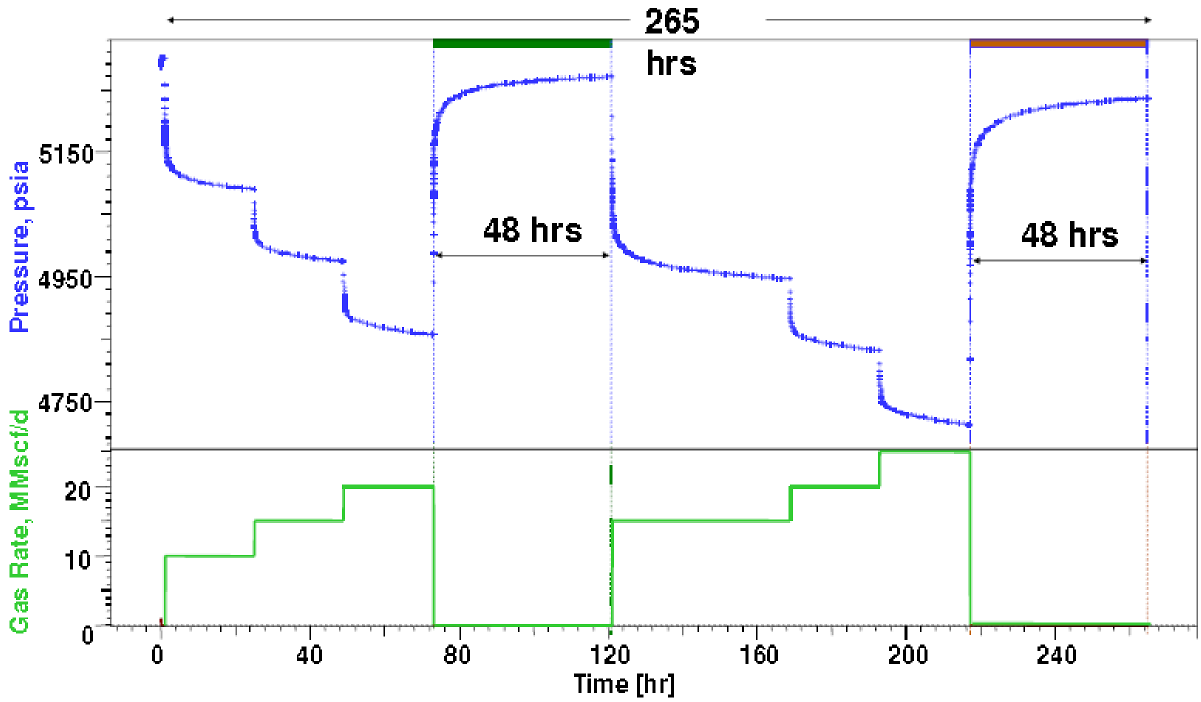

Figure 10: Pressure and Gas Rate versus time example[12]

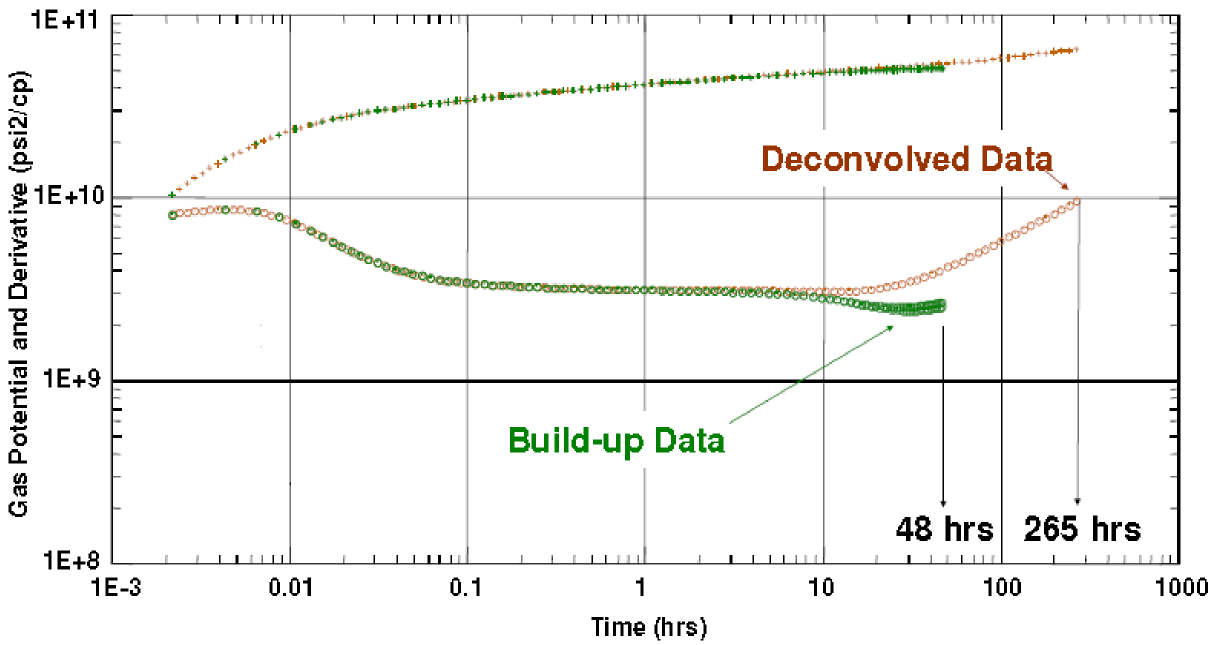

Figure 11: Example of a Deconvolution Response on a log-log plot for the case of Figure 10 [12]

However, deconvolution is a tool which holds so many limitations, and should be used with caution. One of its limitations is that it needs linear flow equations to work, when the superposition principle is valid[17]. Thus, deconvolution cannot predict actions like water breakthrough, or like release of gas due to the pressure going under the bubble point or because of high GOR, and this will lead to inaccurate results. Moreover, deconvolution is too sensitive to small pressure changes, and sometimes won't give a reliable result[17]. This fact will be demonstrated later on in the paper, with figures used from Saphir Kappa software. Also, there will be some cases where small changes in parameters are changed, and the result of deconvolution will vary due to these changes, and will be demonstrated in figures as well; therefore, it is better if the wellbore and reservoir properties don't change with time in a significant way[16].

Another important feature that should be focused on is the test sequence of the total test, in other words, the duration of the drawdown and the build-up periods with respect to each other. Hence, PBU duration should be sufficient in comparison to the drawdown, especially that the deconvolution is performed on the build-up period since it has better quality. The right thumb rule states that the build-up should be 1.5 times the drawdown period. Most of the times, more than one active well may exist. This issue may affect the deconvolution method which is applied on one well, since interference will occur between all the wells according to the distance, and the pressure will propagate from one well to another, with a certain time delay[18]. This will lead to inconsistencies which will negatively affect the results of deconvolution. But when we talk about 2 or more wells, in this case, the term Multi-well deconvolution takes over, which is becoming a general technique for interference well test analysis, but not yet commercial[18]. The ordinary Deconvolution algorithm (applicable only to one active well) cannot be used for well test analysis when there are several active wells in same reservoir with interference happening with respect to bottom hole pressure data. So, a different deconvolution algorithm has to be generalized[18]. However, this method is difficult to use, and is still being developed.

In order to obtain better results from deconvolution, these additional issues should be taken into consideration[16]:

- Filtration of data to remove unnecessary and detached points
- Usage of a reliable initial pressure
- Having a valid rate history
- Build-up type-curves consistent with each other

As a result, before using deconvolution as a way of reconstructing the characteristic pressure transient behavior of a reservoir-well system, it is critical to confirm its validity, and this need a bit of experienced personnel and expertise.

Methodology for Deconvolution on Saphir

Pressure transient behavior analysis usually initiates with the investigation of the test data on different analysis, derivative, superposition, or Cartesian Plots. From these plots, a united and more recognizable picture can be built which will enable us to understand the main features of the test transient pressure behavior. Deconvolution will be used in several cases to analyze the test data, through Saphir NL, which is the industry standard PTA software, developed by Kappa. It offers a unique combination of analysis tools, analytical models and numerical models. Different cases will be studied, and for each case we will have different inputs. According to the workflow of the software, first the rates and the durations are entered, followed by the creation of the test design. After that, the history plots and the pressure derivatives will be extracted mainly for build-ups, with one of them being a reference in case of more than one build –up exist. Then, for each case, deconvolution will be applied, and the results will be studied. In case it does work, we will take a look at the extra benefits that it provides with respect to the normal conventional way. In case it doesn't work, the main reason behind its malfunction will be stated, and the solution, in case of any, will be demonstrated, with some recommendations given. Four deconvolution algorithms are implemented into the software and can be selected by the user as options:

1. Deconvolution on all extracted periods, all data at once (Von Shroeter et al): The algorithm will deconvolve all the PBU's selected at the same time and provide one response.
2. Separate deconvolutions with common Pi (Levitan et al): The algorithm will extract a deconvolved response for each PBU, and a comparison is done at the end to see if the responses are consistent (modification through Pi can happen).

3. Deconvolution on one reference period and the end of other periods (KAPPA): The algorithm will provide one deconvolved response which is extracted from one reference period and the end of other periods (good in case of changing properties over time)
4. Method 3 (KAPPA) followed by method 2 (Levitan et al) (KAPPA+)

In all of the cases that will be discussed in this paper concerning the problems and solutions, option 1 and option 3 will be mostly used since they are the most suitable options for the cases.

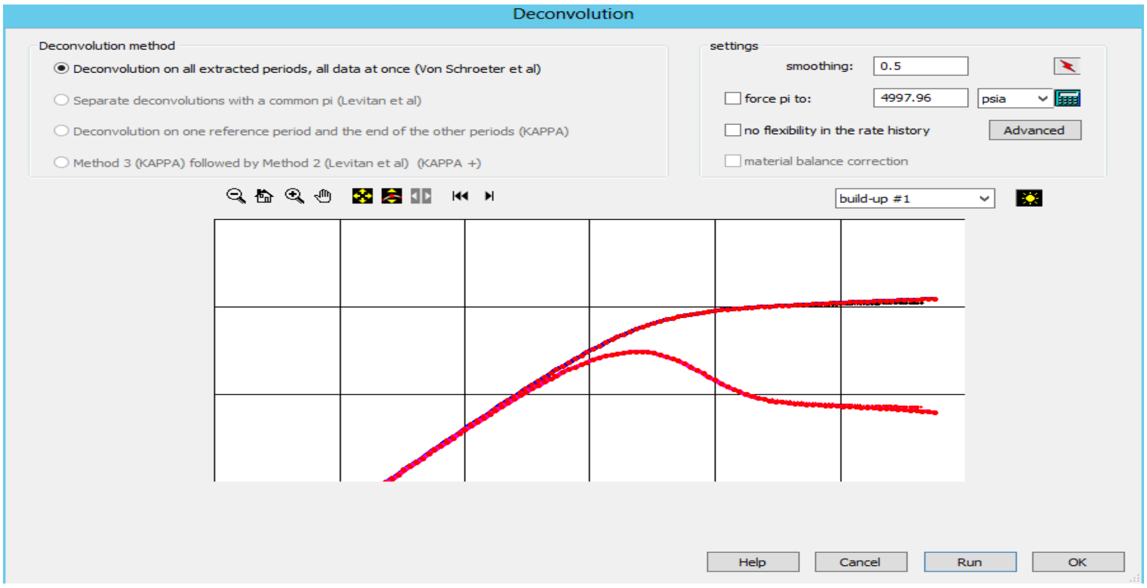

Figure 12: Deconvolution option from Saphir Kappa

Through Figure 12, the four different options for deconvolution that could be selected can be observed. The "no flexibility in the rate history" option is selected and will be used in all of the cases, in order to ensure a fixed rate history. The initial pressure can be forced in some cases (given as an input), and in some cases will be unselected and given as an output. After running the deconvolution, an interpretation on the results will take place.

It should be noted that most of the deconvolutions will be performed on the build-up part since it is clearer than the drawdown part. Thus, we should consider that we have no drawdown data despite its existence, since we are creating our own test designs. Interpretation will take place taking into account the mentioned consideration. All the figures within the cases are taken directly from Saphir NL, the software that I used, except for Figures 51 and 52 which were taken from Excel.

Case Studies on Problems and Their Solutions

The cases which will be elaborated and discussed in this paper are:

1) Long Production Period, Short Build up Period
2) Short Production Period, Long Build up period
3) Pseudo-steady state case (Rectangular reservoir)
4) Harmonic Sequence; Net-Zero
5) Harmonic Sequence; Net-Positive
6) Gap case
7) Changing Wellbore Storage between 2 flow periods
8) Changing Skin between 2 flow periods
9) Interference

1. Long Production Period, Short Build up Period

What happens if deconvolution is performed on a build-up period that is too short compared to its previous long production period? In this case, the pressure isn't given a lot of time to build up after the well is shut in, so the pressure curve won't evolve so much, and will stop way back before reaching static pressure where a sort of plateau with respect to time is attained. As a result, there is no way we can tell if the initial pressure is reached again or not, and especially that only one build-up exists in this case. So it is unknown if we are in a steady state or a pseudo-steady state. There isn't enough data to recover the long drawdown response.

Can the deconvolution of the build-up represent the whole pressure drawdown? For this specific case, a 59 hours test with 1000 BOPD is considered, having a build-up period of 1 hour. Default values of Saphir were taken, where the well radius is 0.3 feet, the payzone is 30 feet, the Porosity is 0.1, the formation volume factor is 1 bbl/stbbl, the viscosity is 1 cP and the total compressibility is 3E-6 psi^{-1}.

As for the test design, it is constituted of a constant wellbore storage, a vertical well model, a homogenous reservoir model and an infinite boundary model, which are also considered to be the default test design of Saphir. What we obtain from the extraction of the pressure curves and their derivatives from the build-up data is shown in the below figure:

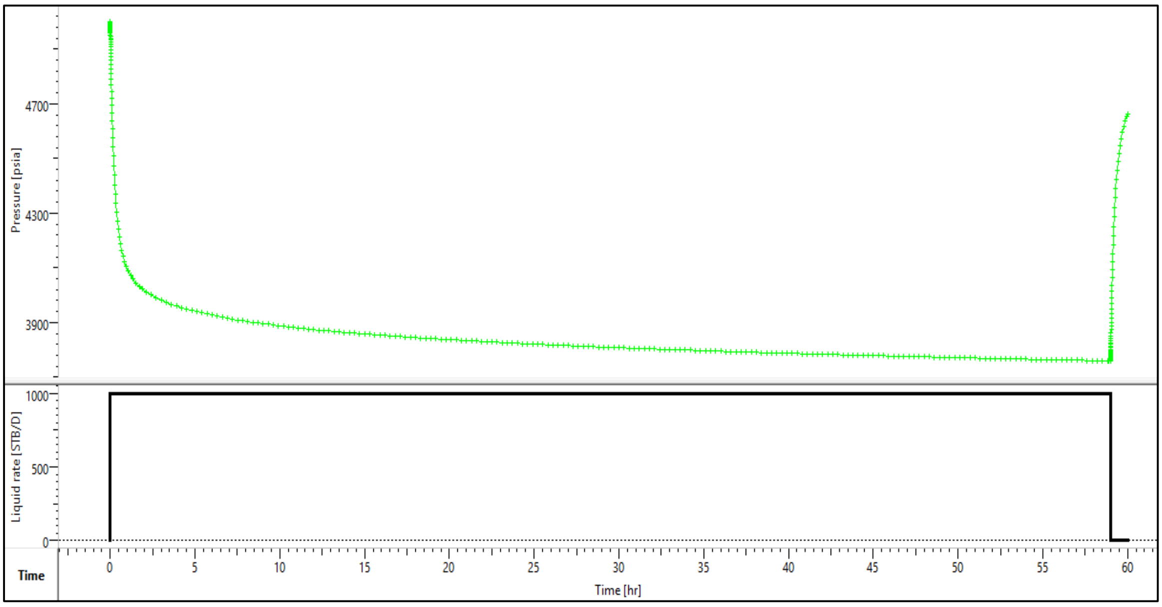

Figure 13: Pressure versus time plot, corresponding to a constant rate of 1000 BOPD for 59 hours, followed by a one hour build-up period

From Figure 13, we can see the pressure drawdown corresponding to a rate of 1000 BOPD for 59 hours, compared to the short build up period for one hour. Deconvolution is performed on the build-up phase in this case, using the first option of deconvolution (performed on all extracted periods). We should imagine that we don't have the drawdown period.

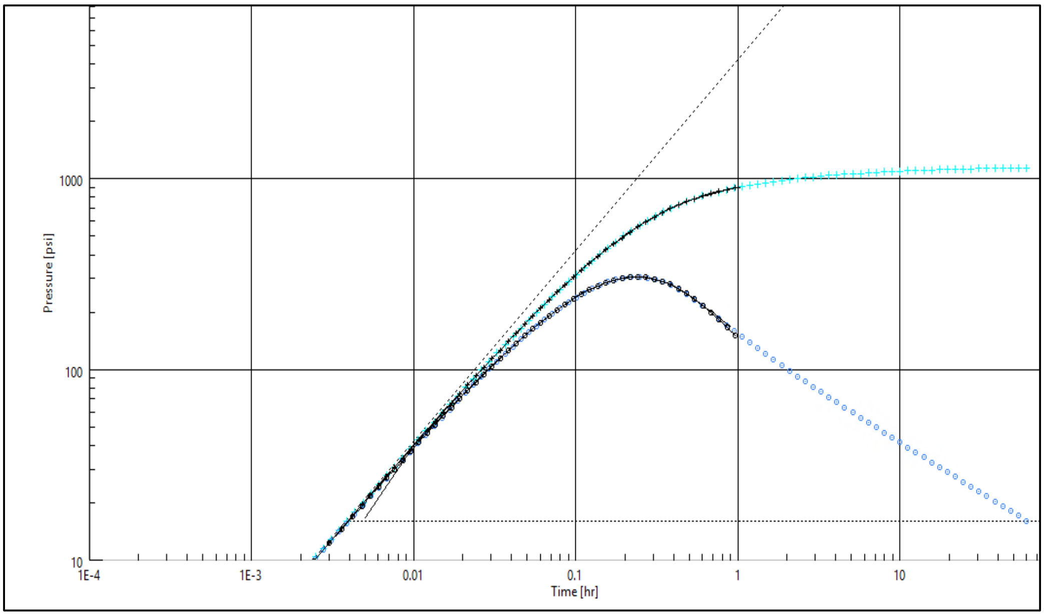

Figure 14: Log-log plot of the deconvolved response, in addition to the original build-up period of 1 hour

The original build-up data and the deconvolved response can be seen through Figure 14. The light blue dotted curve represents the deconvolved response which is equal to the whole duration of the test (60 hours), while the black dotted curve represents the original pressure response representing the build-up which is equal to one hour. The initial pressure in this case wasn't forced, but was given as an output and turned out to be 4912 psi (which is different from the initial pressure assigned for the test at first of Pi=5000 psi). The deconvolved pressure response in this case matches the build-up pressure history but does not match the pressure drawdown data. This is due to the fact that the initial pressure is unknown in this case because there is only one short build up (Figure 15).

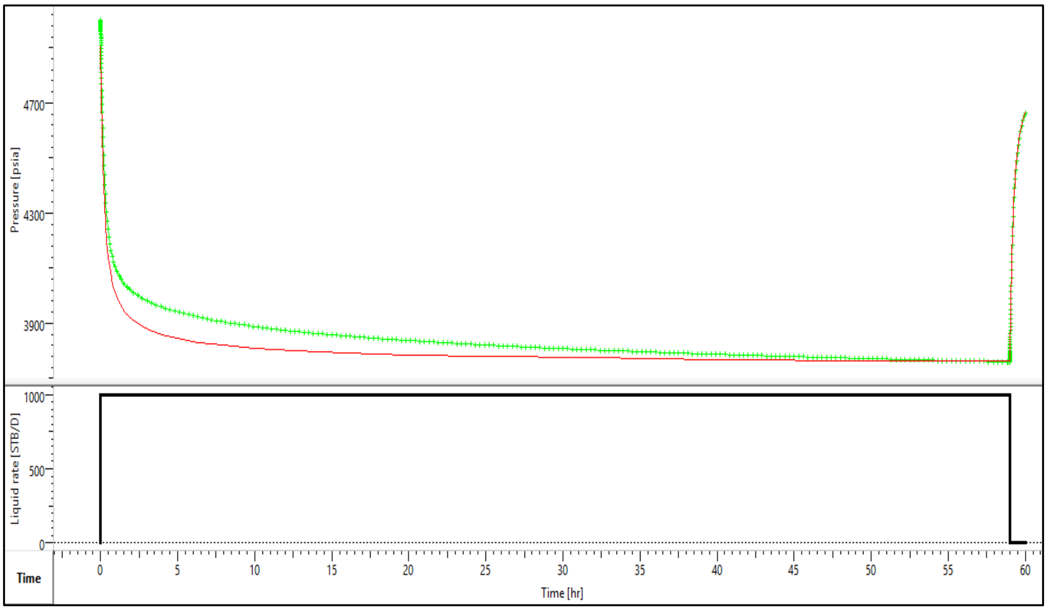

Figure 15: Pressure versus time plot showing the mismatch between original pressure data and deconvolved response

Note that when deconvolution is performed on the build-up phase, the pressure drawdown shouldn't be taken into consideration (we should pretend as if this phase doesn't exist). It should also be noted that when Pi is not forced, the software uses the value there as an initial pressure guess, but if it is forced, then the changes through the curves shall be seen.

Not knowing the initial pressure means that we can have several shapes of deconvolved responses corresponding to a huge range of Pi, where the deconvolved pressure response will always match the build-up pressure data, but not match the pressure drawdown data. For instance, the deconvolved response may have a "downward" shape indicating that we are under steady state, or have an "upward" shape indicating that we are under pseudo-steady state and still match the pressure build up data. Hence, the deconvolution will indicate a successful result, but in fact, it isn't the correct one. Hence, the deconvolution is non-unique. This argument was demonstrated by forcing an initial pressure of 6000 psi, and seeing the difference in the deconvolved response.

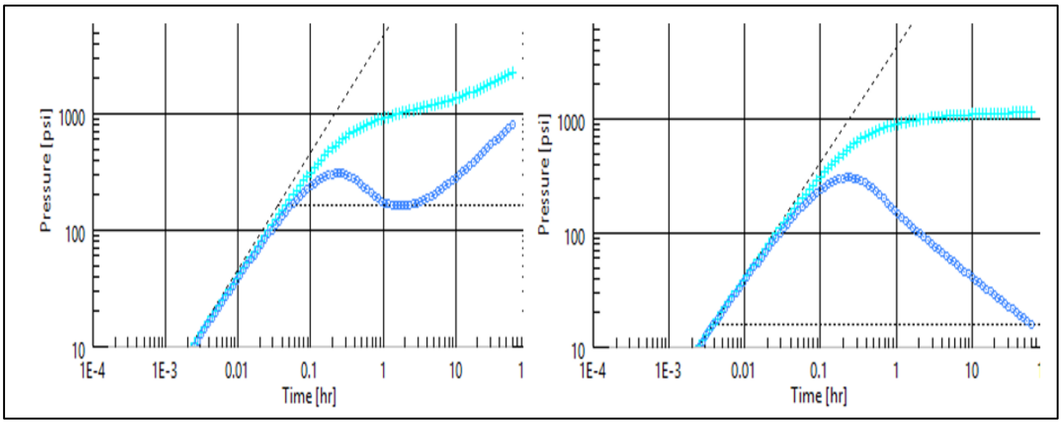

Figure 16: Log-log plot showing deconvolved responses for two different initial pressures Pi= 6000 psi (left) and Pi=4912 psi(right)

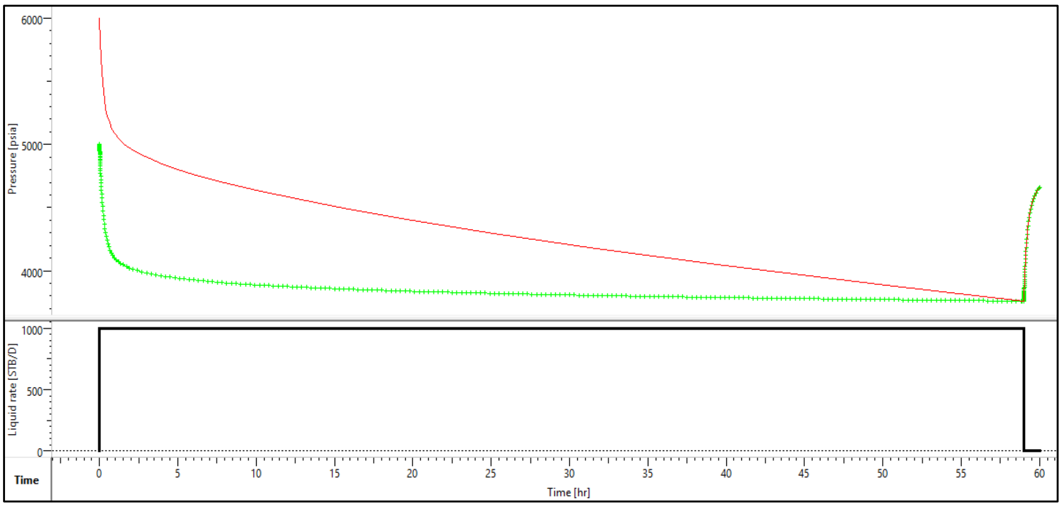

Figure 17: Pressure mismatch between deconvolved response and actual pressure data for Pi=6000 psi

The left graph in Figure 16 represents the deconvolved response for a forced initial pressure of 6000 psi, and indicates that we are under pseudo-steady state since the derivative is going upwards. On the other hand, the right curve in Figure 16 represents the deconvolved response without forcing the initial pressure (Pi as an output is equal to 4912 psi), and indicates that we are under steady-state. In Figure 17, we notice that the pressure build-up data matches the deconvolved data. Nevertheless, we notice a huge mismatch between the pressure drawdown data (which we imagine that we don't have) and its deconvolved response. Thus, the deconvolution is non-unique. So for a certain range of initial pressures, the deconvolved response will always match the build-up data, but the correct initial pressure for this specific case would never be known, unless there exist 2 or more build ups for example, in order to be able to detect if steady or pseudo-steady state exists; this way, the number of uncertainties will be reduced. The comparison between both curves at different initial pressures of 6000 psi and 4912 psi is demonstrated on one graph in Figure 18, in addition to the pressure range represented by the shaded area. The deconvolved response can acquire any shape within this shaded area, proving the non-uniqueness.

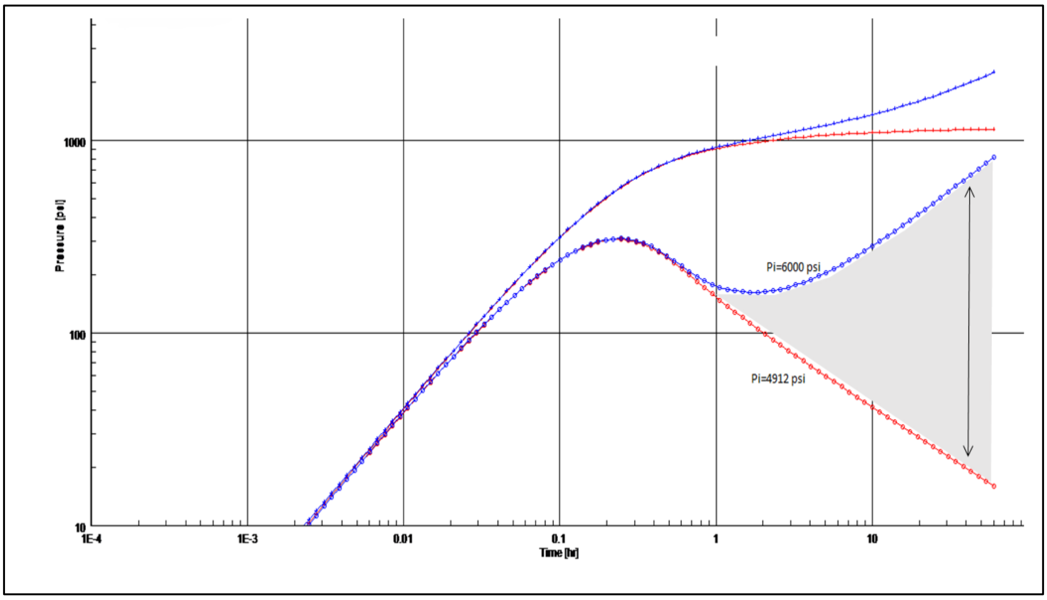

Figure 18: Log-log plot showing deconvolved response on build-up phase, and also showing range of possible shapes in the shaded area corresponding to different initial pressures

As a conclusion, having a short build up isn't good for deconvolution, since we won't know the exact Pi, and we will have many results generated that seem to be true, but don't represent the optimal deconvolution. As a result, a better test sequence is needed. However, it is really difficult to reach one optimal result, but as the range of initial pressure is narrower, we will obtain higher probability of good deconvolution results with reduced uncertainties. We should note that if we analyze build-up without knowing drawdown, it is preferable to have Pi as an input (it is better if we are familiar of the value of initial pressure), or else deconvolution will work using a range of initial pressures that matches the pressure build up data.

2. Short Production Period, Long Build up period

This case is the opposite of the previous case, in which we have a short production period, and a long build-up period. A flow period of one hour with 50 BOPD is input, as well as a 59 hours build up, with a resolution of pressure gauges equal to 0.04 psi, and a permeability of 33 mD. After the extraction of the pressure derivatives, deconvolution was performed on the build-up period and the results were discussed. The main problem in this case is the limitation in the resolution of pressure gauges, where we will run out of resolution, and the pressure data won't be clear enough, leading to an unclear pressure derivative with dispersed data. Figure 19 shows the scattered pressure derivative on the log-log plot, while Figure 20 shows the pressure data on the history plot (pressure versus time);

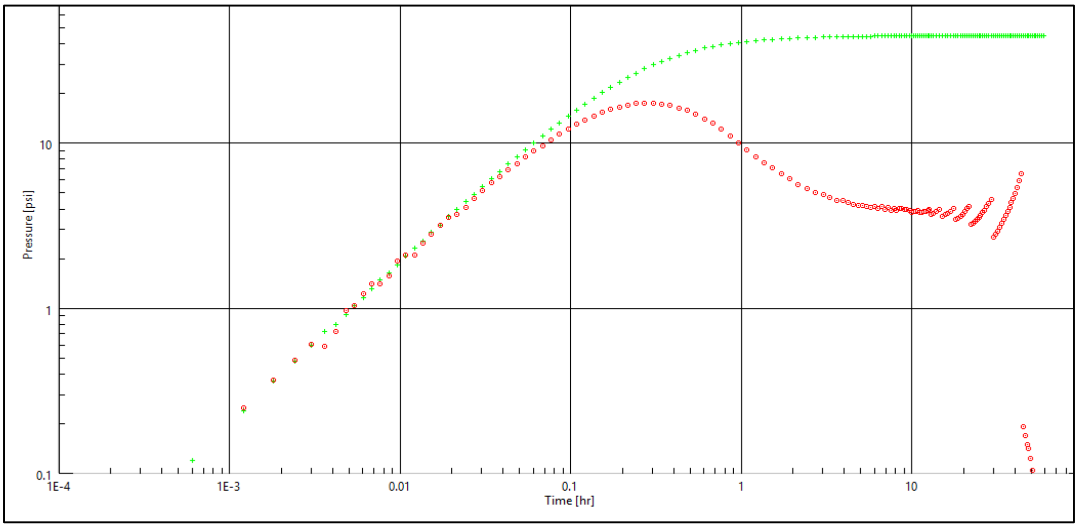

Figure 19: Log-log plot with scattered data of normal and derivative pressure curves with a resolution of 0.04 psi for the build-up phase

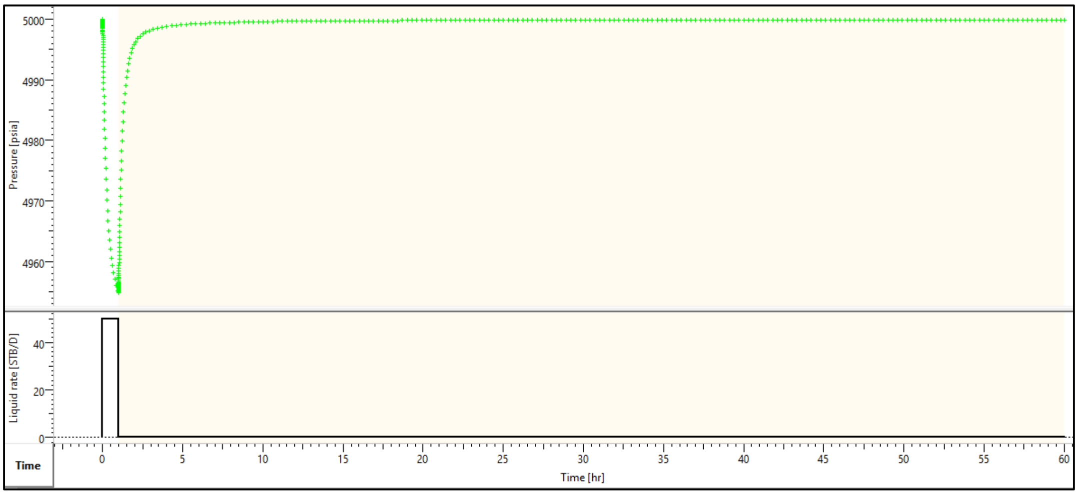

Figure 20: History plot of pressure versus time for the short production long build-up case

If we zoom in into the build-up derivative, it will be noticed that it isn’t clear enough because we won’t have enough resolution. The pressure change became approximately constant from t=7 hours till the end of the build-up period. We realize that the pressure drop was around 45 psi only, from 5000 psi till 4955 psi. After performing deconvolution on the pressure build-up (using first option), our main concern is related to the probability of obtaining a clear and correct deconvolved response, using the scattered pressure data. It is obvious that the deconvolution will be non-unique and might not be trustful, because of the scattered data.

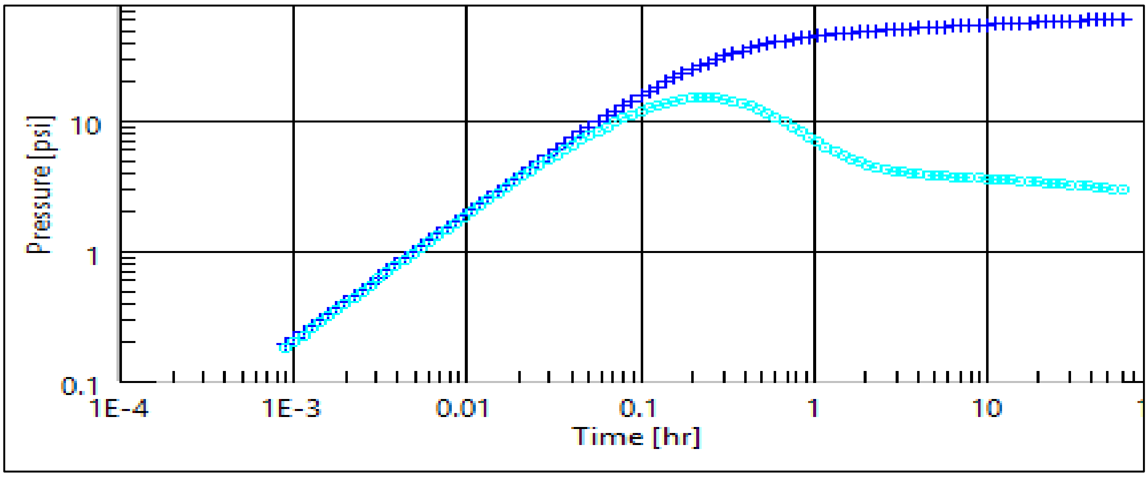

Figure 21: Log-log plot showing the deconvolved response equal to 60 hours

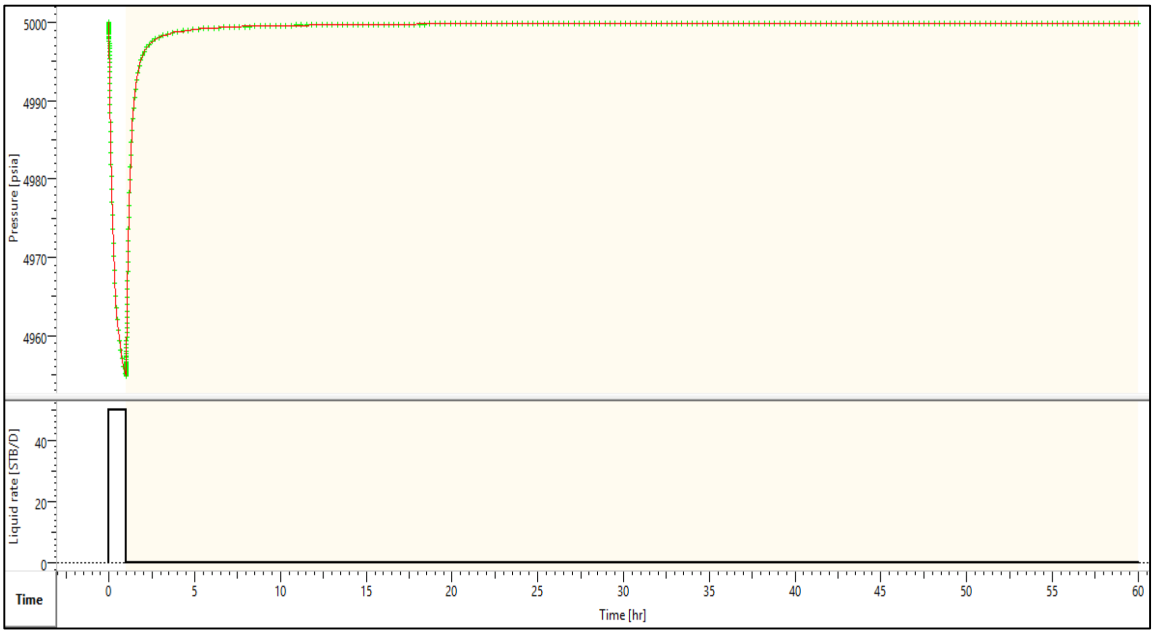

Figure 22: The history plot showing the match between deconvolved response and pressure data

The deconvolution produced a good match, as perceived in Figure 22, although we have some places where we have dispersed pressure data if we zoom in. But is it “the” correct deconvolution that we could trust? Not having enough resolution will lead to deconvolution being insensitive to the data that we have, which will in turn sometimes lead to lowering my confidence in this deconvolution of being unique. To prove the non-uniqueness in this case, I will try to change the shape of the deconvolution curve at late times, until I have a maximum of 0.04 psi mismatch between the actual noisy pressure data and the deconvolved response, which is considered acceptable since my resolution is 0.04 psi. The results of this action will show that for slightly different deconvolution shapes, we will have a mismatch that does not exceed 0.04 psi, and can be considered acceptable to some interpreters. Again, this case is showing the non-uniqueness of the deconvolution. We conclude that for different resolutions according to certain ΔP, a given range of deconvolved shapes may be valid, where the match will be acceptable. Figure 23 shows 2 different analyses, other than the above one (Analysis

1), where the deconvolved response was modified. Figures 24 and 25 shows the given pressure versus time plots and the match that is around 0.04 psi for Analyses 2 and 3 after the modification is done.

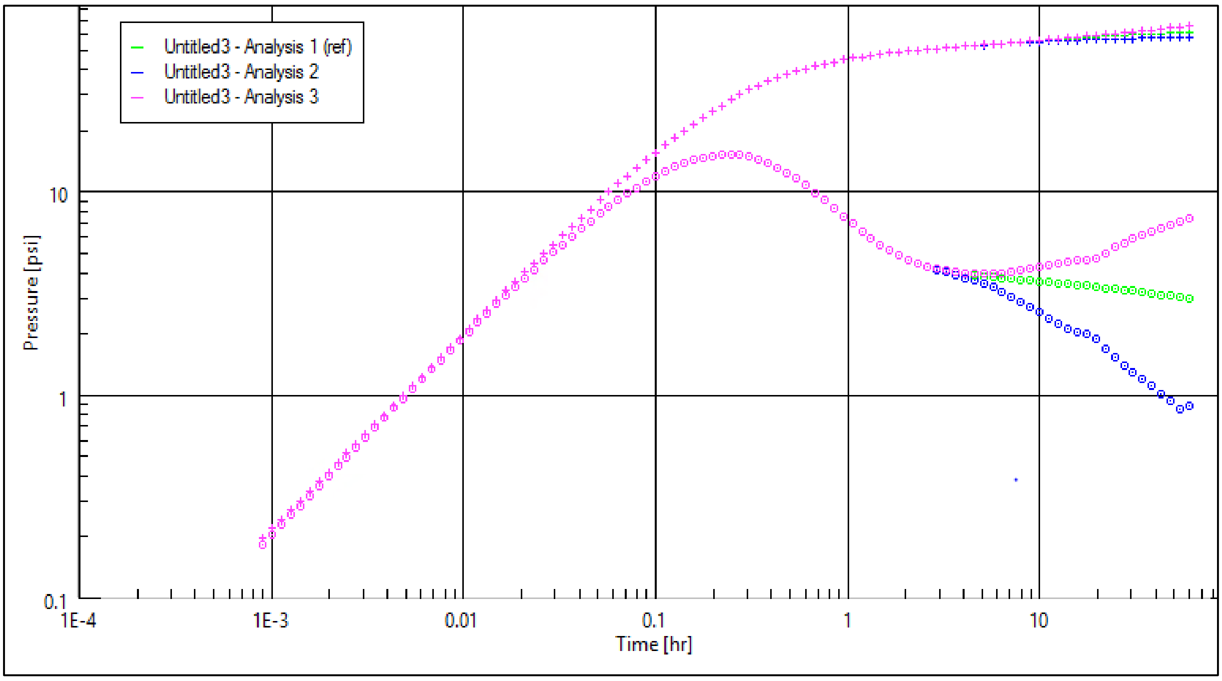

Figure 23: Log-Log plots for 3 different analyses, where the deconvolved response is modified and changed in every case

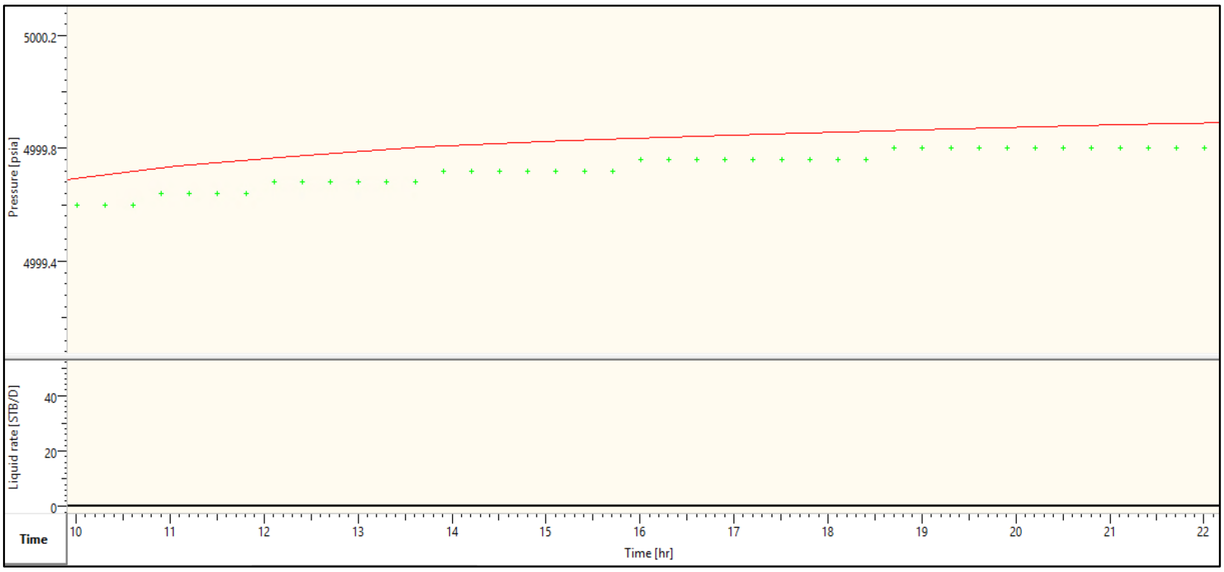

Figure 24: Zoomed-in Pressure versus time curve for Analysis 2 in figure 23 showing mismatch

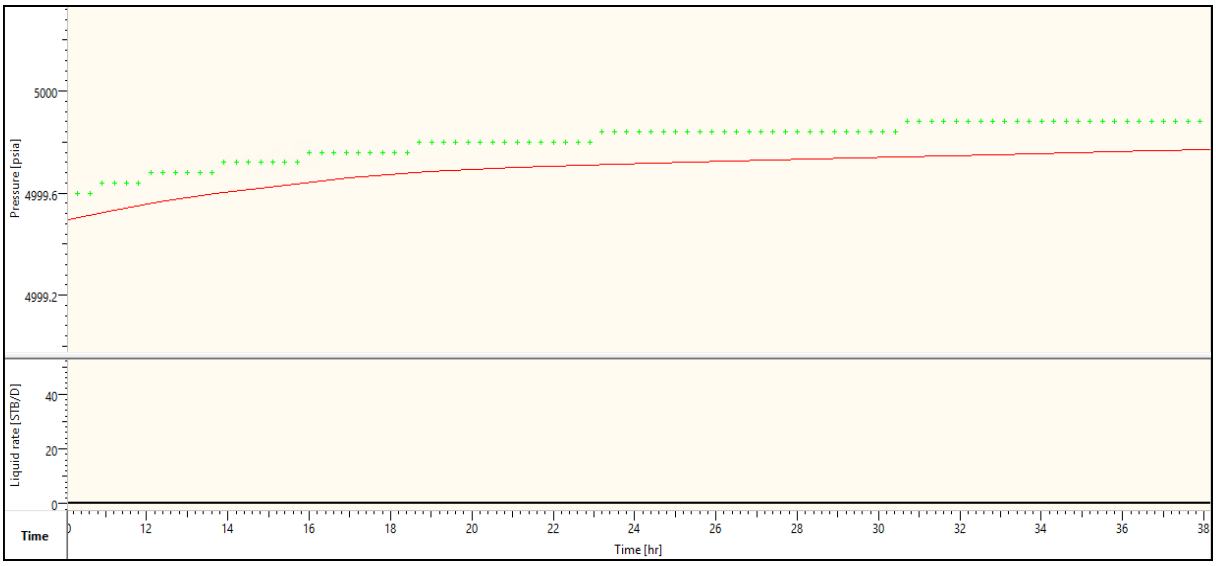

Figure 25: Zoomed-in Pressure versus time curve for Analysis 3 in figure 23 showing mismatch

Conclusively, a more appropriate test sequence should be used, in which the production period isn't so short corresponding to the build-up period, to reduce the non-uniqueness.

We should note that permeability is a very important factor. If we reduce the permeability and repeat the same test design, the pressure drop this time will increase and the bottom hole pressure (Pwf) will decrease, which will lead to an extra reduction in the pressure curve on the graph, compared to the previous case. Hence, the reduction in permeability will lead to better results than the previous case, where we will still obtain scattered pressure data but not as before. The non-uniqueness of deconvolution will be less. The permeability is changed from k=33 mD to k=5 mD, and the derivative have been extracted and showed on the log-log plot .The history plot is shown in Figure 26, where we can see the extra decline in pressure drawdown. The log-log plot is shown in Figure 27. The pressure data this time is ordered in a better way than the previous case; yet, it is not perfect.

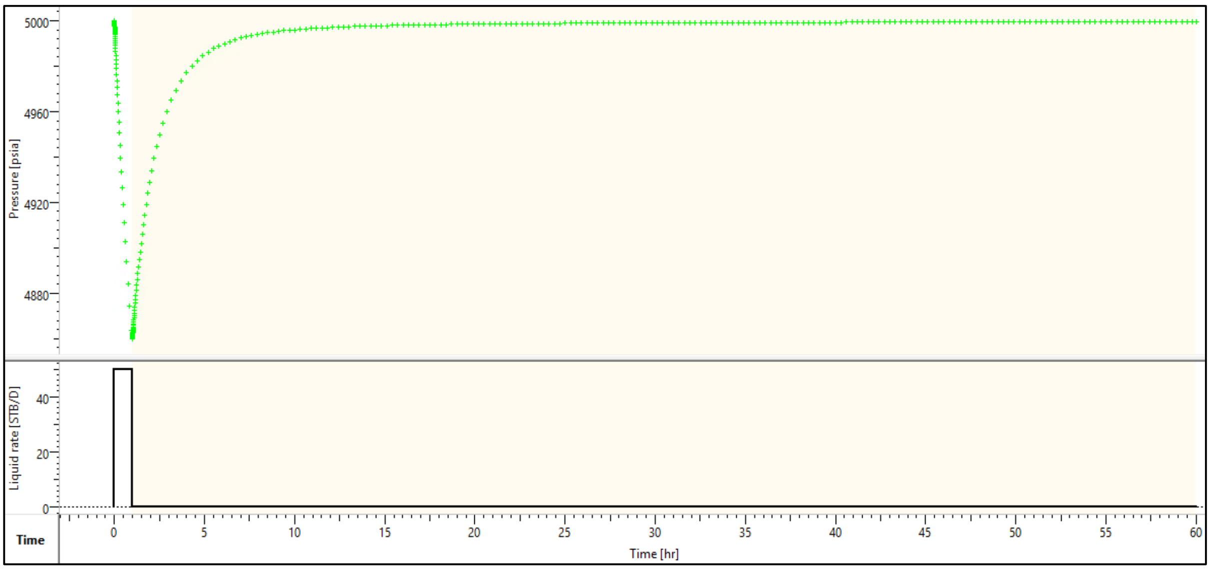

Figure 26: History plot showing extra decline in pressure drawdown for k=5mD

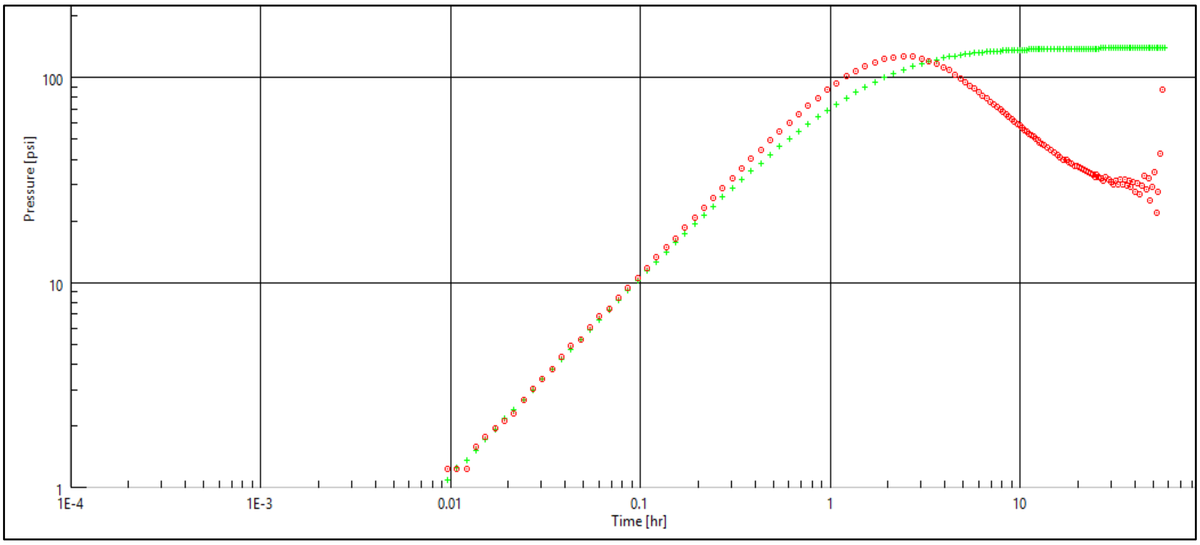

Figure 27: Log-Log plot with a permeability of 5 mD and resolution of 0.04 psi

Deconvolution was also performed for the second case. Finally, we compared the two tests with different permeabilities (Figure 28), and we noticed a big difference between both deconvolved responses with k=33 mD (represented by the green dotted curve) and k=5 mD (represented by the blue dotted curve), concerning the shape of both curves, and concerning wellbore storage, where we realize a bigger wellbore storage effect for the case of lower permeability. It is known that wellbore storage effects are higher when the permeability is low, and vice versa.

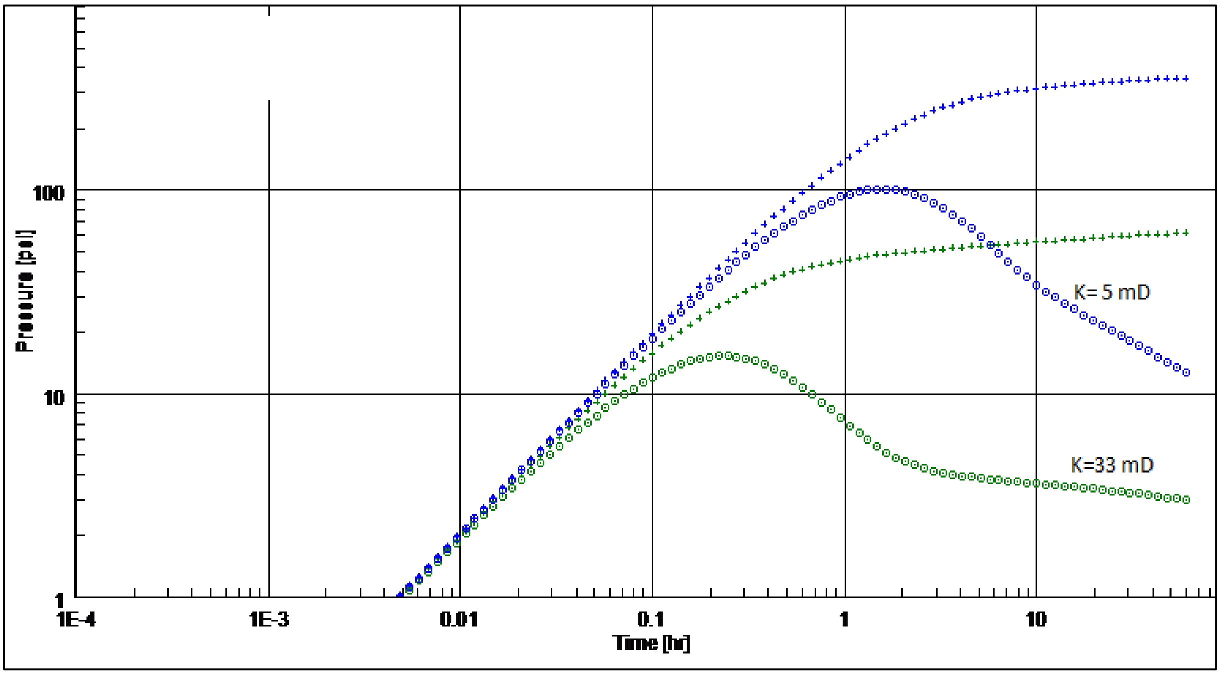

Figure 28: Comparison of the deconvolved responses of 2 different permeabilities on a log-log plot

3. Pseudo-steady state case (Rectangular reservoir)

If we have only one short build-up, then the situation would be vague when applying deconvolution, and sometimes it would be difficult to know if we are under pseudo-steady state or steady state, so we should at least have two build-ups in order to make sure. If I only have a build up without knowing drawdown response, then Pi is preferred to be an input in the deconvolution. If I have only one build-up, and Pi as an output, then the range of Pi values becomes huge (different deconvolved response shapes), since we can either be under steady state or pseudo-steady state. As a result, the deconvolution is non-unique, having different shapes (all might be true). Thus we need extra data to reduce uncertainties.

In the case of two build-ups, where each build up reaches a different level, we will be sure that we are under pseudo-steady state, so the range of different deconvolution shapes corresponding to different initial pressures will decrease. The log-log plot will show increasing range of curves representing PSS.

To demonstrate the idea with 2 build-ups, a certain test design was considered, having the following input:

Production 1: 24 hours, 1000 BOPD
Build-up 1: 36 hours
Production 2: 24 hours, 1500 BOPD
Build-up 2: 59 hours
Boundary model: Rectangle, with 4 no flow boundaries, 100 feet far from the South, 120 feet far from the East, 500 feet from the North, and 1000 feet from the West.

After that, the extraction of the pressure derivatives for both drawdowns and build-ups was performed and the result can be seen through Figures 29 and 30.

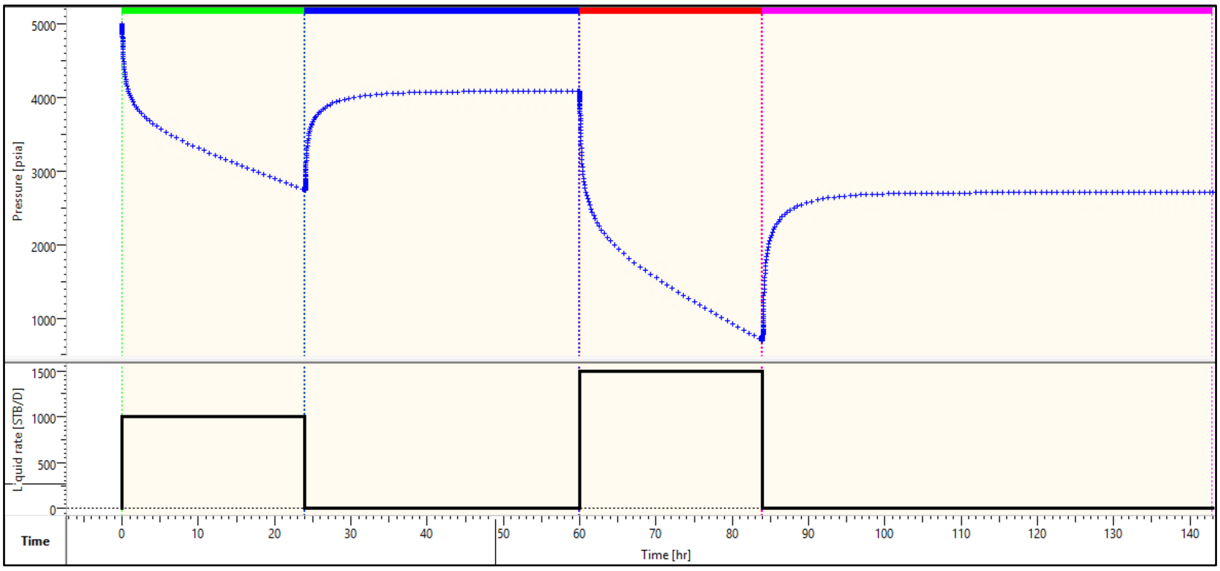

Figure 29: History plot of presure versus time, with 2 flow periods of 1000 and 1500 BOPD respectively for the rectangular reservoir

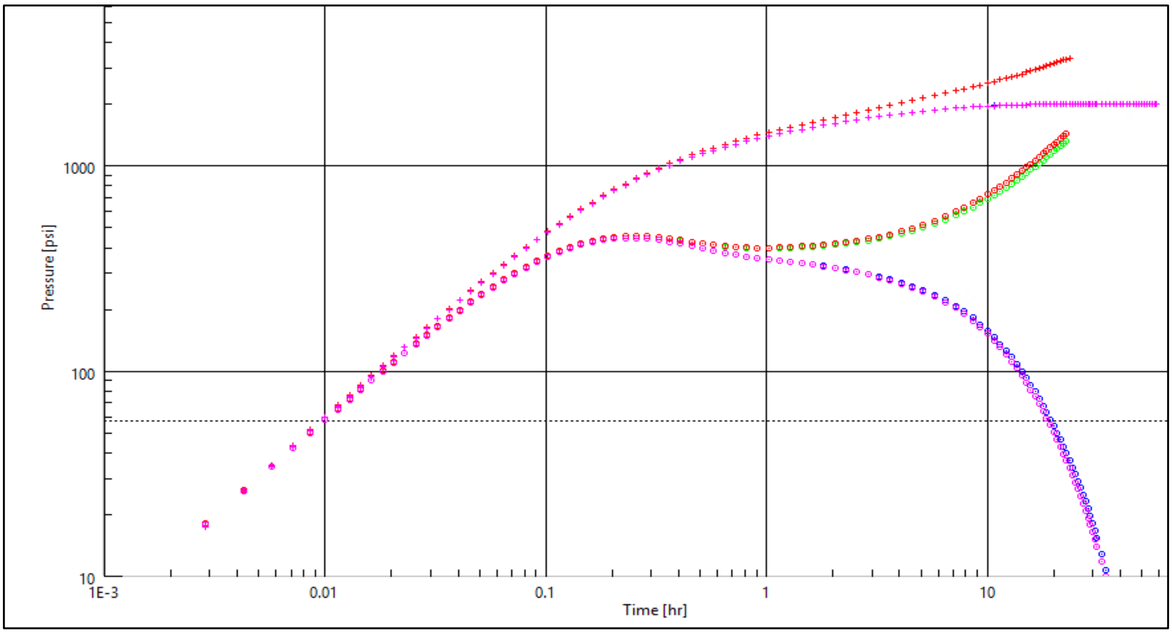

Figure 30: Log-log plot showing drawdown and build up responses

Figure 29 shows that each of the build-ups reached a different static pressure, indicating that we are under PSS. We should note that in a closed reservoir, the drawdown response on a log-log plot goes upwards, while the build-up response goes downwards, and this is demonstrated through Figure 30. After performing deconvolution for the 2 build-up periods (using the first deconvolution option on Saphir), we obtain a curve on the log-log plot which is going upwards since we have PSS, with a duration equal to 120 hours, since in this case we have extra information due to the two build-ups not reaching the same static pressure (Figure 31). We also have a match between the deconvolved response (represented by the red line) and the pressure data (represented by the blue curve), that is shown in Figure 32.

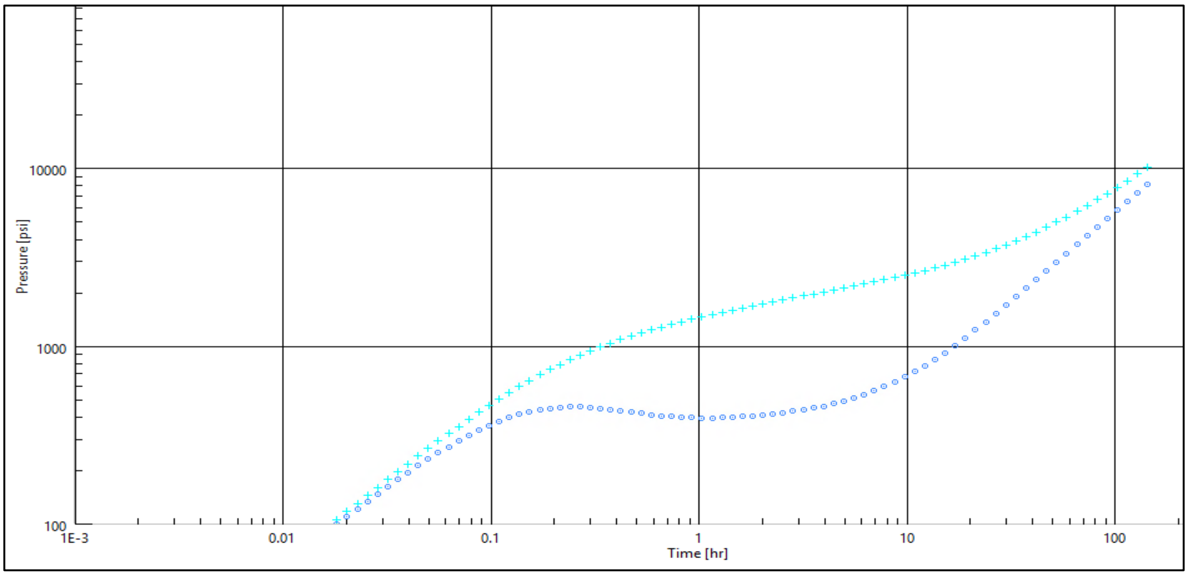

Figure 31: Deconvolved response of the build-up phases shown on a log-log plot in case of PSS

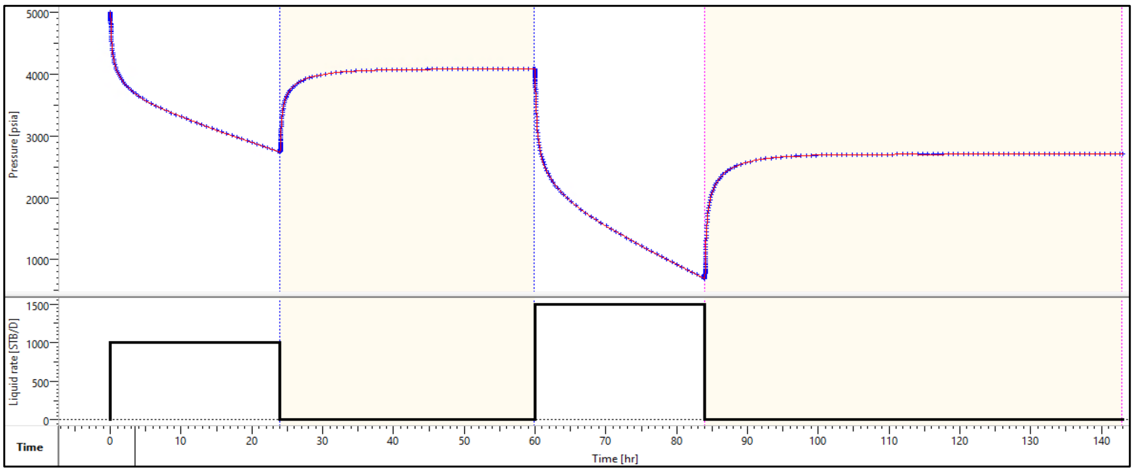

Figure 32: History plot of pressure versus time showing match between deconvolved response and pressure data under PSS

Since we know that we are under PSS, the non-uniqueness for deconvolution decreased for this case. What is the range of initial pressures in which we will always have a pressure match and the deconvolution will always give acceptable results for the above case? The initial pressure will be forced into the deconvolution method, until we start having a mismatch in order for the pressure range to be specified. After doing this experiment, it is noticeable that we have a small interval of Pi which varies between 4985 and 5010 psi (excluding these values), where the deconvolved response will match the pressure data (as long as the pressure is inside this range). Outside this range, we will detect a mismatch as shown in Figures 33 (Pi= 5010 psi) and 34 (Pi= 4985 psi). This decrease in pressure range and uncertainties is due to the fact that this time we have 2 build-ups and much more data interpreted.

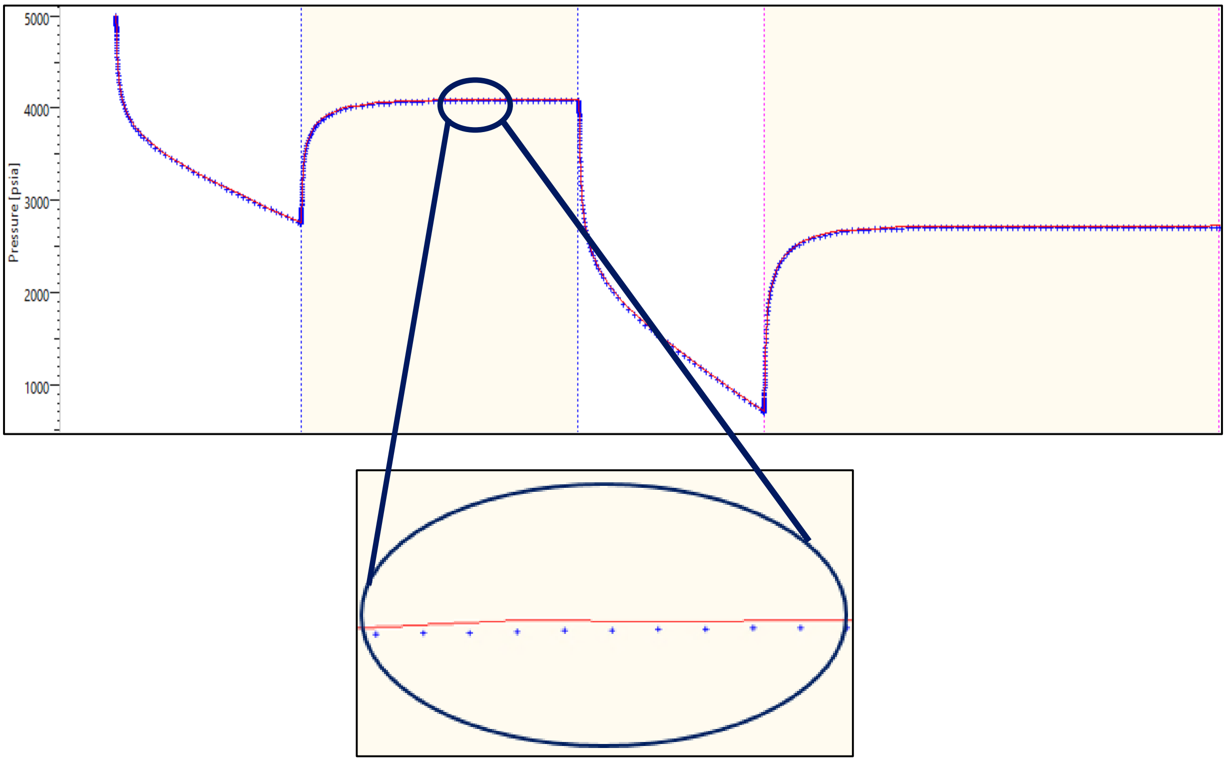

Figure 33: Mismatch between deconvolved response and historical pressure data for Pi=5010 psi

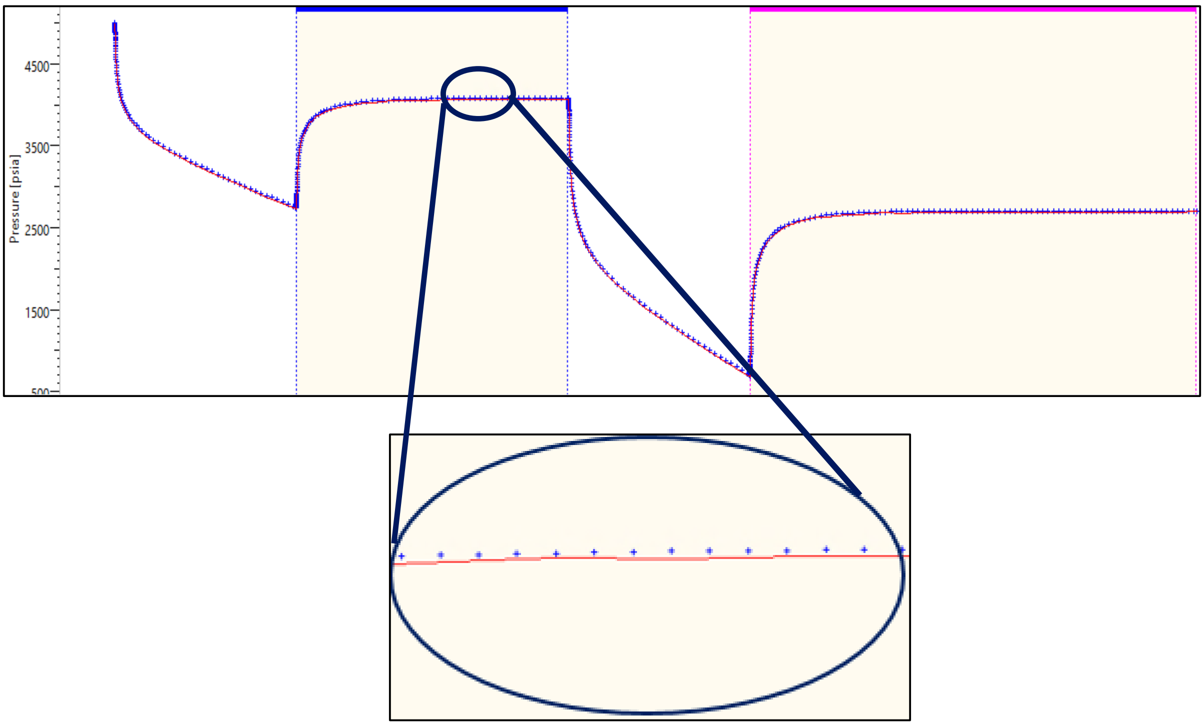

Figure 34: Mismatch between deconvolved response and historical pressure data for Pi=4985 psi

However, a very important consideration should be kept in mind; the mismatch that is taking place, which represents the difference in pressure, can be considered as a mismatch for some people, while can be considered acceptable for others, with respect to the total range of pressures being 25 psi in the above case. It depends on whether the person trusts his/her data available. As a conclusion, for the PSS case, we will obtain higher probability of good deconvolution results with reduced uncertainties.

4. Harmonic Sequence; Net-zero

We have a periodical sequence of 10 hours of flow period of 500 BOPD, followed by 10 hours of injection period of 500 BOPD, and the sequence repeats itself for 6 times, where the total time of the test is 120 hours. In other words, we will have positive and negative rates in this case. This case is represented by a function of *f (t+T)= f (t)* where T is the time-frequency of one cycle, corresponding to 20 hours. A test design was then performed with the default values of Saphir, and pressure data of these periodical are obtained and shown in Figure 35.

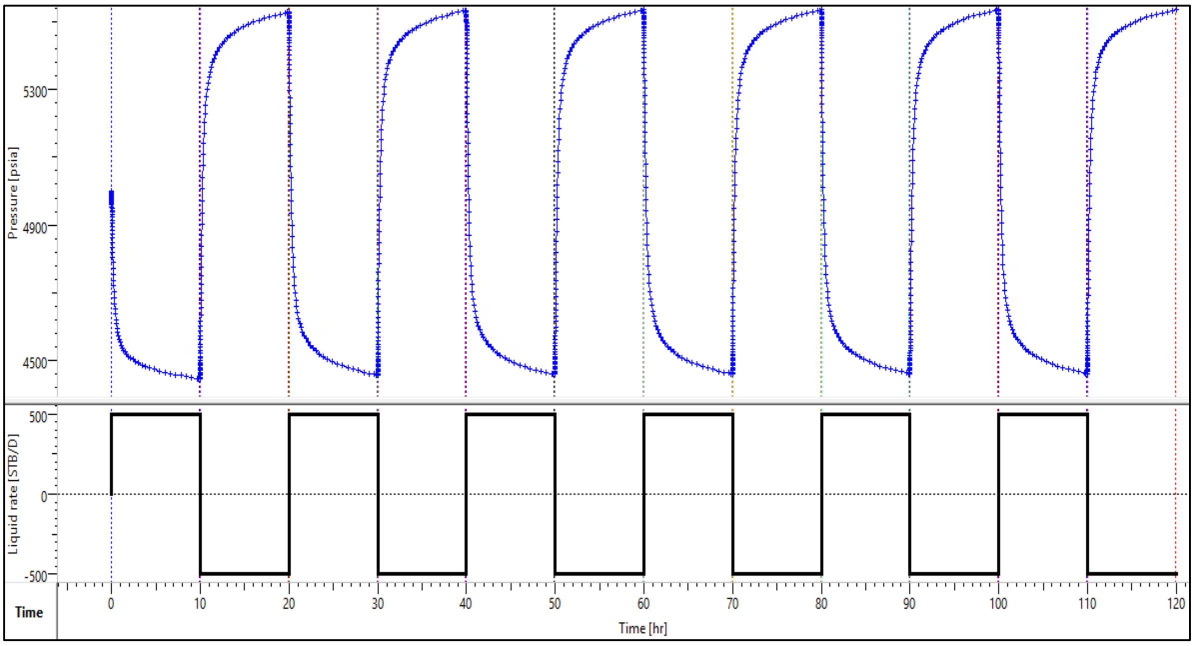

Figure 35: Harmonic pressure signals versus time with a net-zero rate of +500 and -500 BOPD along 120 hours

It is called a net-zero case, since if we add up the positive and negative rates, we will obtain a net zero rate with respect to time. Usually when we speak of harmonic sequences in these cases, the sequence corresponds to the summation of periodic responses and trend responses. The periodic response corresponds to the positive and negative rates and the behavior of the pressure change for every rate, while the trend responses corresponds to the trend behavior corresponding to the constant net average rate, which is zero in this case. The pressure trend due to the net rate is constant with respect to time in this net-zero case, and this is due to the equal production and injection periods of equal rate, generating a zero difference in pressure between cycles. Therefore, we mark that all the information that we need are contained in one cycle of 20 hours (which includes one production and one injection period), since everything later is the same and is being repeated, with no change in the pressure trend curve between all the cycles. Thus, if deconvolution is applied to this case (using the first option out of the four), it will surely give the response of entire test which is equal to 120 hours (Figure 37), but the information is only contained within one cycle. This may lead to a dilemma. We can see the pressure match between the actual data of the harmonic sequence and the deconvolved response in Figure 36.

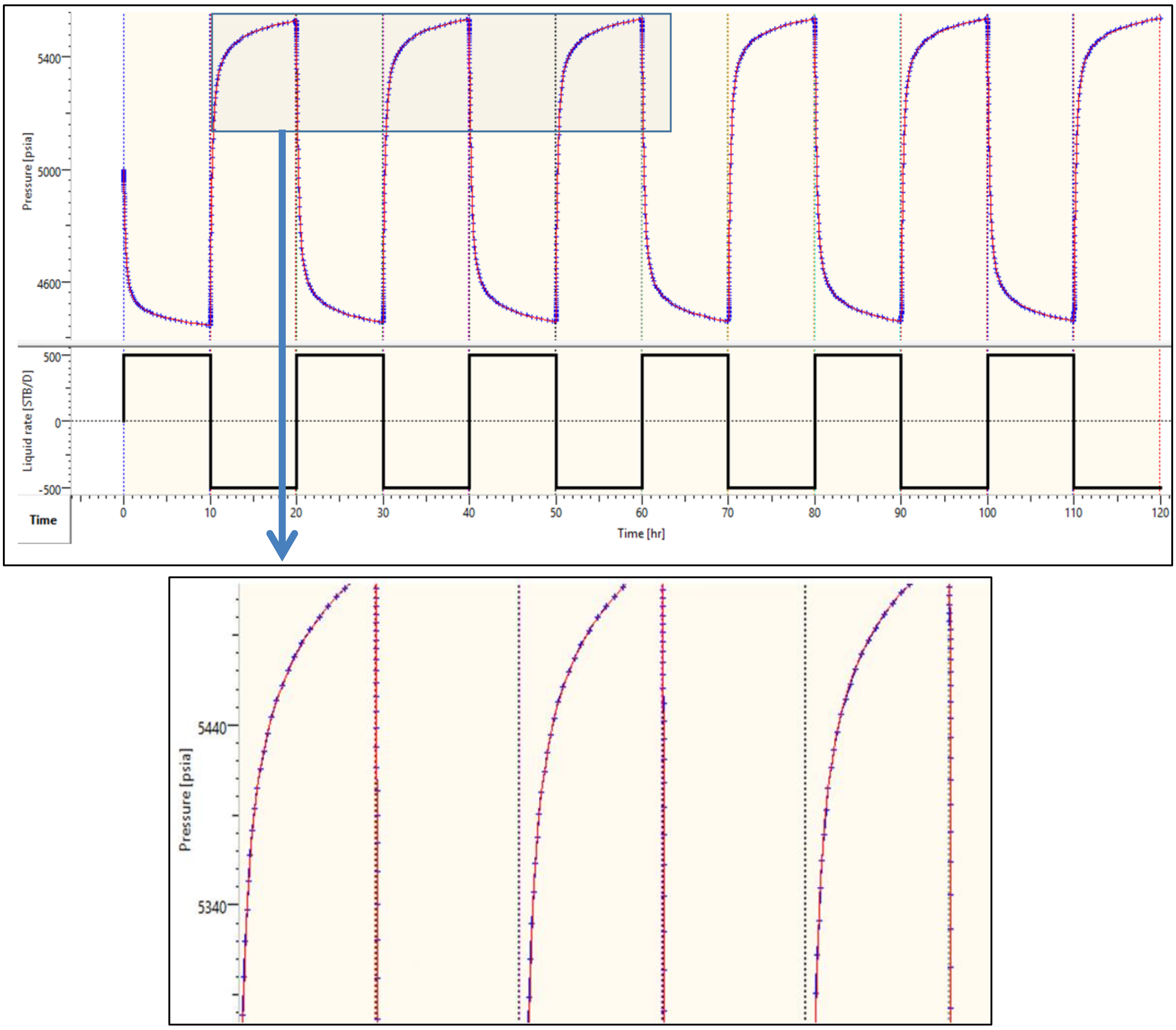

Figure 36: Pressure versus time plot showing match between deconvolved response and pressure data in a zoomed way

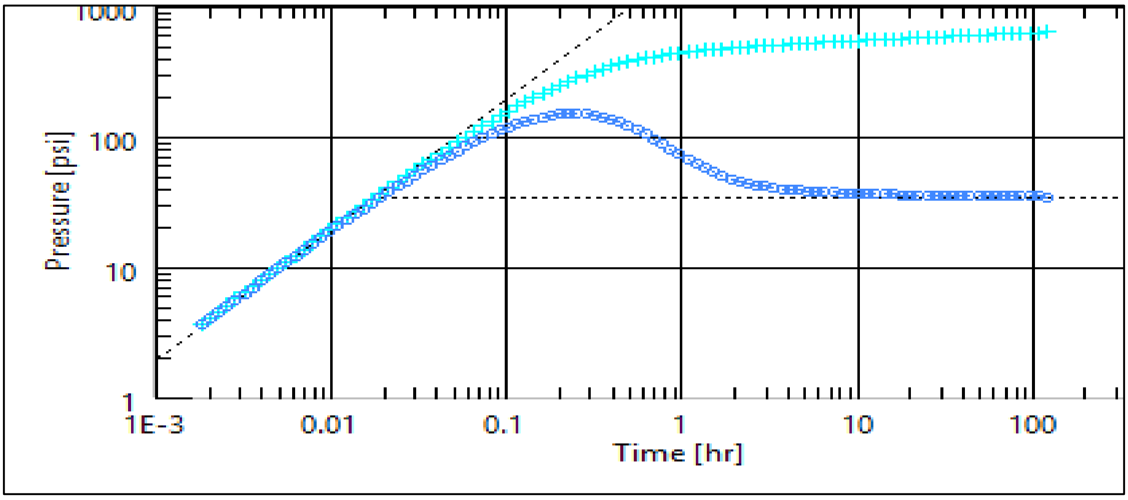

Figure 37: Log-log plot showing deconvolved response for the harmonic net-zero case witha total duration of 120 hours

In order to prove that the data is contained within one cycle, we will play around with the deconvolved response after time T (20 hours), and see if the match between the actual pressure data and its deconvolved response will break.

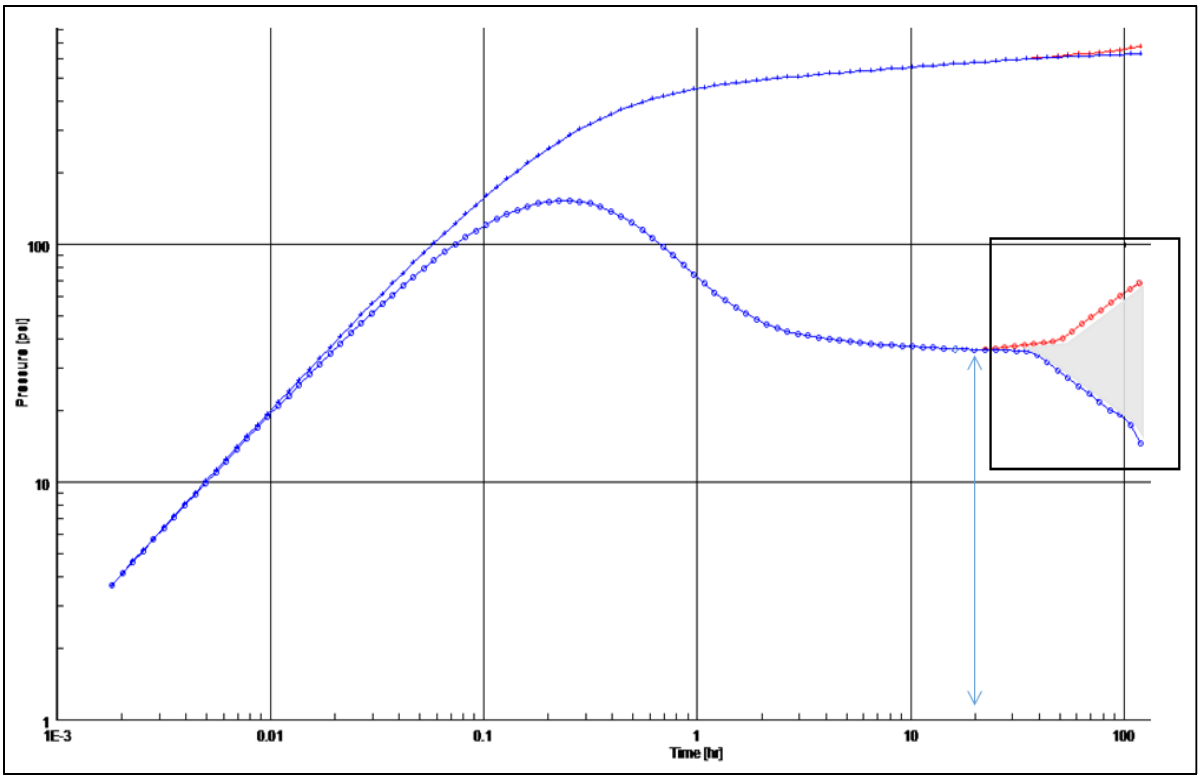

Figure 38: Log-log plot showing the changes made or that can be made on the deconvolved response after T=20 hours in terms of a trumpet shape

Figure 38 shows a range of changes in the points of the deconvolved response after the first 20 hours, and what we will realize is that this change didn't affect the pressure match, since the information needed is fixed within the first 20 hours of the periodical sequence. Whatever shape we yield after T of 20 hours, will give the same result, in which the pressure match will still exist. As a conclusion, the match wasn't affected by this change. The results are displayed in Figure 39 below, where the red line represents the deconvolved response. This kind of dilemma should be avoided. We must pay attention on whether we have a harmonic sequence with a net-zero case, and we should re-consider using deconvolution.

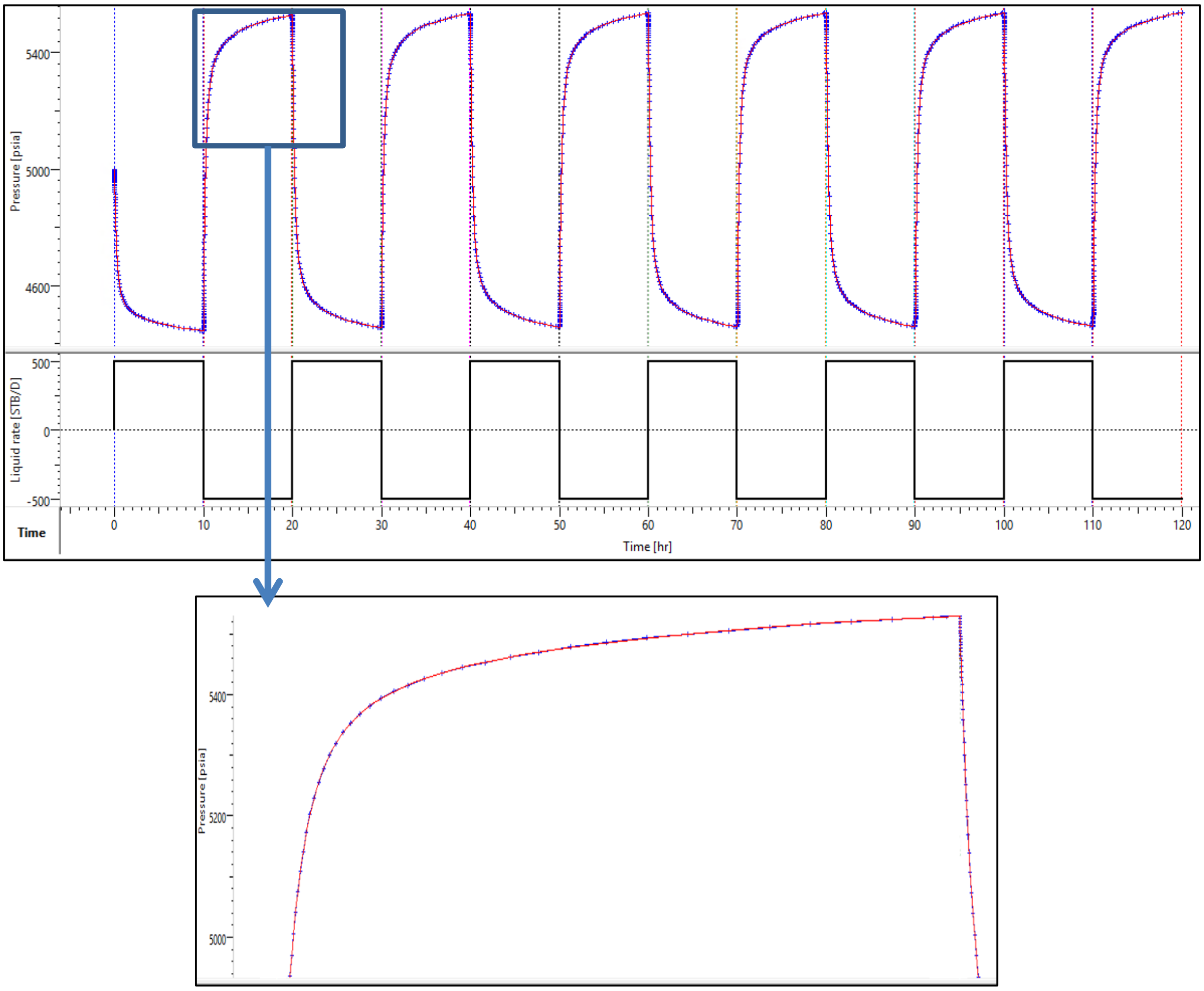

Figure 39: Pressure versus time plot showing the unchanged match even after the adjustments made on the deconvolved response after T=20 hours

5. Harmonic Sequence; Net-Positive

In this case 6 flow periods are taken, each one for 10 hours with a rate of 1000 BOPD, and 6 shut-in periods of 10 hours each, with the default input of Saphir. The difference between this case and the net-zero case is that the net-positive will result in a positive constant rate equal to 500 BOPD after summing all the rates, as if we have a test with a constant rate of 500 BOPD for 120 hours. As a result, a test having 500 BOPD for 120 hours, should have a similar deconvolved response to this net-positive case with different cycles.

First, we entered the data, and then extracted the pressure derivative curves. The results are represented by Figure 40, which reveals the pressure data with respect to time, and Figure 41, which displays the pressure data on a log-log plot, where each period is extended till 10 hours and is represented by a different color.

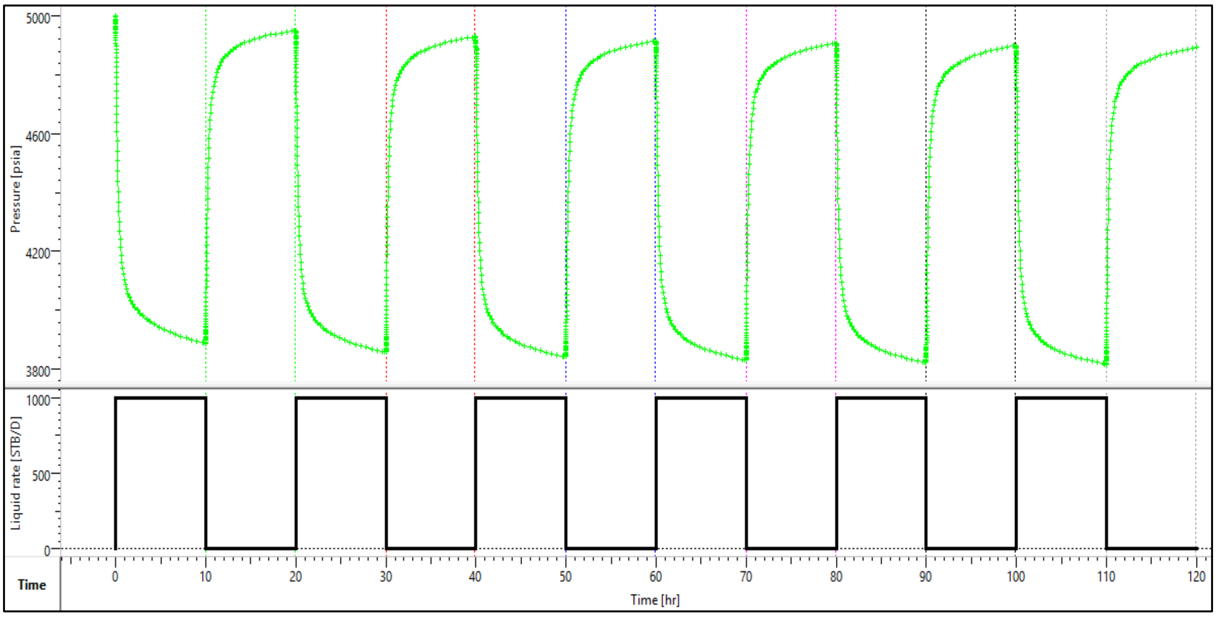

Figure 40: Pressure versus time plot for net-positive case

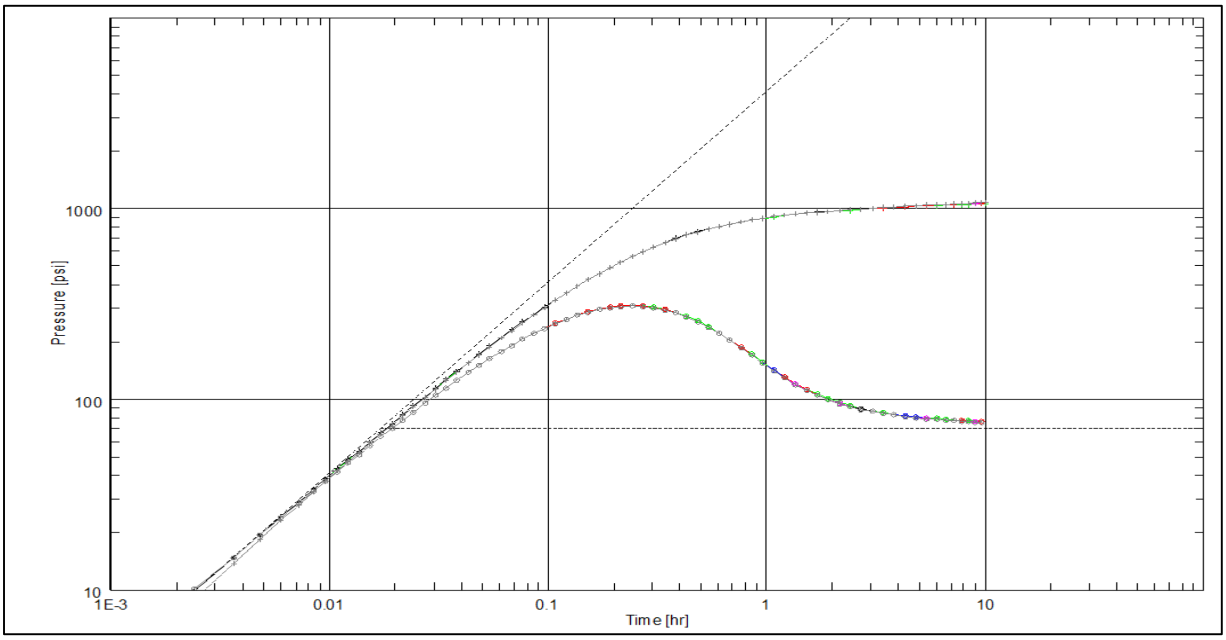

Figure 41:Log-log plot for all periods for net-positive case

Deconvolution was performed on the build-up periods (6 in total), using the first option of deconvolution out of the four. Consequently, the deconvolved response will extend till 120 hours (Figure 42), which is equal to the entire test duration, and will also match the pressure data (Figure 43).

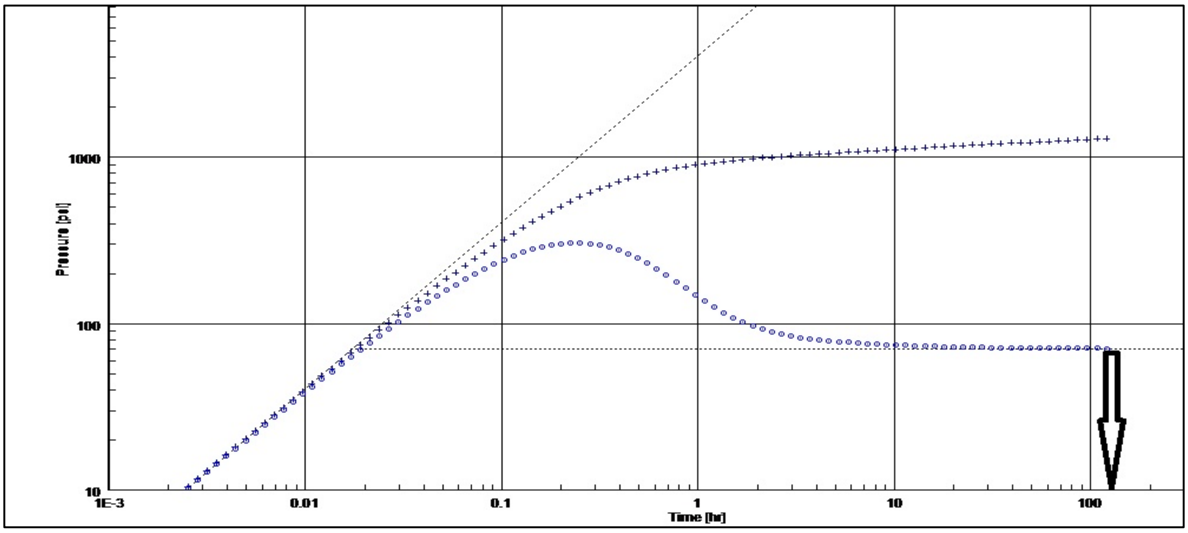

Figure 42: Log-log plot showing deconvolved response with the duration of 120 hours for net-positive case

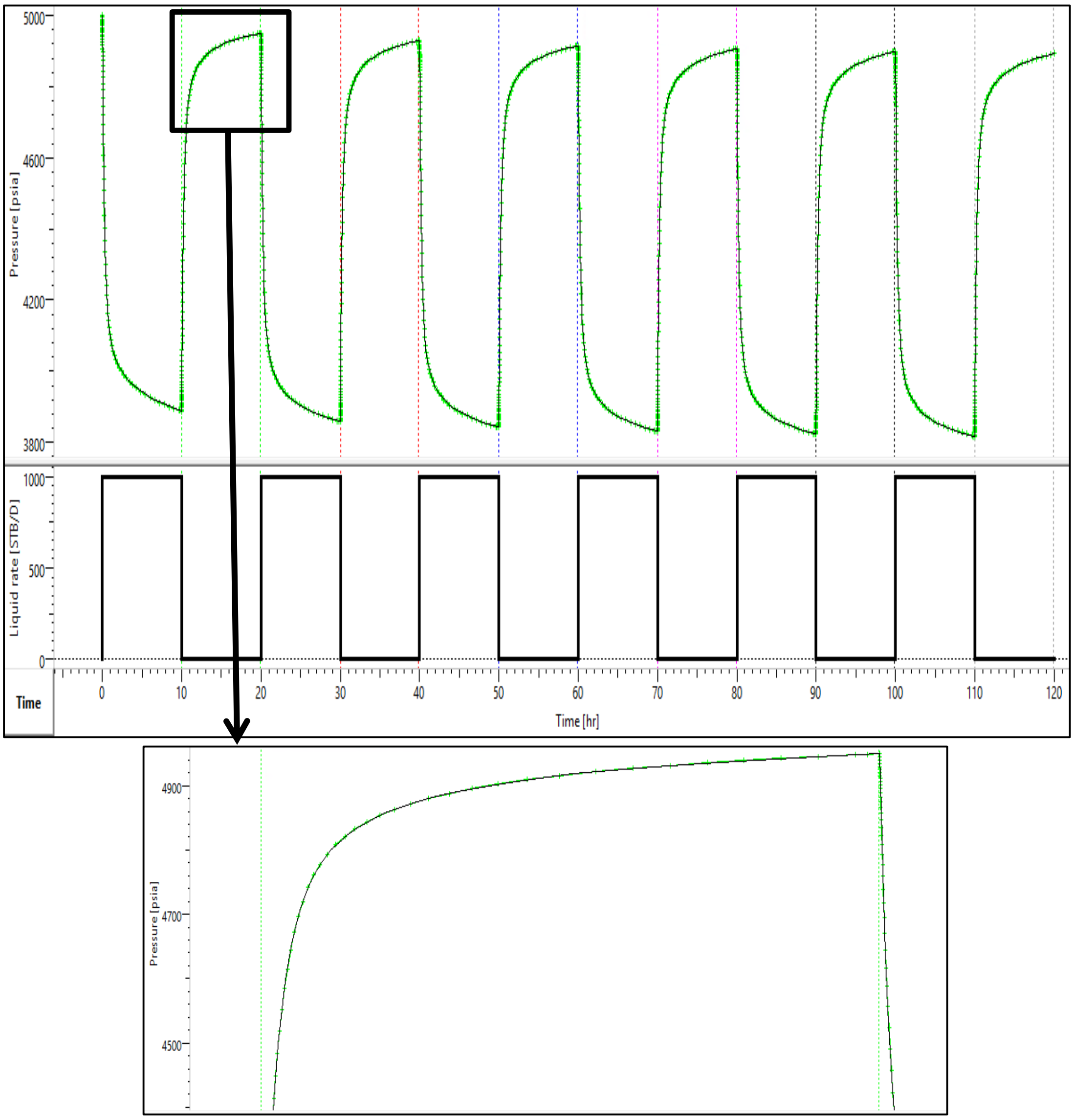

Figure 43: Pressure versus time plot showing match between deconvolved response and actual pressure data for net-positive case

As previously stated, the harmonic sequence is a summation of periodic responses and trend responses where the periodic response corresponds to the positive and negative rates and the behavior of the pressure change for every rate, while the trend responses corresponds to the trend behavior corresponding to the constant net average rate, which is 500 BOPD in this case. The pressure trend due to the net rate in the net-positive case is decreasing (represented by a red line in the Figure 44), unlike the net-zero case where it was held constant. The fact that it is decreasing signifies that the information is contained in the trend response as well, unlike the previous case (net-zero) where the information was only contained in the periodical response. For this reason, whatever or wherever points we change in the deconvolved response, from the beginning till the end of the test, will result in a mismatch with the actual pressure data, which is dissimilar to the net-zero case, where a change of deconvolved pressure points after T= 20 hours would never affect the final match.

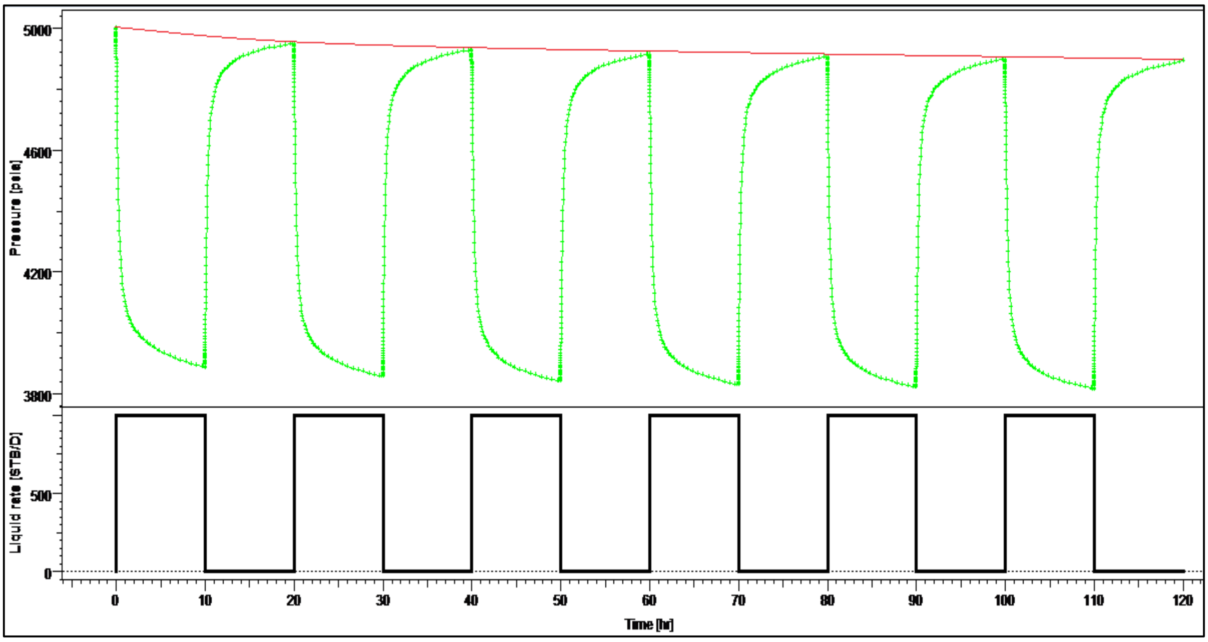

Figure 44: History plot showing pressure trend due to the net rate represented by the red line

Finally, a specific test of a constant 500 BOPD for 120 hours was taken (Figure 45), where pressure versus time plots were extracted and deconvolution was conducted. The main reason behind constructing this test is to compare the final deconvolution outcomes with the net-positive results, which should be similar. The deconvolution of a 500 BOPD constant rate test is the same as the pressure drawdown response equal to the entire test duration.

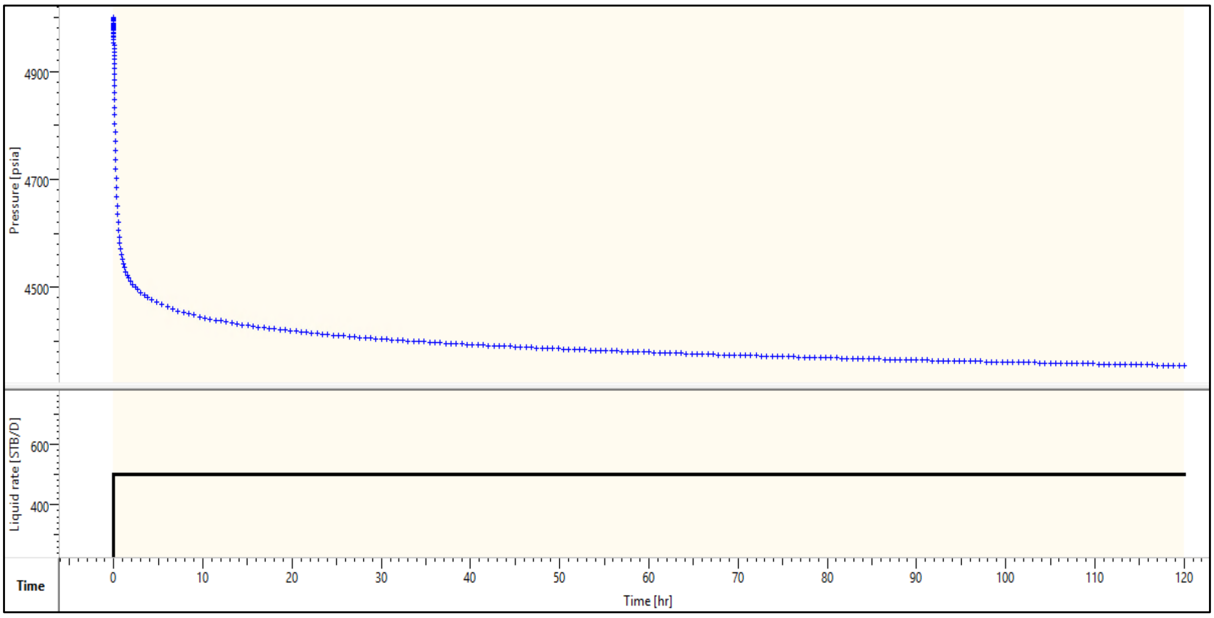

Figure 45: Pressure versus time plot for a constant average rate of 500 BOPD

After comparing both curves, we realize that both the Net-Positive and the Constant rate of 500 BOPD deconvolution responses coincide, as shown in Figure 46:

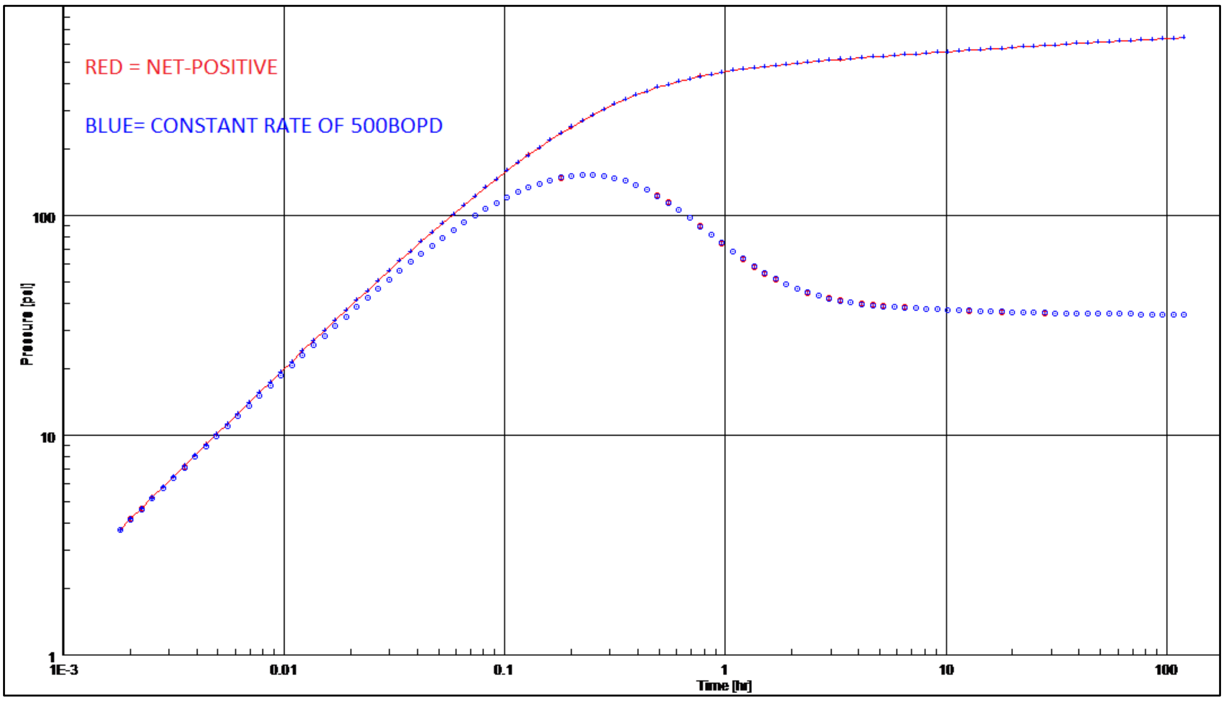

Figure 46: Comparison between net-positive case and constant rate of 500 BOPD on a log-log plot

6. GAP Case

A new test will be studied, in which we have a 48-hour flow period with a rate of 1000 BOPD, and a 12-hour shut-in period. The build-up equation which is developed by using the superposition in time principle, is demonstrated by the following equation:

P(t) = Pi - $\Delta P_{DD}(tp+\Delta t) + \Delta P(\Delta t)$ -- EQN 8

where $\Delta P_{DD}(tp+\Delta t)$ is the drawdown response corresponding to a single rate, and the $\Delta P(\Delta t)$ is the pressure drop corresponding to the build-up period. The Δt in the above test, represents a 12 hours shut in period, while the $(tp+\Delta t)$ represents duration between 48 hours and 60 hours (since tp=48 hours). Figure 47 represents the extracted log-log plot for the build-up phase corresponding to 12 hours. If we apply deconvolution for the above test on the build-up period (using the first option), then it is predicted that we will obtain a deconvolved response equal to 60 hours, which represents the duration of the entire test (Figure 48).

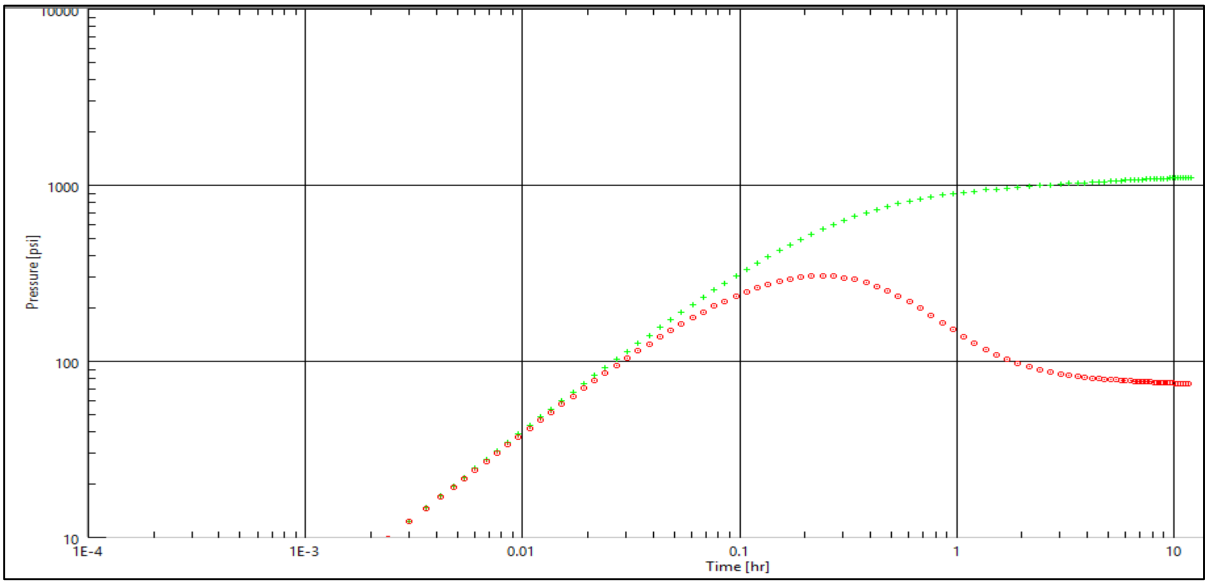

Figure 47: Log-log plot for the gap case showing normal and derivative pressure curves for the build-up phase

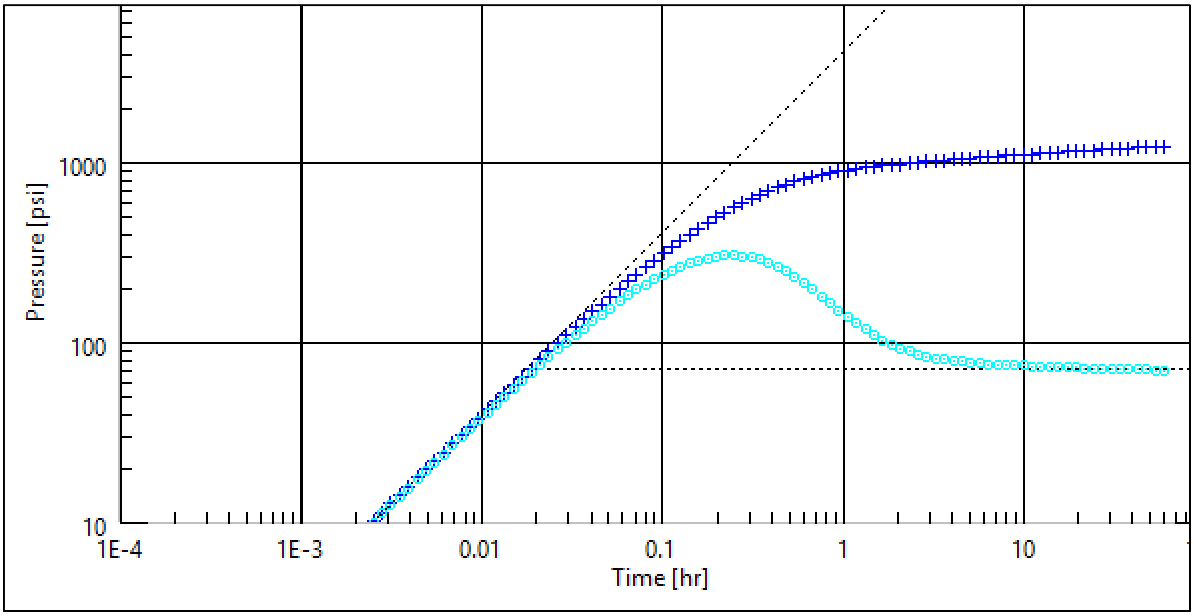

Figure 48: Deconvolved response on a log-log plot for the Gap case with a duration of 60 hours

In equation 8, there isn't a term that represents the duration between 12 hours and 48 hours; we only have 12 hours shut in period, and the *(tp+Δt)* period (value between 48 and 60 hours). What if we play with, or change the points of the deconvolved response, that are located in the gap between 12 hours and 48 hours. Will the deconvolved pressure signal still match the actual pressure build-up data? In the figure below, we misplaced some points inside this gap (Figure 49).

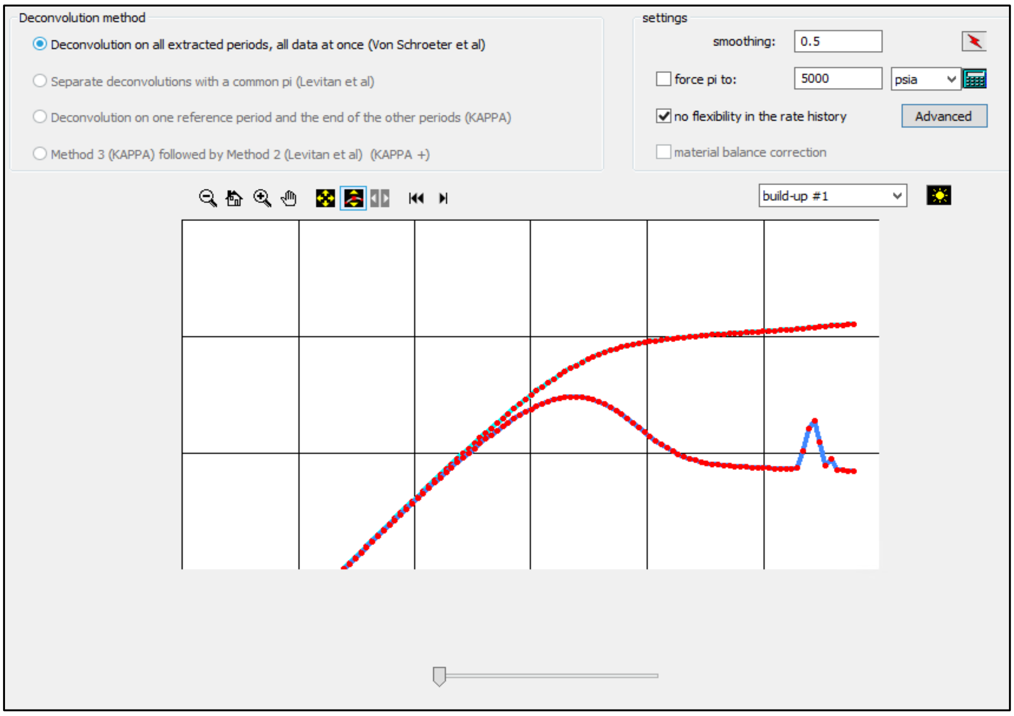

Figure 49: Deconvolution option on Saphir showing the change of the deconvolved response points inside the gap

After performing this displacement of points, we will still obtain a good pressure build-up match. As for the drawdown curve (which we imagine that we don't know since our deconvolution study was performed on build-up period), a mismatch is located. Thus, what we see from the deconvolution shows that our deconvolution is good, but actually it isn't "the" optimal deconvolution to trust since we don't have a perfect match with the pressure drawdown response (Figure 50). This case also demonstrates the non-uniqueness of deconvolution. As a result, we should minimize this "gap" that we have, since it may affect our final outcome negatively. So, it is suggested to have a better test sequence between flow and shut-in period, for this gap to be reduced. Figure 50 shows the pressure build-up match and the pressure drawdown mismatch on the pressure with respect to time curve, corresponding to a specific rate of 1000 BOPD.

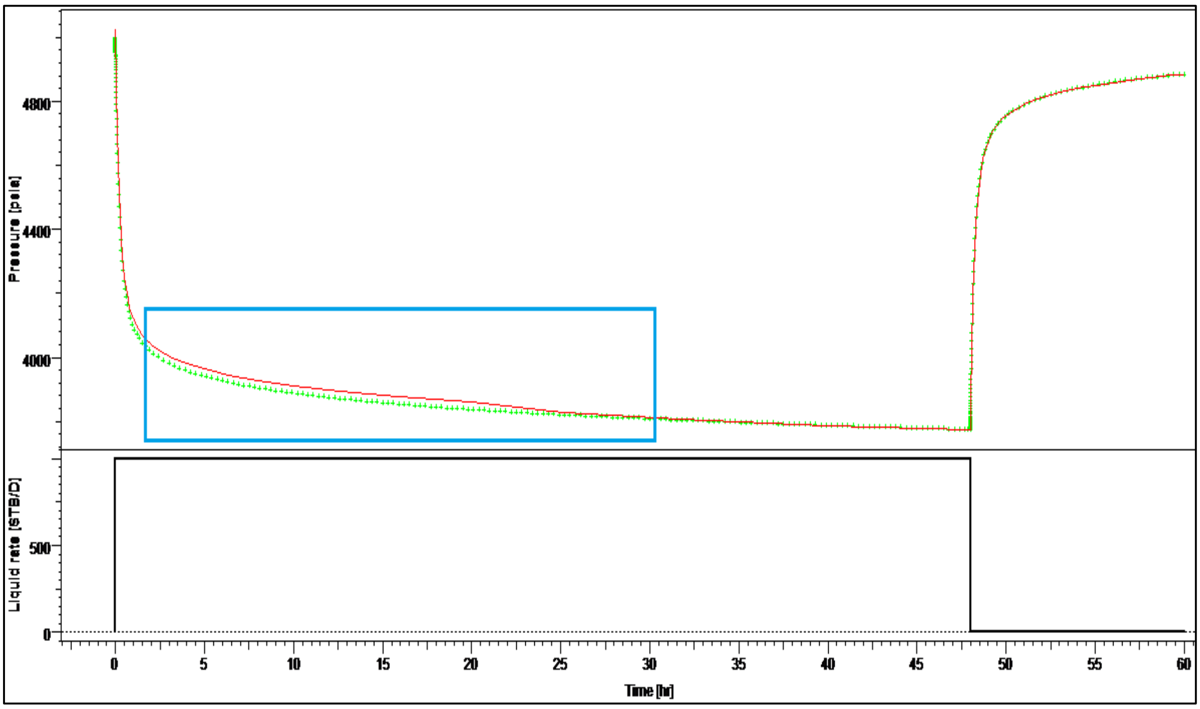

Figure 50: Pressure versus Time plot showing drawdown mismatch and the build-up match between the deconvolved response and actual pressure data

When the derivative is changed when using Saphir, the normal pressure change on the log-log plot was affected. Due to this integration, the initial pressure of the reservoir of this test will change. So, we don't have control on how the pressure is changing. In other words, when we modify the derivative, it does like a kind of integration and modifies the pressure change, where we will end up with a different ΔP having a different shape, equivalent to having different skin. Hence, when we do the deconvolution, the deconvolved response won't match the starting point of the pressure build-up data at shut-in at t=48 hours (it will be located under the actual pressure build-up data). In order to lift this point and enable the deconvolved response to match the pressure data, I changed the initial pressure guess of the deconvolution to a higher value of 5023 psi (as if I lifted the deconvolved response that is represented by a red color). Figure 50 shows that the deconvolved response and the real pressure at the beginning of the shut-in period at 48 hours in the above figure are matching (because of the modification in initial pressure that I made). As a result, the modification was performed due to the pressure change that happened (change in skin), following the change in the derivative.

For the same case, an experiment was performed on excel, to demonstrate the gap case without facing the previous type of integration. In this experiment, a kind of compensation will happen, where the ΔP will stay the same and will generate no change in skin. Thus, by using a specific method on excel and some algorithms, the initial pressure in this case is 5000 psi, and will be constant for the whole test. In other words, it will be guaranteed that for the same initial pressure and the same flowing pressure, we will have match for pressure build-up data, even with a derivative that has a weird shape inside the "Gap". Figure 51 shows the change in derivative, which is a function of ΔP, while Figure 52 the build-up curve that is matched with the deconvolved response. The difference between the actual pressure build-up data and the deconvolved pressure data was then calculated on excel, and resulted in a difference of zero, indicating a perfect match.

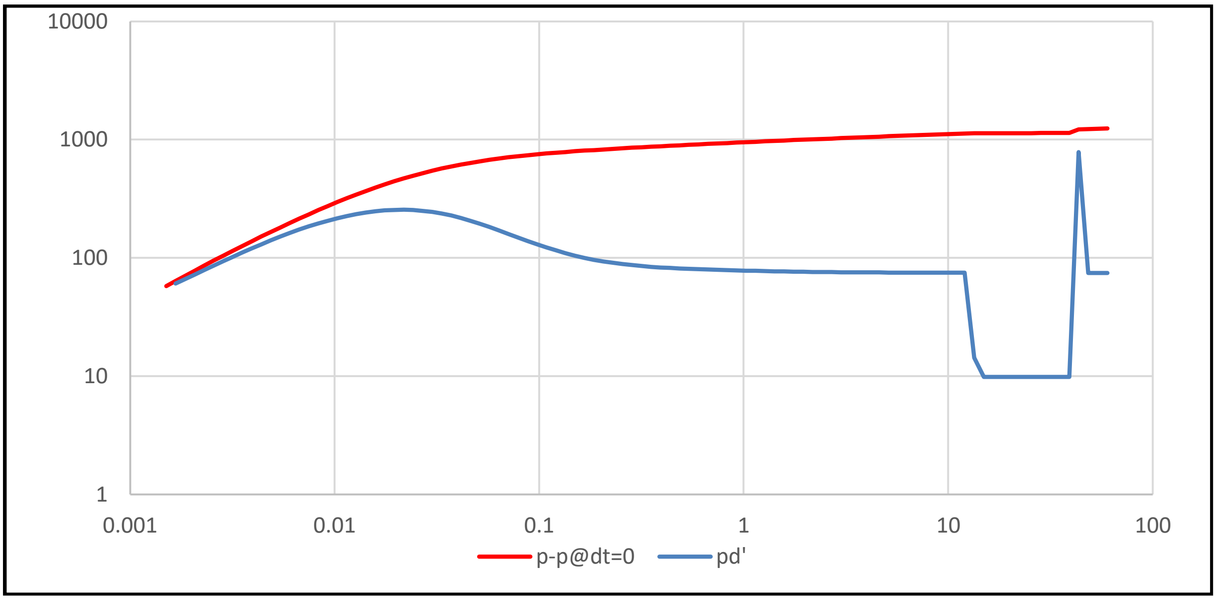

Figure 51: Log-log plot showing the change of the deconvolved response of the pressure derivative inside the gap

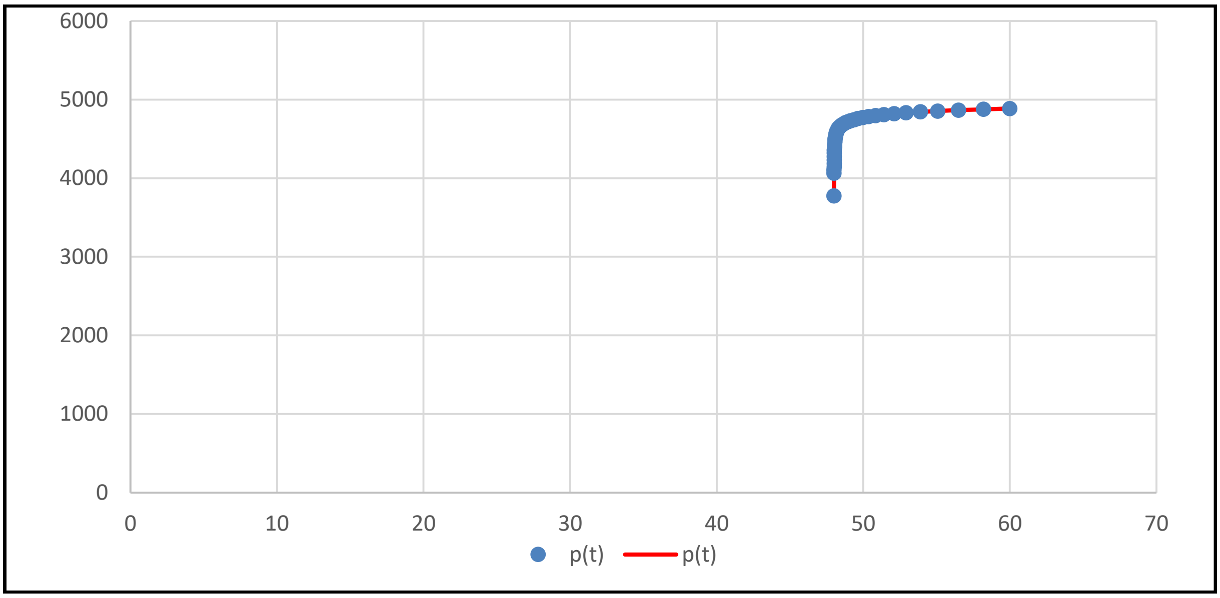

Figure 52: Match between pressure build up (blue) and deconvolved response (red) of the build-up of the Gap case after the modification in Figure 51

What if we modify the points located in the first 12 hours of the deconvolved response (0-12 hours) using Saphir? In this case, the pressure build-up data and the deconvolved response won't match this time, since Equation 8 contains the term that will be fluctuating, which is $\Delta P(\ \Delta t)$, so the pressure response will change. The modification of points, and the results of the mismatch are demonstrated in the Figures 53 and 54 respectively.

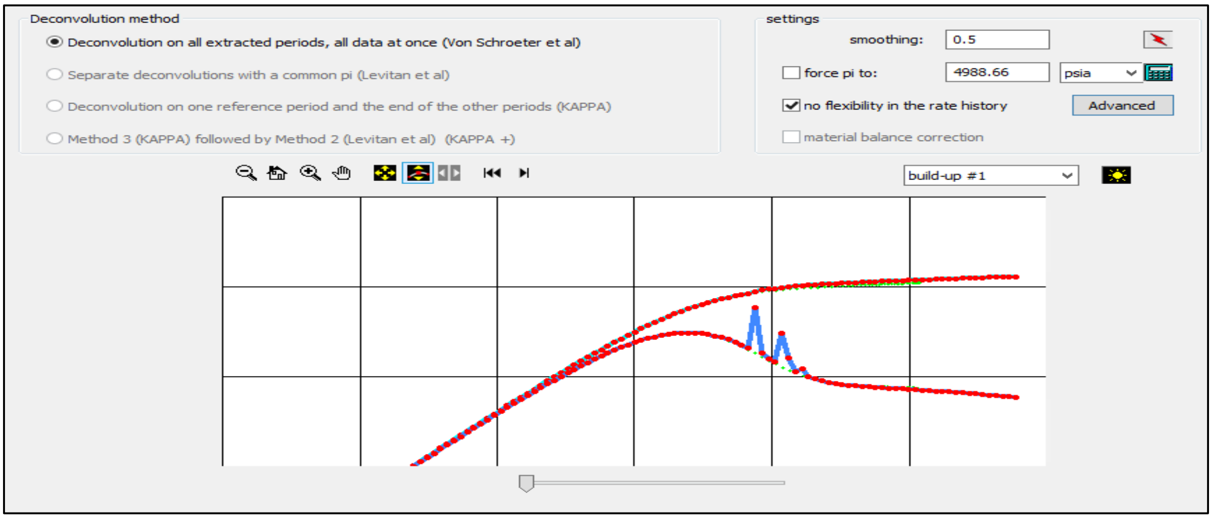

Figure 53: Deconvolution option on Saphir showing the adjustment of the deconvolved response points outside of the gap

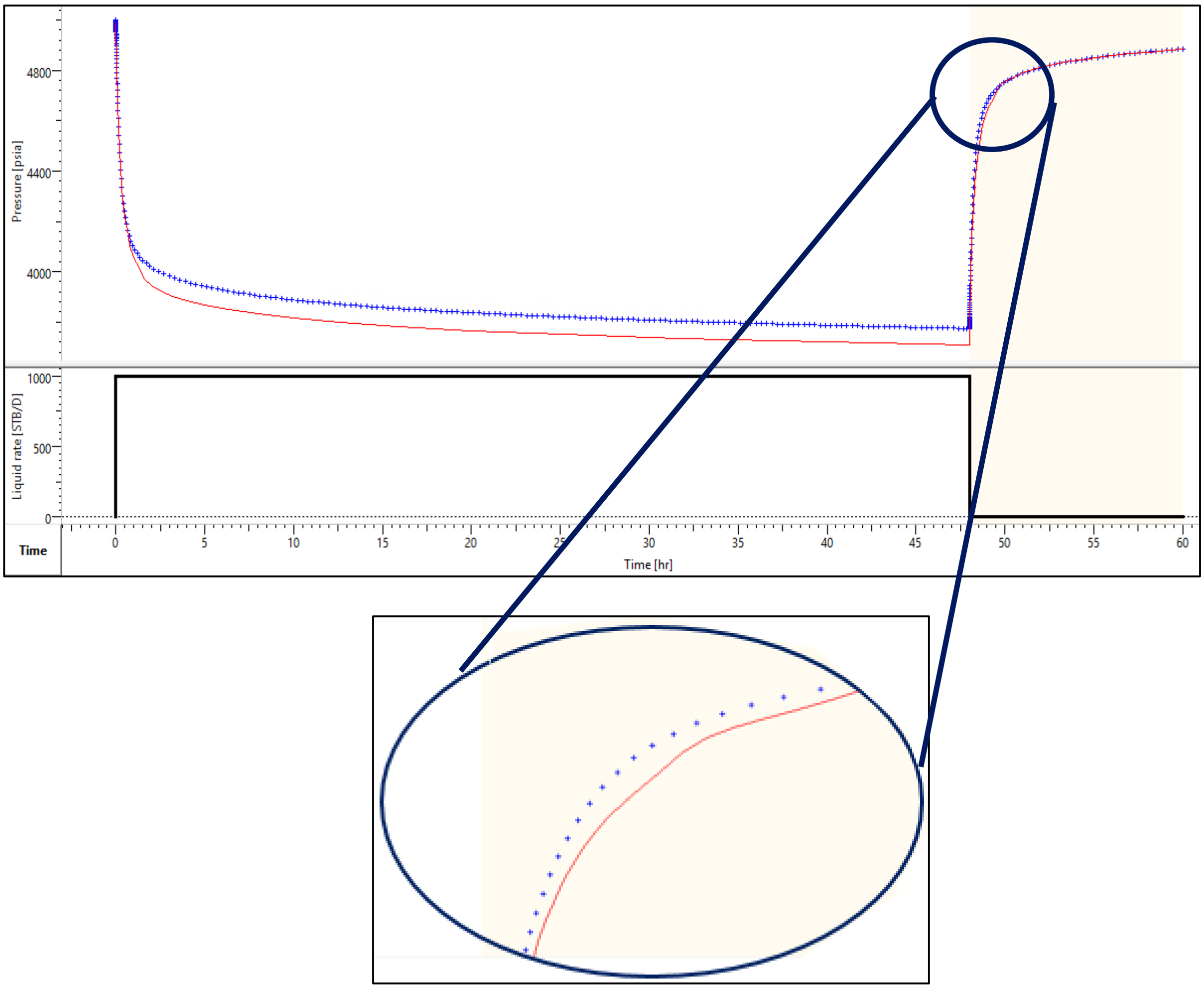

Figure 54: Mismatch of the actual pressure data and the deconvolved response in a zoomed way, due to the adjustment of the points in figure 53

As a result, the pressure build-up and the deconvolved response slightly mismatched in specific places, because the varying term is included inside Equation 8. As a conclusion, the so called "Gap" between a specific flow period and build-up period should be reduced, in order to reduce the non-uniqueness of the deconvolution. This will be fixed by choosing a more suitable test sequence.

7. Changing Wellbore Storage between 2 flow periods

It is possible for the wellbore storage to change from one flow period to another. This is due to the possible change in fluid phases and their compressibility, or to the time for pressure to propagate through the well after shut-in and reactivating the well again. A test design of 2 flow periods of 24 hours each, with a flowrate of 1000 BOPD and 1500 BOPD, and 2 build-up periods of 36 hours each, was simulated. Instead of choosing a standard model, we chose the changing well model option, and assigned a 0.01 bbl/psi wellbore storage for the first flow period, compared to 0.001 bbl/psi of the second flow period. The build-up periods were both extracted (Figure 55) and the log-log plot was plotted (Figure 56).

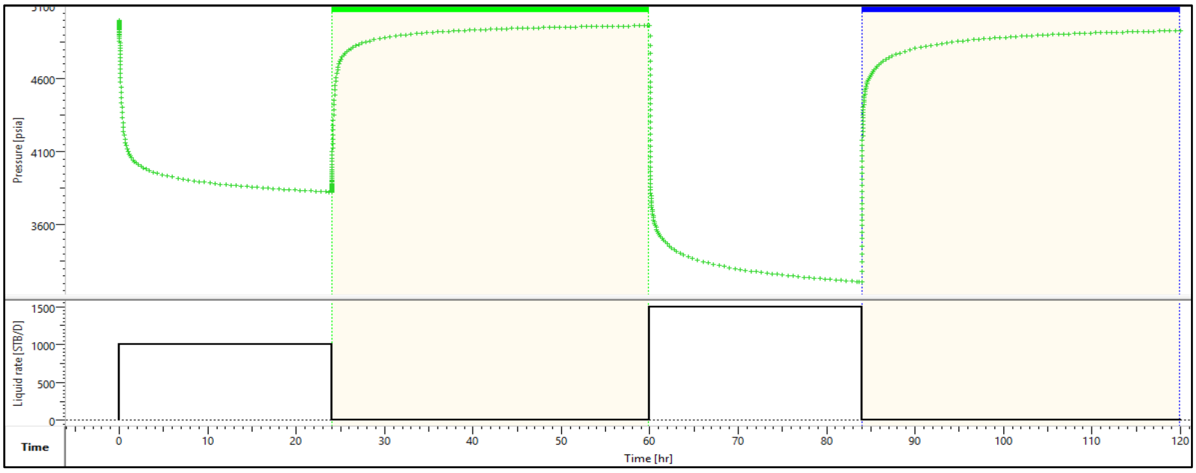

Figure 55: Pressure versus time plot showing two different flow periods with two build up periods with different wellbore storage effects

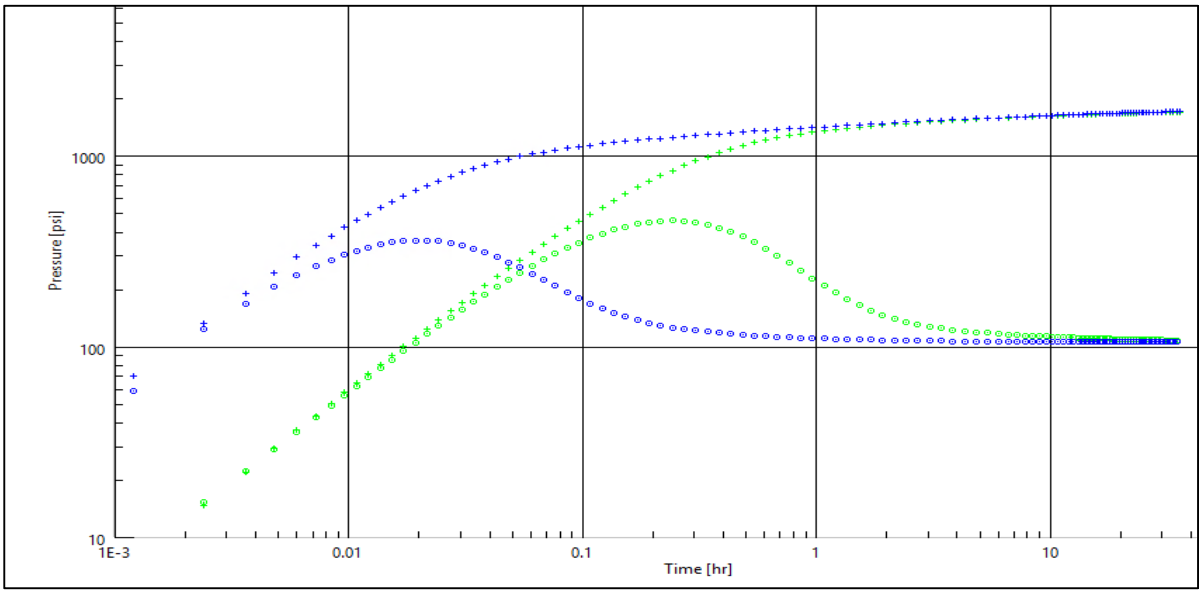

Figure 56: Log-log plot showing the difference in wellbore storage effects on the build-up periods with duration of 36 hours

The blue curve in Figure 56, which represents the second flow period with lower wellbore storage, is the reference in this case. The period characterized by a lower WBS is typically selected to be the reference, since it contains more information about the reservoir behavior.

The first option of deconvolution ("Deconvolution on all extracted periods, all at once") was chosen for this case. Our extracted periods were the build-up periods, so the deconvolution is performed on both build-up periods all at once. After checking the results, it turns out that we won't have a good match between build-up pressure data and the deconvolved response, even after forcing different initial pressures and trying to fix the match. This is due to the huge difference in wellbore storage effects between the two phases, and to the difficulty of merging the two different values of WBS by using the first option. The output initial pressure will be equal to 4891 psi, which is a far value from the actual initial pressure in our case, which is 5000 psi. Figure 57 shows the log-log plot showing the uncommon derivative shape that is decreasing at late times. Figure 58 shows the history plot and the mismatch along the whole duration of the test.

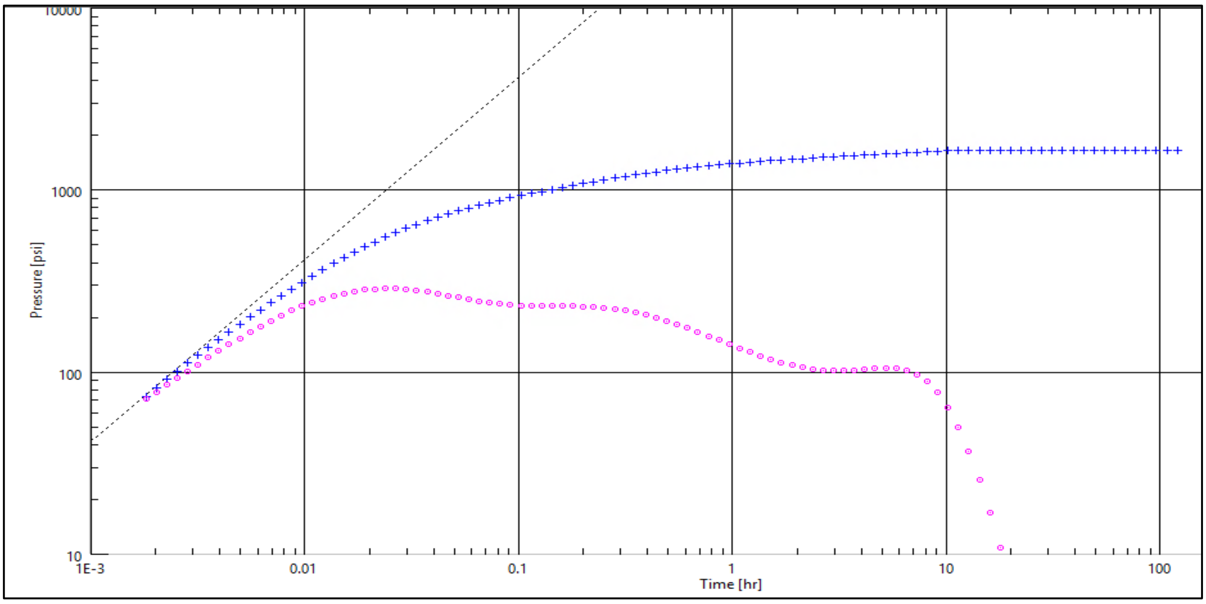

Figure 57: Log-log plot showing the results of the deconvolution extracted on all periods for changing wellbore storage case

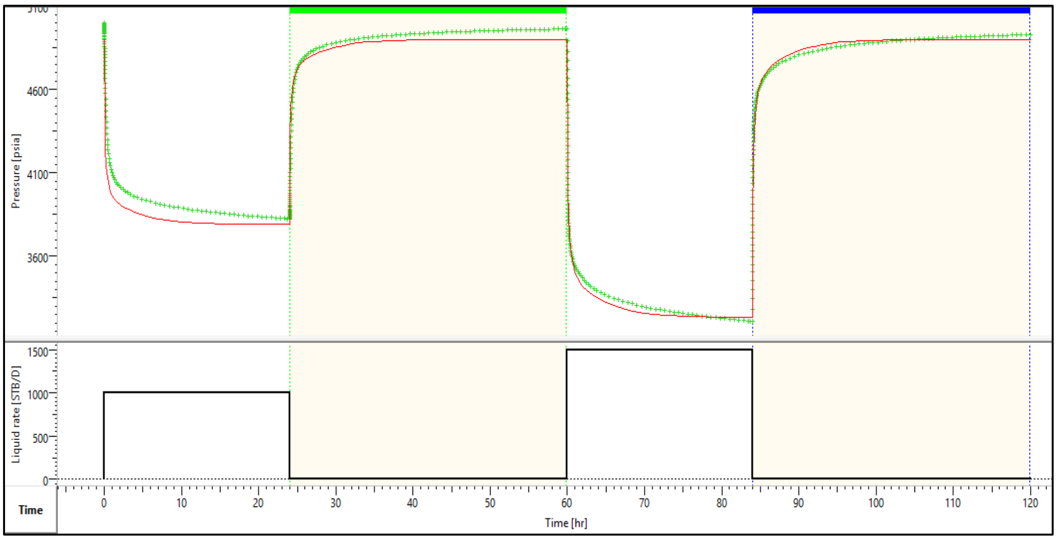

Figure 58: History plot showing the mismatch of the actual pressure data and deconvolved response after the deconvolution on all extracted periods (build-ups)

Instead of choosing the first option as the previous cases, which is done on all extracted periods, we now choose the third option, which is "deconvolution on one reference period, and at the end of other periods", since both ends of the two curves are similar, while the beginning of both phases is different (because of changing WBS). As we choose the third option, we will be able to move a light blue line, placing it before the end of both curves, where we have an infinite acting radial flow. This blue line will enable Saphir NL to perform the deconvolution at the end of the both build-up periods, while taking the second build-up period as reference (represented by blue line in Figure 56). The use of third deconvolution option is illustrated through the Figure 58:

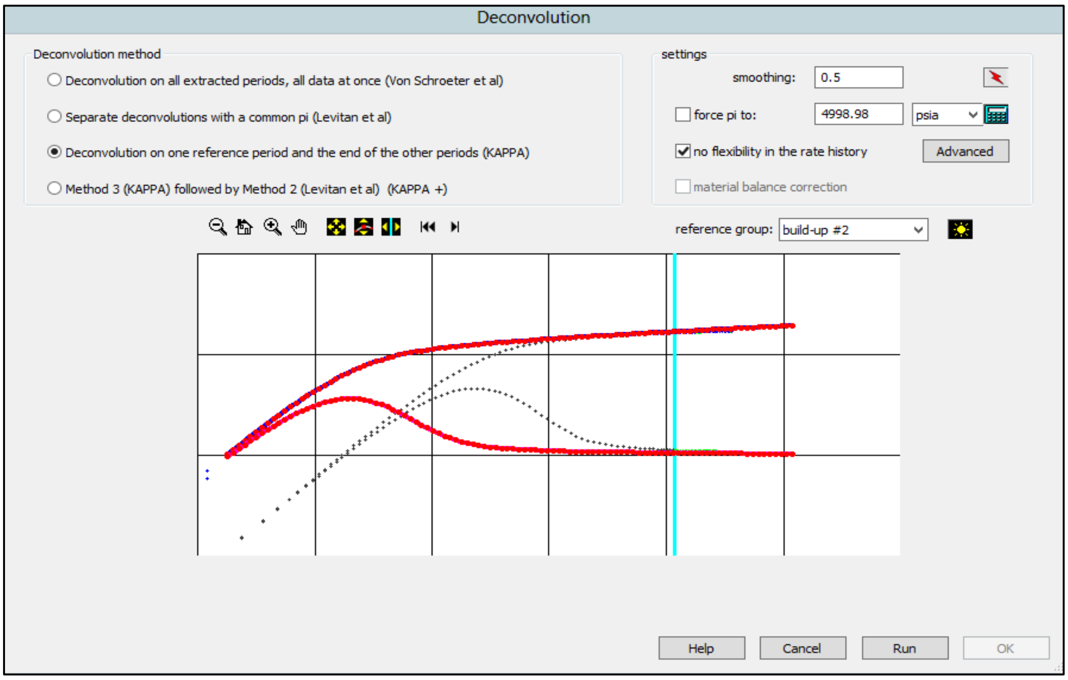

Figure 59: Deconvolution option on Saphir showing the usage of the third deconvolution choice and the light blue line to locate the end of the both build-up periods, where the properties are the same

After doing the deconvolution, we obtained a good pressure match, as well as a longer deconvolved response equal to the entire duration of the test, which is 120 hours in this case (Figure 60 and 61). However, if we zoom in, we might realize some small pressure mismatches along the curve, but may be considered acceptable by some interpreters. This is due to the change in properties over time.

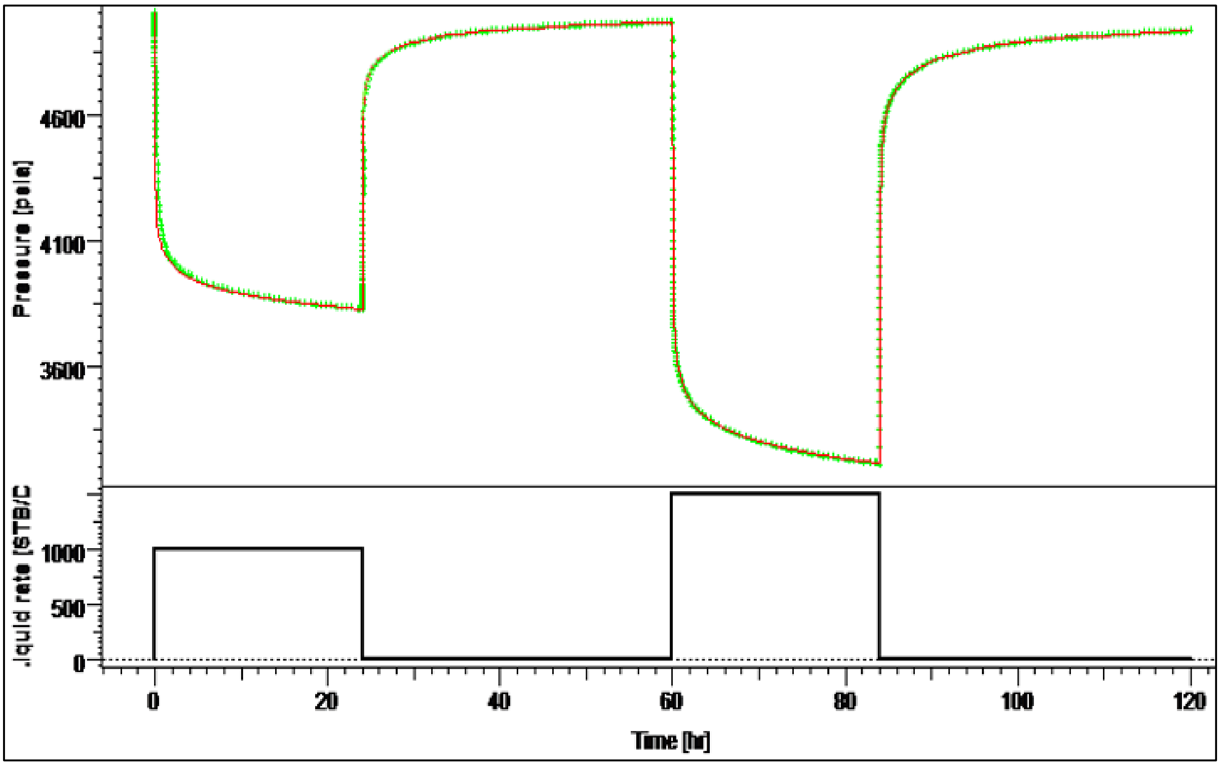

Figure 60: Pressure versus time plot showing match after using third deconvolution option

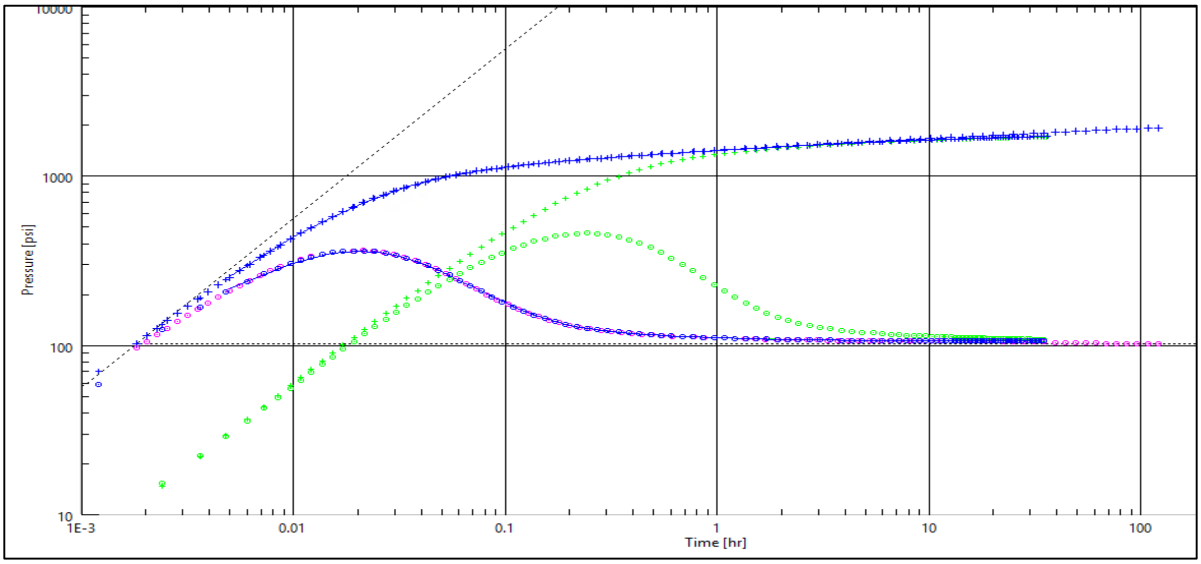

Figure 61: Log-log plot showing the normal and pressure derivatives and the deconvolved response (pink color) for the build up periods

We must consider using the deconvolution method when we have significant changes with time of wellbore and reservoir properties, since sometimes we won't obtain good results. So, if we decide to use it, it should be used with caution. It is preferable not to have significant changes between flow periods in order to obtain better deconvolution results.

8. Changing Skin between 2 flow periods

Damage can occur from one flow period to the other, leading to a change in the skin. Similar to what we previously demonstrated and analyzed about the changing of wellbore storage, a changing skin case will be studied, taking also the model as a changing well model.

Input:
Flow Period 1= 24 hours, with 1000 BOPD and skin=0
Shut-in Period 1= 36 hours
Flow period 2: 24 hours, with 1500 BOPD and skin=3
Shut-in Period 2= 36 hours

Extraction of curves is performed on the build-up periods, and the results of the log-log plot and the pressure versus time curves are shown in Figures 62 and 63 respectively. The orange curve represents the second flow period with higher skin, and is taken as reference in this case, while the green curve represents the first flow period with skin=0.

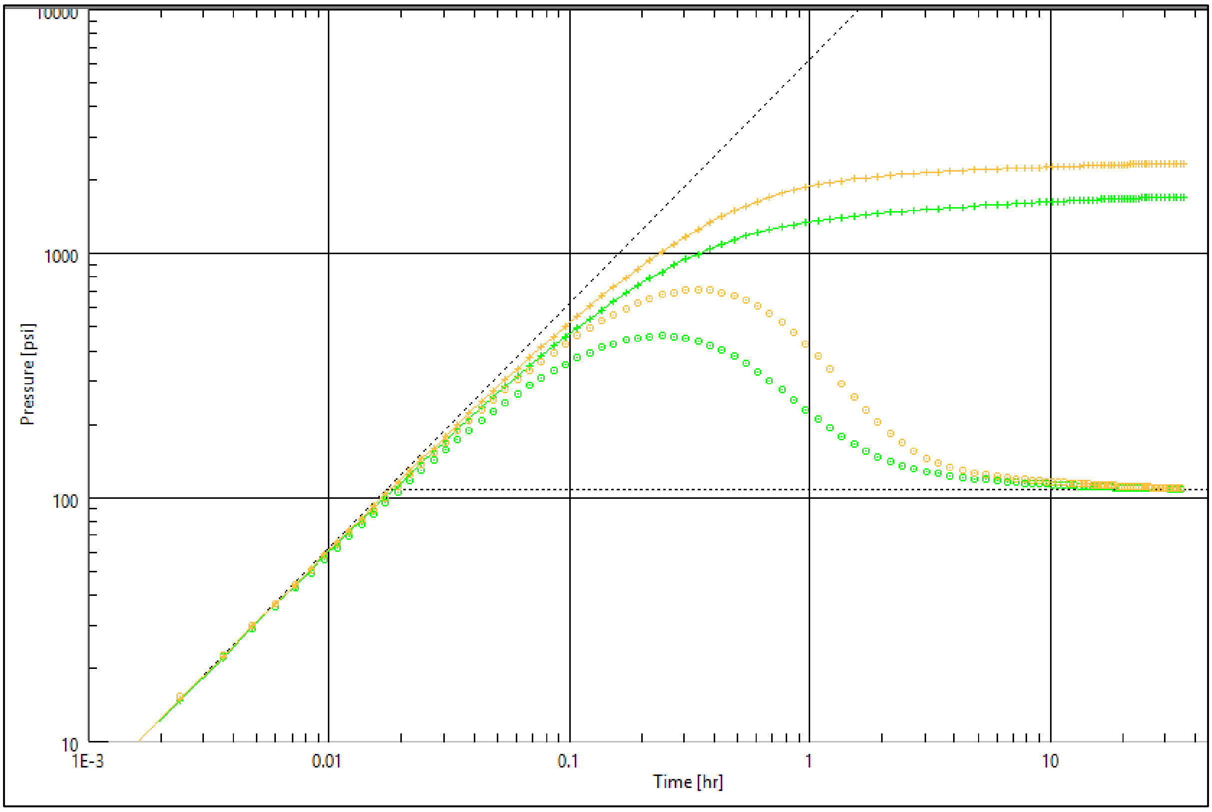

Figure 62: Log-log plot showing two different build-up periods with changing skin between them

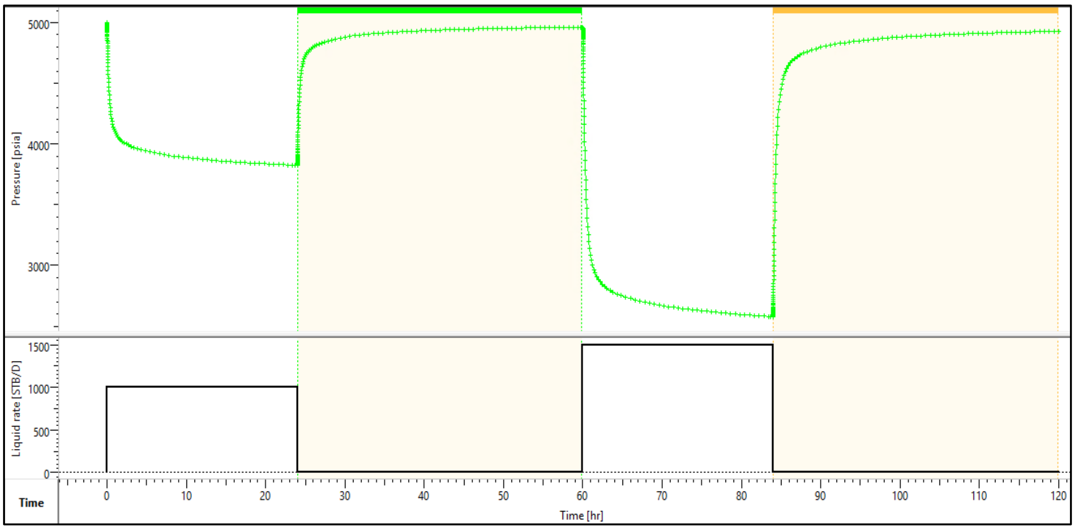

Figure 63: History plot showing pressure change corresponding to different rates for 2 flow periods with changing skin

At first, the "Deconvolution on all extracted periods, all data at once" option was used. Figure 64 shows the deconvolved response on a log-log plot for this case, where the response is going downwards, and the IARF is unclear. Figure 65 demonstrates the results where a mismatch existed along the whole build-up curves, as well as the drawdown curves, which leads to the conclusion that the deconvolution isn't good. This is due to the changing properties, which cannot be merged together and used once at the same time, by selecting the first deconvolution option.

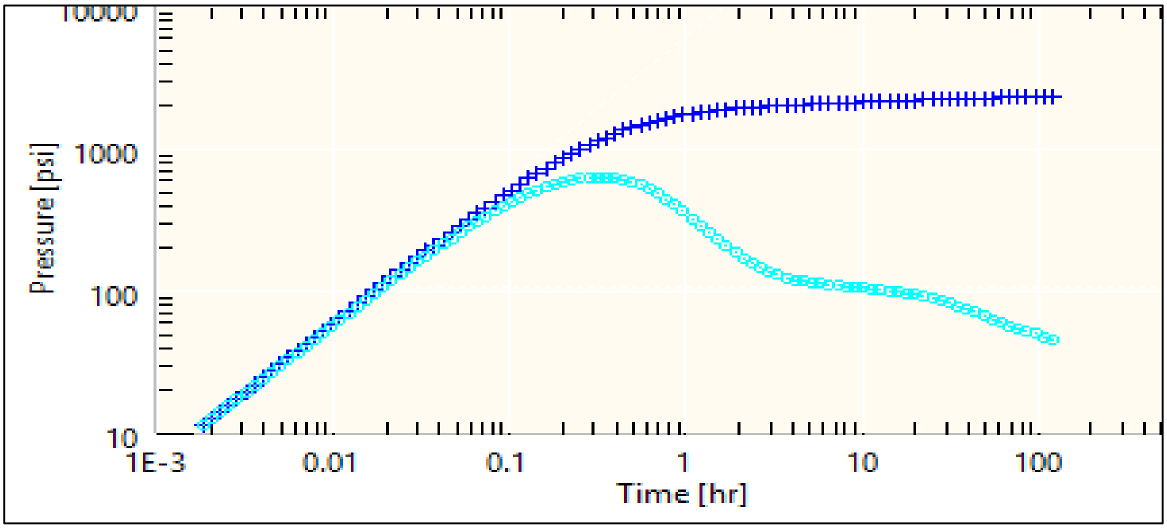

Figure 64: Deconvolved response on a log-log plot of the changing skin case, where deconvolution on all extracted periods was done

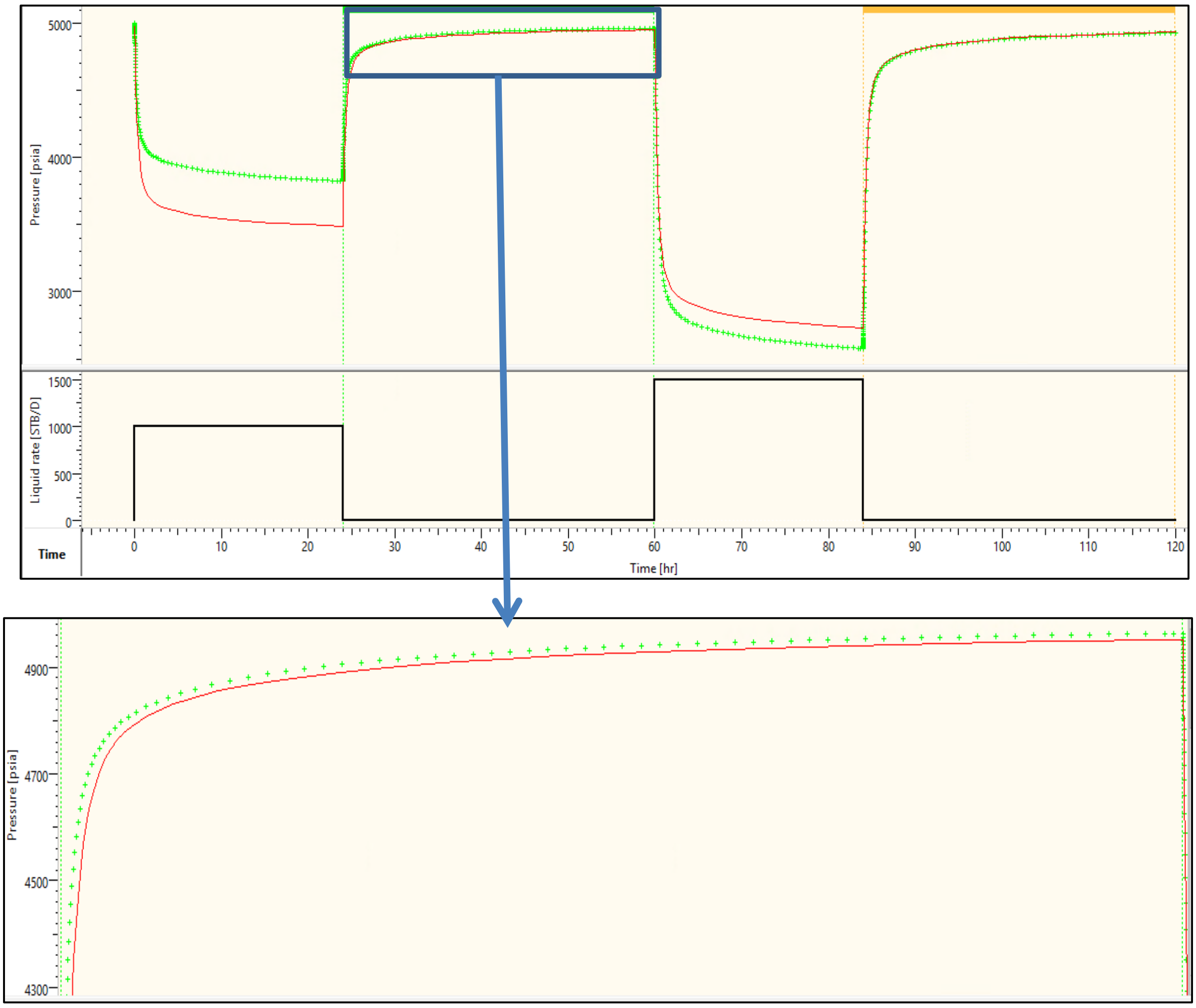

Figure 65: History plot of Pressure versus time showing the mismatch (in a zoomed way) between deconvolved response and actual pressure data for the change in skin case when deconvolution on all exctracted periods was used

In order to obtain a better deconvolution, the third option, similar to what we did in the changing wellbore storage case, should be chosen, which is "deconvolution on one reference period, and at the end of other periods", with the second build-up period being the reference. Surely, the deconvolution is applied on the build-up periods because they are clearer. The line is placed at the end of both build-up periods, and we run the deconvolution which will give a response equal to 120 hours (Figure 67). Figure 66 shows the deconvolution results, with a better match between the deconvolved response and the 2 build-up periods than the case before; however, we still can notice a small mismatch at the beginning of the first build-up period. Moreover, there wasn't a good match between the deconvolved response and the first flow period (drawdown), which symbolizes the change in skin between both flow periods. As a conclusion, using the third option of deconvolution which includes having one reference period and includes the end of other periods, is better for cases with changing properties; however, sometimes deconvolution won't give a perfect match, so it is better to reconsider using deconvolution when having significant changes pf properties with time.

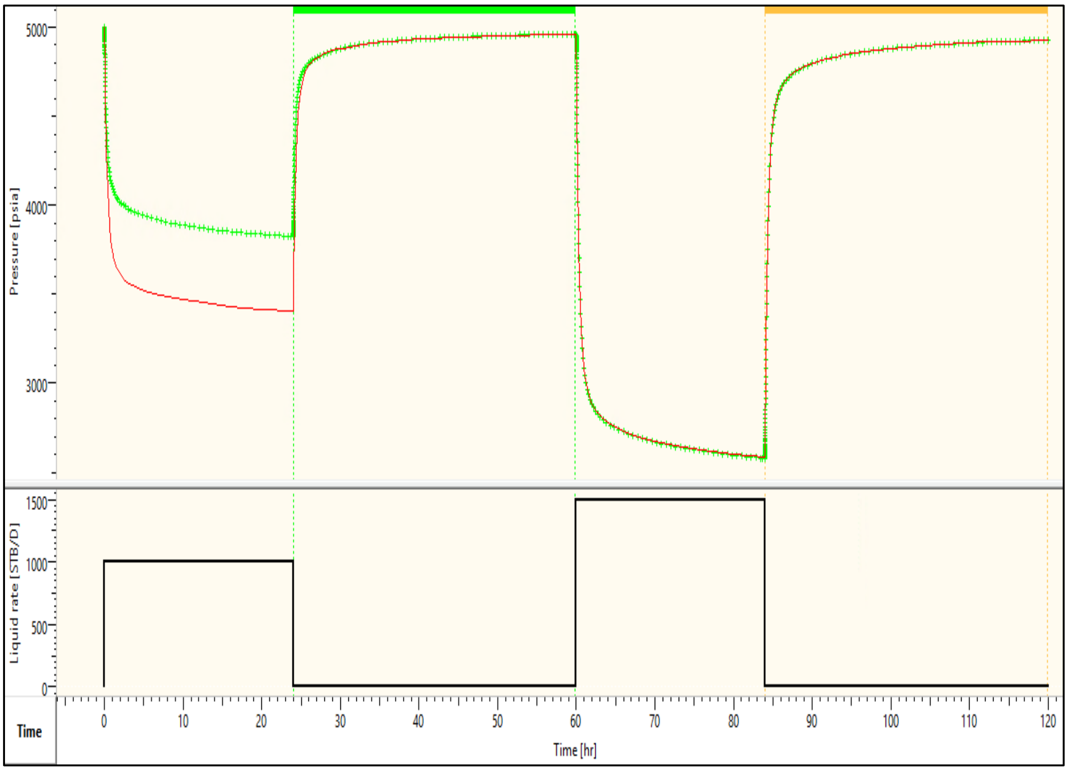

Figure 66: History plot showing deconvolution results and match on the drawdown and build-up periods corresponding to different rates

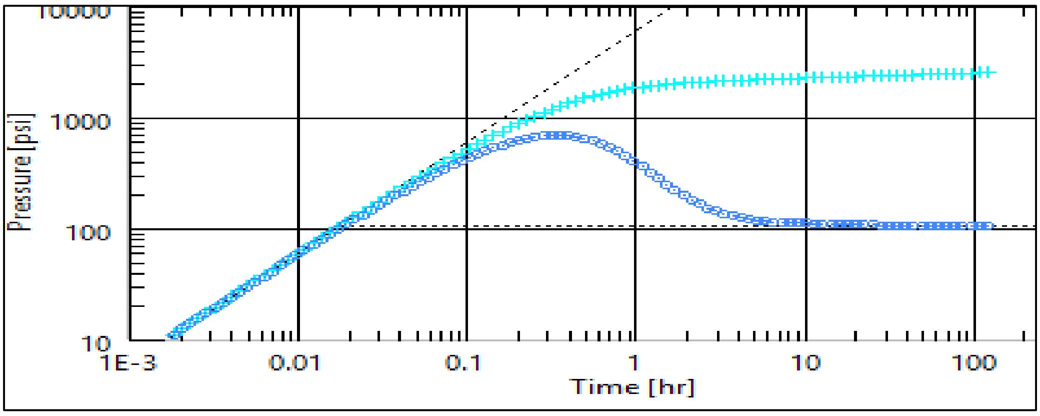

Figure 67: Deconvolution on a log-log plot where the response is equal to the whole duration of the test

9. Interference

An interference test includes more than one well, in which at least one well is producing and other wells are considered as observational wells. Surely, more than one producing well can be active in our test. This test determines whether pressure communication exist between two wells, where different properties like the average permeability, k, and Storativity, can be estimated, as well as anisotropy[19]. The term mobility thickness in this case, is defined by kh/μ, while the term Storativity is defined by ΦC_t. We know that during a well test, the pressure response of a reservoir to production (or injection) is monitored. The diffusivity equation describes how this pressure is propagating inside the reservoir, and the diffusivity constant is equal to the ratio between mobility thickness and Storativity.

When we have two wells, one active and one observational, the pressure signal will take time to propagate and reach the observational well, so the pressure change measured of the observational well won't appear directly. Instead, it will stay constant at first, or will have a plateau shape, and after a certain time delay, the pressure will start decreasing. The time delay depends on the diffusivity term, while the magnitude depends on the mobility term. As the active well is shut in, the pressure change over time for the observational well won't directly show as well; it will continue falling for a certain time before increasing again. This phenomenon is observed through Figure 68.

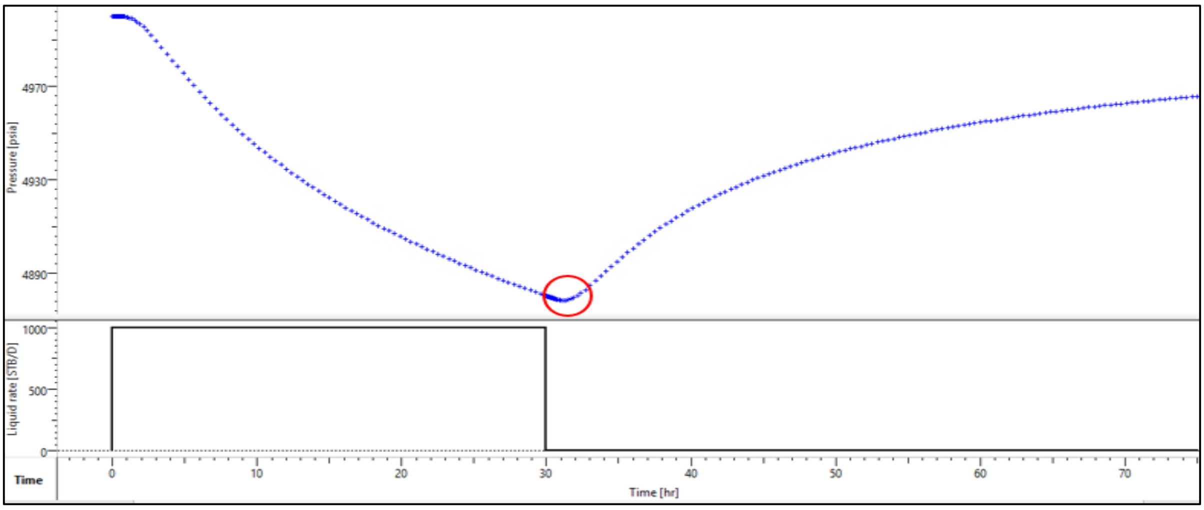

Figure 68: Pressure change with respect to time of the observational well with a time delay due to interference from an active well

A very important term that needs to be understood when interference or multi-well cases exist, is reciprocity. Reciprocity means that when we have two wells in the same reservoir, the effect of each well on the other is the same. To elaborate more, the effect of well 1 on 2 is the same as the effect of well 2 on 1. Let's say we have a close rectangular reservoir, with many faults intersecting each other, and the wells are located far from each other, separated by some of the faults; what will be observed at well 1 from the effect of well 2, will be similar to what is observed on the opposite due to reciprocity. As a result, reciprocity reduces the number of pressure signals needed to study the wells and the reservoir. If 3 wells are present in the same reservoir, then 6 total signals will be needed for well testing instead of 9 signals if the term reciprocity didn't exist.

A certain test will be taken; in which interference is included, and it is given that:

<u>Active well 1:</u>

Drawdown period= 30 hours with 1000 BOPD

Buildup period= 45 hours

<u>Active Well 2:</u>

Drawdown period= 30 hours with 1000 BOPD

Build-up period= 45 hours

Location: 700 ft north of Active well 1

In this case, we added the active well 2 to the test, as shown in Figure 69. The history plot and log-log plot were then extracted for the build-up phase for well 1, and the results were shown in figures 70 and 71. In Figure 71, we detect an increase in pressure after the infinite acting radial flow case, as if the propagated pressure has encountered a sealing fault. But in fact, in our case, no boundaries exist; what happened is that the 2 active wells are producing at the same time, so when the pressure propagation of both reach each other, they will act as a no flow boundary to one another, and that's why the pressure derivative will increase. For a random interpreter that doesn't have any idea about the reservoir, he/she can think of two possible interpretations; the first being the interference between the two wells, and the second being the existence of a fault.

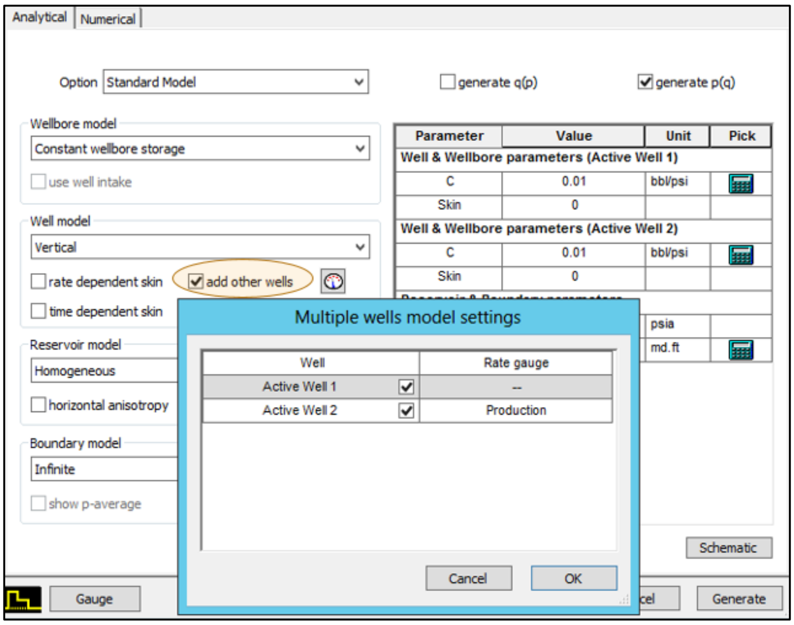

Figure 69: Test design on Saphir showing the addition of the other well

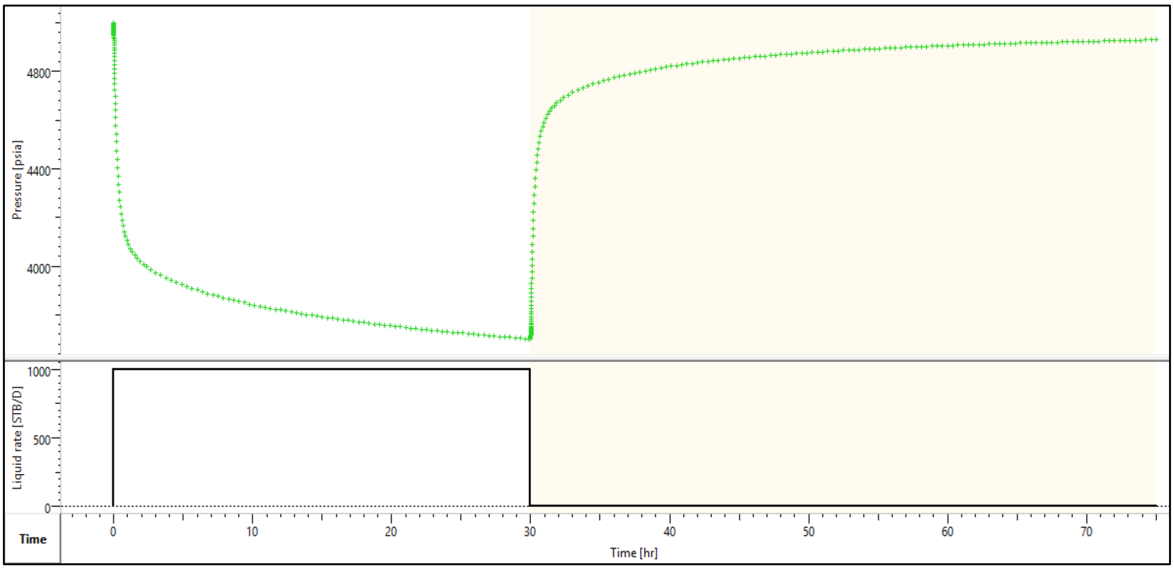

Figure 70: Pressure versus time plot extracted for the build-up phase of well 1

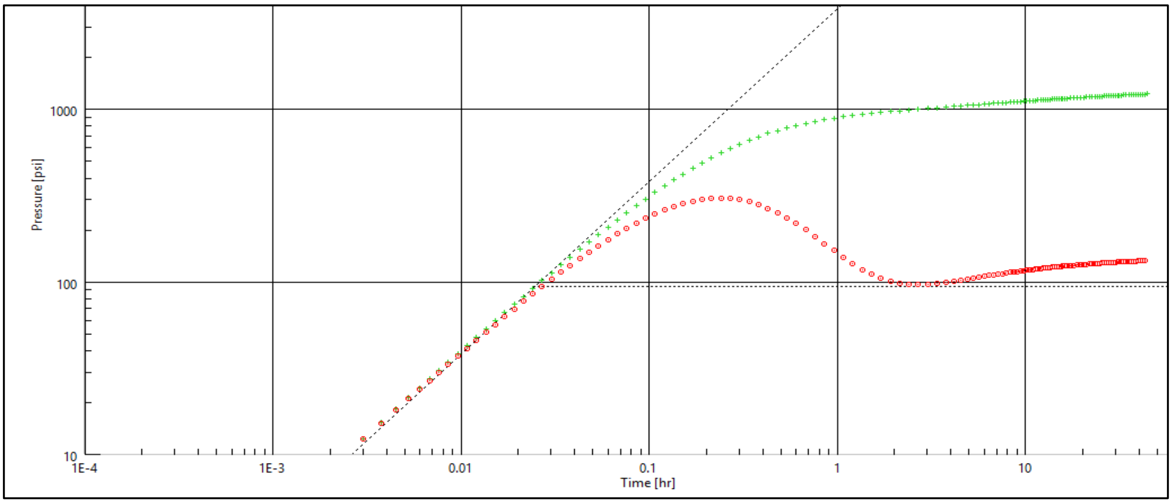

Figure 71: Log-log plot showing the normal pressure change and its derivative for the build-up phase of well 1, being interfered by active well 2

After performing deconvolution for the extracted pressure build-up phase (using the first option of deconvolution), the results obtained show the same observation as before, but of course with a duration equal to the entire test (75 hours). We can see that the pressure change is increasing after the IARF, indicating that either we have a sealing boundary or it is due to interference (Figure 72). As a matter of fact, this case is showing the inconsistencies of deconvolution in case of interference, for a certain test sequence, where we can have two interpretations. Uncertainties should be reduced in order to minimize non-uniqueness and inconsistencies.

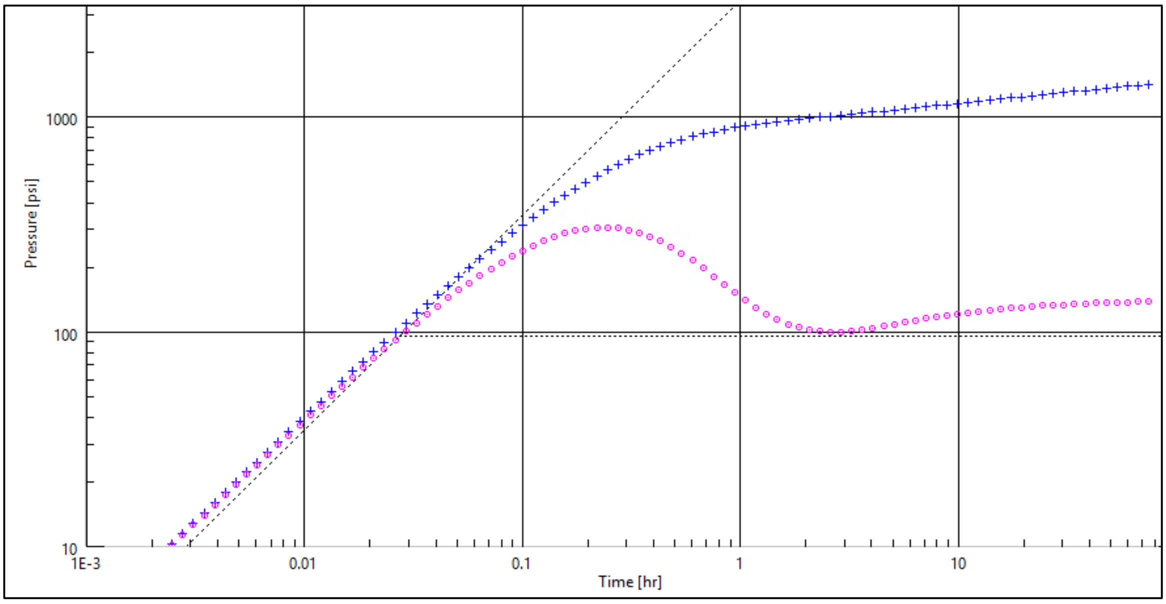

Figure 72: Log-log plot showing the results of deconvolution on he build-up phase of well 1

The above case is an ideal case that is difficult to occur in real life. In real life, we would have an idea about the reservoir we are testing or producing from, thus, we would know if there is another well producing and would know that interference is taking place.

A second case was taken which also includes interference, where the test sequence of Active well 1 was changed, while the sequence of Active well 2 remained the same.

<u>For active well 1:</u>

Delay time: 25 hours of no production

Drawdown:25 hours with 1000 BOPD

Build-up: 25 hours

The new log-log plot is extracted, and deconvolution was performed. The results are shown through Figure 73.

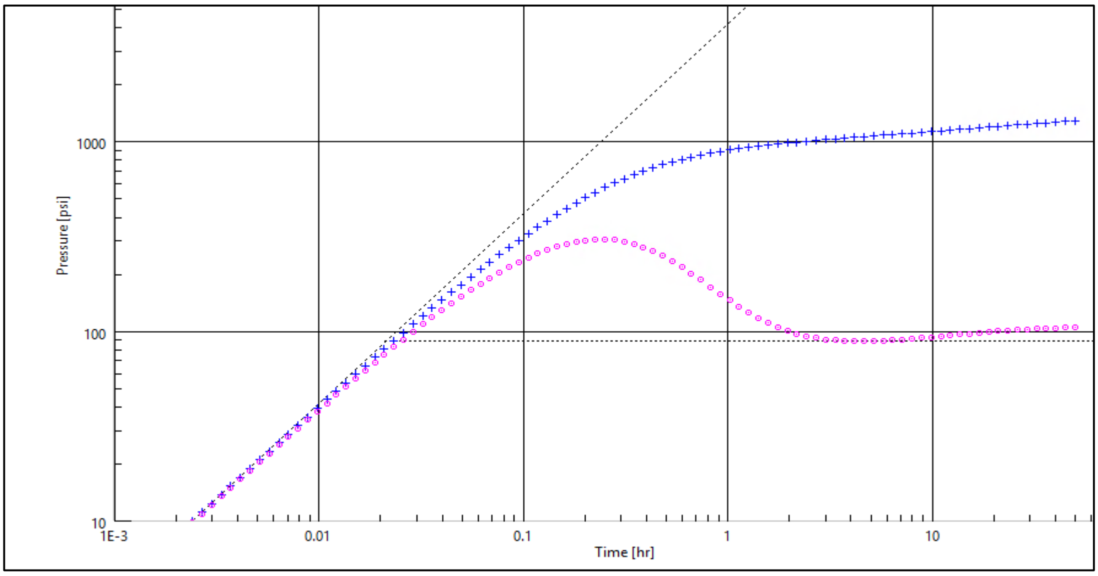

Figure 73: Log-log plot extracted for the build-up phase of well 1 after the change in the test sequence, showing the results of deconvolution

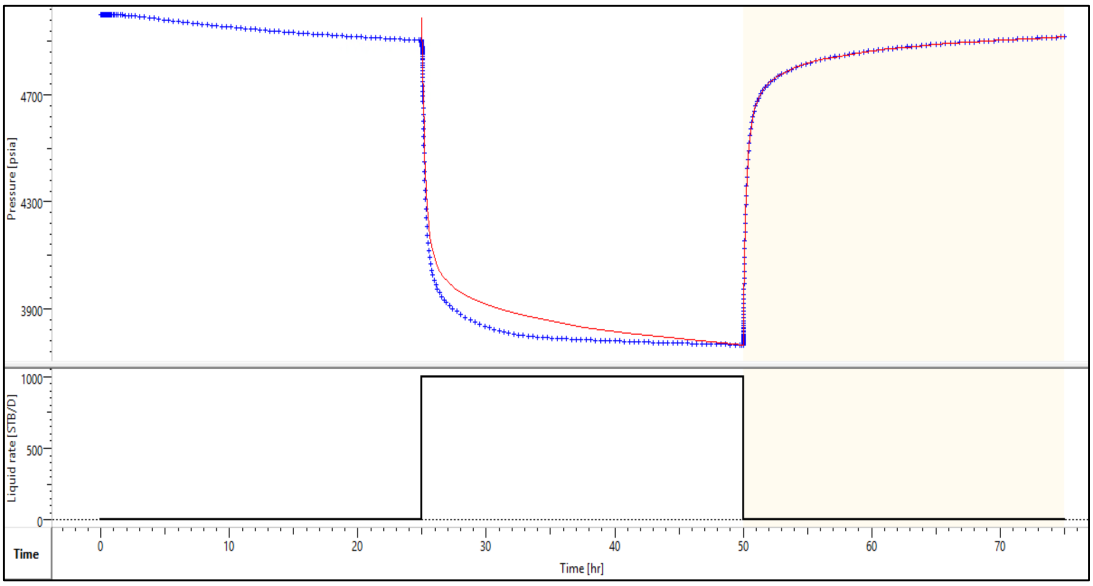

Figure 74: Pressure change versus time for well 1 after the change in test sequence of well 1, corresponding to a specific rate sequence for duration equal to 75 hours

In Figure 74, we realize a drop in pressure till 4900 psi during the first 25 hours, even if the well is not producing. This is due to the effect of the other well (active well 2) which is producing 700 feet north of Well 1. What happened is that the pressure propagation due to well 2 reached Well 1, which is acting as an observational well in this case. After 25 hours, Well 1 was set to produce for a flow period of 25 hours for 1000 BOPD, and Pwf started decreasing. Later, well 1 was again shut-in for 25 hours. The deconvolution was done on the pressure build-up phase, where it showed a match between the build-up pressure response and the actual real data of the test, but a mismatch in the drawdown phase. This is due to the fact that the deconvolution was made, taking into consideration the original initial pressure which was equal to 5000 psi at the beginning, and not taking into account that the pressure decreased inside the reservoir in the first 25 hours due to the production of Well 2 (note that initial pressure wasn't forced, but was given as an output). That's why we notice that the initial point of the deconvolved response is higher than the actual pressure data at t=25 hours (beginning of the production). On the log-log plot, the deconvolved response shows the infinite acting radial flow, with a slight increase in pressure during late times, due to the interference of the other well. It can be seen that the deconvolution still provides inconsistencies, if the deconvolved response on the log-log plot is given alone as data for interpretation. Figure 75 shows a comparison between the first original case (blue dotted line), and the second case when the test sequence of well 1 was changed (green dotted line). In both cases, the deconvolution had 2 possible interpretation, if the log-log plot was the only data that we have. As a conclusion, deconvolution usage should be re-considered in case we have interference since we might have inconsistencies, and in case of usage, it should be used with caution.

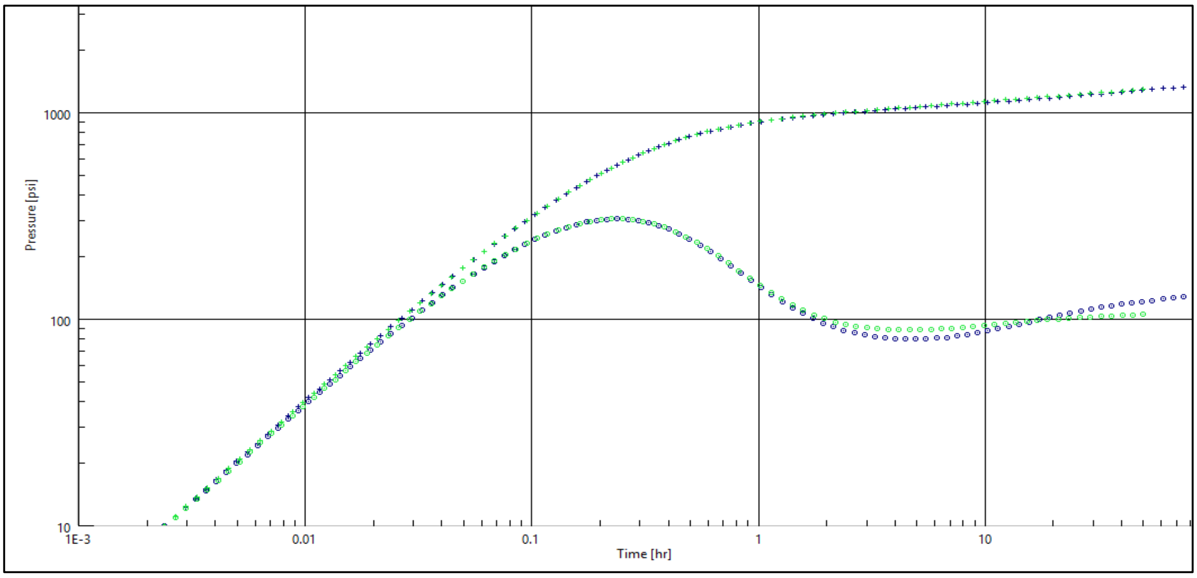

Figure 75: Log-log plot showing the comparison between both test sequences

Conclusion

This paper has presented a brief introduction to well testing, which will enable readers that have little knowledge about Petroleum Engineering to possess a quick overview of this sector, and will allow them to understand different terms and concepts elaborated in the body of the paper. Moreover, it introduced a new method that has been recently gaining popularity, and which is considered an addition to the conventional well testing analysis rather than a replacement or a substitution, which is called Deconvolution. It is starting to be used routinely nowadays. The main benefits of deconvolution were presented, in addition to its many limitations. It requires knowledge and intuition from the user, and should be used with caution. Each user aquires his own interpretation of results, depending on how much he/she trusts his/her data. Deconvolution transforms variable rate and pressure data into initial constant rate pressure response equal to the duration of the whole test. It therefore allows one to develop additional insights and extra information into pressure transient transient behavior.

Several cases were developped in this paper, where the main problems and limitations were demonstrated, and reccomendations were listed. In all of these cases, deconvolution was mainly performed on the build-up phases, since the build-up is usually clearer than the drawdown period, and is free of distorions. The credibility of the deconvolution had to be confirmed in each case, by verifying that the pressure history calculated from the deconvolved derivative can closely match the actual pressure data measurments. The main concentration was on the build-up phases and therefor we imagined as if the drawdown period doesnt exist, despit the fact that we know the drawdown period since all of the cases were test designs. It was realized that in most of the cases, the deconvolution was non-unique, where different ranges of initial pressures can signify a correct deconvolution which were presented by trumpet shaped figures. The aim is to reduce this non-uniqueness and the uncertainty, in order to reach an optimal and better result. It was realized that the choosing of the test sequence is one of the most important factors that need to taken into considertion and chosen correctly. Choosing an inaccurate test sequence may lead to non-uniqueness, and sometimes having a gap in the pressure derivative. It may also lead to confusion and inconsistencies in case of interference. It is advisable for the build up phase to be 1.5 times the drawdown phase. Other than that, it is preferable to have non-changing properties between flow periods inside a test, especially changing wellbore storage and skin, in order to have better deconvolution results. Also, while using harmonic sequences, deconvolution should be used carefully since these cases lead to many uncertainties. As a conclusion, there is no guarantee that deconvolution will provide us with a meaningful result, but once it works, it will surely gift us with extra benefits concerning reservoir properties.

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