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New technique revives direct deconvolution methods for Wellbore storage removal in pressure transient analysis [☆]

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ABSTRACT

Eliminating wellbore storage (WBS) effects inherent in pressure transient data is one of the challenges in well test analysis. The available WBS-removal techniques are either direct or time-consuming approaches. The direct methods are mostly unstable and require accurate data with almost no noise. However, well test data often have noise in both rate and pressure measurements.

This work discusses the development of a stable technique to overcome the shortcomings in the available WBS-removal methods. The technique presented here takes advantage of the recently developed stable deconvolution algorithms (e.g. von Schroeter algorithm) to achieve a stable WBS-removal process. The developed approach provides longer WBS-free reservoir response signal (extended over the entire test duration) than the previous methods. In addition, the approach introduced here can remove WBS-effects in noisy data and does not require sandface rate measurements.

Different simulated and field examples were used to validate the proposed approach. The examples included data with different levels of rate and pressure measurement errors and covered wide variety of well/reservoir models. The available approaches were implemented to the same examples. A comparison of the results shows the superiority of the approach presented in this paper.

1. Introduction

Wellbore storage phenomenon usually distorts the early period of pressure transient data. However, only the pressures collected during a constant sandface rate are helpful for analysis. There are many cases where WBS-effects obscure a part or the entire features of the reservoir pressure signal. These situations necessitate revealing the WBS-free pressure signal for complete evaluation of reservoir parameters. These cases include data sets where boundary effects appear before the WBS-effects end, heterogeneity features hidden in the WBS period, and cases where all pressure signal affected by WBS.

Removing WBS-effects is one of the challenging issues in well test analysis. This process can be performed by deconvolution. Deconvolution is a mathematical technique that aims to eliminate the effects of rate variation from the acquired well test pressure signal. In other words, deconvolution converts the multi-rate pressure response into a constant-rate pressure profile. Deconvolution is accomplished by solving the convolution integral [1] for the reservoir response function g(t):

$$\Delta p(t) = p_o - p(t) = \int_0^T q(\tau) g(t-\tau) d\tau \quad (1)$$

Many deconvolution methods have been presented to recover the WBS-free pressure profile since the 1950s. These direct techniques are in limited use in practice because they are unstable and require accurate well test data [2]. The objective of this work is to develop a technique to overcome the shortcomings of WBS removal methods and revives the use of direct methods in real life applications.

2. Previous work

Over the last six decades, many techniques for eliminating WBS-effects from well test data have been introduced in the literature. Russell technique [3] uses a trial-and-error procedure and ploting to correct the pressure signal of build-up test data. One of the limitations of the method is that it assumes prior knowledge of reservoir model.

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Nomenclature

B_o	Oil formation volume factor, bbl. /STB
$C(z)$	Design matrix of pressure match
D	Matrix in curvature measure
$g\ (t)$	Derivative of constant rate pressure drop function, psi/hr
K	Constant vector in curvature term
m_{wbs}	Wellbore storage slope, psi/hr.
m	Number of pressure points
$N_{p,wbs}$	Cumulative production, bbl
N	Number of flow periods
p_0	Initial pressure in deconvolution objective function, psi
p	Measured pressure, psi
q_{wbs}	WBS rate function, bbl/day
q	Flow rate, STB/D
Y_m	Vector with each component equal to 1
y	Estimated flow rate, STB/D
Z	response function
Δp_s	Rate-normalized pressure drop function, psi
Δt_{mb}	Material balance time, hr.
Δp_{wf}	Pressure drop, psi
υ	Flow rate weight parameter in deconvolution objective function
λ	Smoothing parameter in deconvolution objective function

Rate normalization technique [4] corrects the WBS-distorted pressure signal of build-up test data by dividing the pressure change after shut-in by the instantaneous downhole rate change. The rate-normalized pressures are plotted versus the logarithm of shut-in time for the analysis. This method resulted in shifted semi-log straight line and requires downhole rate measurements. Material balance (MB) deconvolution [5] was developed to overcome the problem of shifted straight line of the rate normalization method on semi-log plots. MB method requires an additional step for time correction (material balance time) in addition to the rate-normalized pressure correction. van Everdingen and Hurst model [1] was then involved in calculations to exclude the downhole rate measurements [2].

Beta deconvolution [6,7] was derived based on a profile that expresses the sandface rate as an exponential function [8,9]. This model is a function of a parameter "Beta" which is assumed constant and evaluated from downhole rate observations. Beta-deconvolution was then generalized such that the parameter "Beta" becomes time-dependent, and can be estimated from downhole pressures instead of sandface rates [2]. Explicit deconvolution [10] developed similar formulas to employ the bottomhole pressure data to remove WBS effects.

Fast-Fourier-Transform-based deconvolution [11] is a direct method that can account for variable WBS-coefficient in the general case. This method accomplishes the task of deconvolution in frequency domain and uses effective denoising technique to remove measurements errors to overcome the stability problem. This method requires downhole rates during after-flow/unloading period. In case of unavailable downhole rates, blind deconvolution can be implemented using downhole pressures only.

Bahabanian et al. [2] discussed Russell technique and investigated the methods of rate normalization, material balance and Beta-deconvolution including improvements they introduced. They reported that Russel's formula had limited accuracy and was not recommended for practical use. They stated that material balance deconvolution was probably the most accurate method. Many authors dedicated their efforts to assess the applicability of these methods [10,12–14]. They concluded that the performance of different techniques depends on the quality of the pressure transient data.

All the above techniques process separate buildup and drawdown periods of the WBS-distorted data. In addition, these methods are direct techniques that require accurate well test data. Many of the above techniques provide excellent results with simulated data but fail entirely when they are used to treat real pressure data. This has been our observation and the observation by others [2].

Al-Rbeawi [15] presented different techniques that are able to restore data distorted by WBS effects. The techniques are applicable to horizontal and hydraulically-fractured wells. Analytical models were developed to describe the early time pressure data. The researcher provided two complete sets of type curves for horizontal and hydraulically-fractured wells. In addition, a comprehensive study on WBS effects on different flow regimes was presented.

Two-step deconvolution method [16] removes WBS-effects in two stable deconvolution steps, providing longer WBS-free pressure signal than the direct techniques. The method uses the output of the first deconvolution in van Everdingen and Hurst model [1] to estimate the sandface rate. The calculated continuous sandface rate is then approximated with a stepwise function to be input (along with the deconvolved pressure signal) to the second deconvolution step. The main drawback of this technique is that it requires relatively long processing time as stated by the authors.

This paper discusses the application of a new technique that performs stable WBS-removal calculations in shorter CPU time. The technique can lead to a WBS-free reservoir signal that is extended over both the drawdown and buildup periods, and can work with data suffering from the noise usually seen in real life pressure measurements.

3. Developed method

The method developed in this work combines the stable deconvolution (e.g. von Schroeter algorithm) and the direct WBS-removal deconvolution techniques (e.g. material balance deconvolution). The approach developed benefits from combining the robust deconvolution techniques to generate a long pressure signal of low error-level to perform stable WBS-removal process. The approach unveils more characteristics features than the conventional approaches as it utilizes all the test data (both drawdown and buildup).

von Schroeter algorithm is probably the first robust deconvolution approach appearing in the petroleum literature. The algorithm accounts for errors in both the pressure and rate measurements and imposes smoothness penalty on the solution (well test derivative). In addition, implicit inequality constrains are utilized by encoding the algorithm in terms of the logarithm of the pressure derivative function to restrict the solution space (i.e. to guarantee positive values for the deconvolved derivative). The technique is a time domain approach and is based on formulating a separable nonlinear total least squares objective function that can be optimized by the variable projection algorithm [17,18].

The following steps show how the approach is used to process noisy data to obtain WBS-undistorted reservoir signal:

1. Use a stable deconvolution technique to convert the multi-rate pressure signal into a constant-rate reservoir pressure signal (drawdown signal). This resulting pressure signal is still WBS-distorted. However, the data will be smoothed as stable deconvolution techniques are capable of removing the noise in the pressure data. The objective function as given by von Schroeter el al. (2004) [19]:

$$\mathrm{Error} = \|p_0 Y_m - p - C(z)y\|_2^2 + \upsilon\|y - q\|_2^2 + \lambda\|DZ - K\|_2^2 \tag{2}$$

$\|p_0 Y_m - p - C(z)y\|_2^2$ is the pressure matching term, $\|y - q\|_2^2$ is the flow rate matching term, and $\|DZ - K\|_2^2$ is the smoothness penalty term.

2. Use one of the conventional WBS-removal deconvolution techniques to restore the WBS-free pressure profile. The material balance deconvolution technique [2] removes WBS-effects in drawdown data as follows:

$$\Delta p_s = \frac{\Delta p_{wf}}{q_{wbs}} \tag{3}$$

$$\Delta t_{mb} = \frac{N_{p,wbs}}{q_{wbs}} \tag{4}$$

where,

$$q_{wbs} = 1 - \frac{1}{m_{wbs}} \frac{d}{dt}[\Delta p_{wf}] \tag{5}$$

$$N_{p,wbs} = \int_0^t q_{wbs} dt = t - \frac{1}{m_{wbs}}[\Delta p_{wf}] \tag{6}$$

Eq. (3) estimates the rate-normalized pressure data (WBS-corrected) by dividing the measured pressure change by the instantaneous sandface flow rate. Eq. (4) gives the material balance time by dividing the cumulative production by the instantaneous sandface rate. The instantaneous sandface rate and cumulative production are calculated using the measured pressure data from Eqs. (5) and (6), respectively. The material balance deconvolution method assumes that the sandface rate profile changes smoothly and monotonically. Practically, this assumption is met for constant WBS coefficient cases.

The first deconvolution (Step 1) of the above technique has the capability to handle noisy data. This first step was discussed by many authors [20–26]. In case of constant-rate tests, Step 1 is still essential to reduce/suppress errors in the pressure signal to form safe input to the WBS-removal techniques. From the first step, the slope of the Cartesian straight line of the WBS-dominated regime is estimated to be used as input to the material balance and/or rate normalization methods in the second step.

Von Schroeter algorithm assumes a linear interpolation scheme of the deconvolved well test derivate results and step-wise scheme for the flow rate measurements.

For von Schroeter algorithm, the number of time nodes chosen is 30 uniformly distributed on logarithmic scale. The weight for the smoothing term (λ) is estimated following the approach presented by von Schroeter et al. (2004). Von Schroeter recommends Eq. (7) to estimate the initial guess, then the value is subjectively changed to obtain smooth deconvolved derivative signal. The weight to the flow rate term (υ) is evaluated using Eq. (8) as given by von Schroeter et al. (2004) [19].

$$\lambda = \frac{\|\Delta p\|_2^2}{m} \tag{7}$$

$$\nu = \frac{N}{m} \frac{\|\Delta p\|_2^2}{\|q\|_2^2} \tag{8}$$

A flowchart for the approach is given in Fig. 1. A computer program was developed following this flowchart and is used in the following validation examples and field applications.

4. Applications

This section presents the implementation of the developed technique in three oil cases. The first two examples are simulated and the third is a field application. The simulated cases were introduced to show the value of the developed approach in case of processing accurate and noisy well test data. The description of the simulated cases are listed in Table 1.

Simulated Example 1: The data set were generated for a 70 hr. multi-rate test for a reservoir where almost all the data are obscured by WBS effects. The exact data of pressures and rates were used during analysis. Fig. 2 shows the test data, and Fig. 3 summarizes the results. In red circles, Fig. 3.a shows the conventional pressure change and pressure derivative (of the first flow period) where the data are completely affected by WBS. In addition, this figure gives the results (of the first flow period) obtain using the conventional material balance deconvolution in blue circles. This approach hardly revealed the horizontal line on the derivative curve, but it did not reveal the boundary effects which are beyond the domain of the analyzed flow period. The resultant pressure values in this figure (Fig. 3.a) correspond flow rate of 500 STB/D (as the first flow period pressure measurements are analyzed using these conventional implementations). Fig. 3.b shows the implementation of this paper technique. The blue line is the results of the first deconvolution (Step 1) using von Schroeter

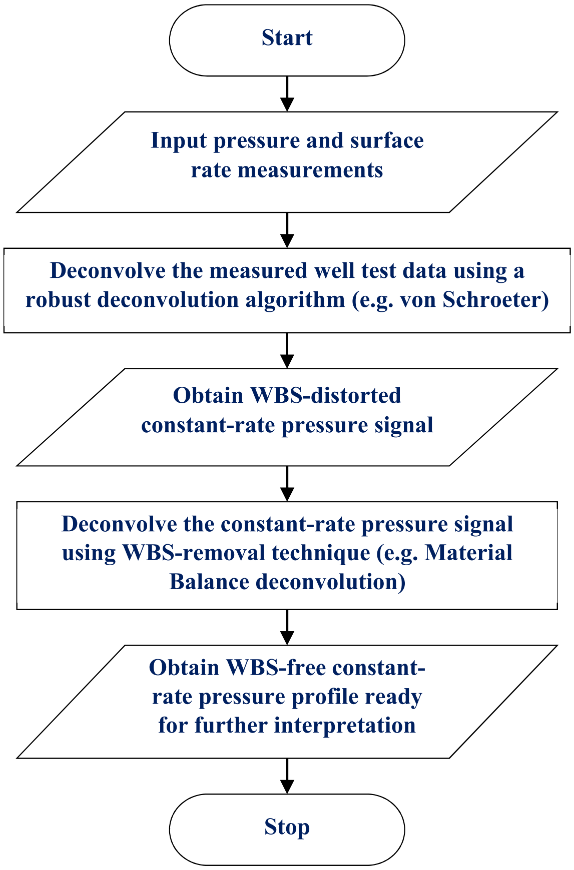

Fig. 1. Flowchart of the approach.

Table 1
Description of the simulated examples.

	Example 1	Example 2
Formation thickness, ft.	45	32
Permeability, md	20	60
Skin	−5	−6
Porosity, %	15	11
Initial pressure, psi	5000	5000
B_o, bbl/STB	1.5	1.08
Viscosity, cp	1.5	12
Wellbore radius, ft.	0.3	0.3
Total	compressibility,psi^{-1}	4.5×10^{-6}
1×10^{-6}		
WBS coefficient,bbl/psi	0.5	0.1
Reservoir	Homogeneous	Homogeneous
Boundaries	No-flow circular (re = 900 ft.)	No-flow circular (re = 1000 ft.)

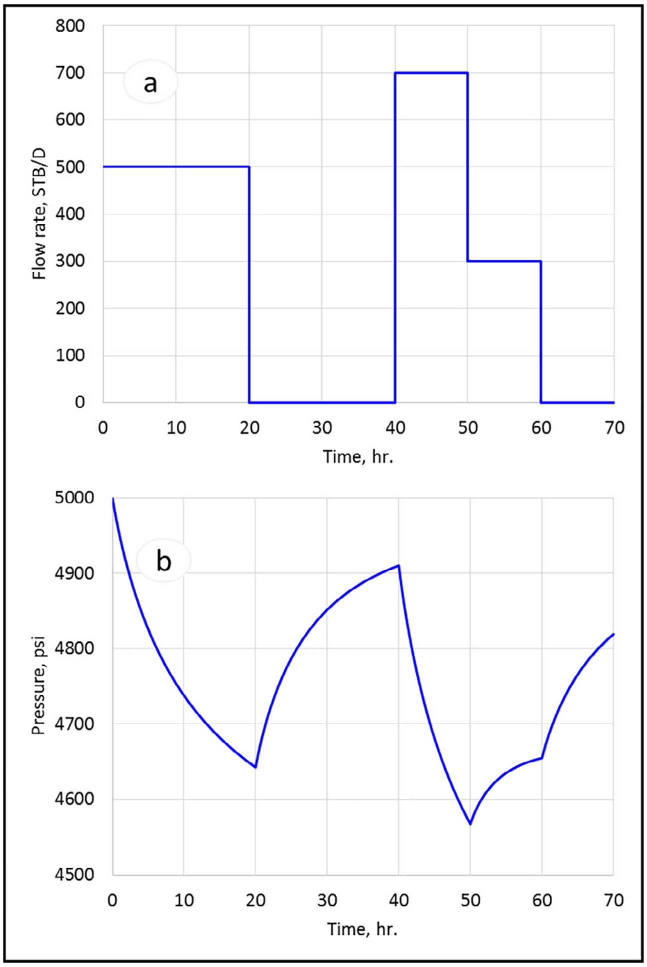

Fig. 2. Well test data - simulated example 1.

technique. In this step, the multi-rate pressure signal is converted into a constant unit rate reservoir pressure response. Although the algorithm provided long pressure signal extended over the entire test duration, the boundary characteristics cannot be revealed because the data are masked by WBS effects. The blue circles demonstrate the advantage of this paper approach where the second deconvolution applied to the first deconvolved signal, eliminating WBS effects. The resultant pressure values in Fig. 3.b are equivalent to constant flow rate of 1 STB/D. Comparing Fig. 3.a and .b, the developed approach provided 64 hrs. of the WBS-free data revealing the boundary features. Applying the conventional MB approach without treating the data with one of the stable deconvolution techniques (as was done in Step 1) provided only 16 hrs. of the undistorted data and could not detect the boundary features.

The pressure signal obtained from the developed method was analyzed, and the results were compared with the exact parameters. The interpretation results are given in Table 2. The error in permeability is 5.5%, and in the skin factor is 4%. The distance to reservoir boundary shows small error (0.5%).

Simulated Example 2: An 80-hr. multi-rate test was simulated for a reservoir of circular no-flow boundary where boundary effects appear before WBS ends. This means that the radial flow period is hidden due to WBS effects. Error level of 0.05% for pressures and of 8.5% for rates was added. Fig. 4 illustrates the test data. The conventional direct WBS-removal techniques (MB deconvolution, rate-normalization method, Beta-deconvolution, and the explicit method) were first implemented in the usual way (without Step 1 proposed in this work). However, these approaches failed and were not able to unveil the undistorted pressure profile. This failure is attributed to the noise in the test data. This work approach was then implemented to the noisy data and the results are given in Fig. 5. The first step of the approach is shown in blue line where smooth and long pressure signal is obtained. In this step, the noisy pressure and rate data are used as inputs to von Schroeter algorithm. Step 1 of the technique corrects the flow rate measurements and recovers the initial pressure. Then, Step 2 (material balance deconvolution) is applied to the constant-rate pressure response produced by von Schroeter algorithm. The results are depicted as blue circles. In this figure, the red solid line represents the WBS-free solution (after Step 2). Examining the results, one can easily observe that the approach gives good results with small discrepancies in the start of the test (before 0.06 hrs). It successfully restored more than two log cycles of the WBS-free pressure profile revealing the radial flow period that is needed for analysis. Other direct deconvolution methods (e.g. rate normalization, explicit, and Beta deconvolution) were tried in Step 2 (results not shown) and best results were obtained from material balance deconvolution. As shown in Table 2, the developed methodology gave 5.8% error in permeability, and 2.17% in skin factor. However, the distance to boundary shows zero error.

Field Application: This case was taken from the literature [27]. It is a buildup test for a stimulated well. Only the pressure data during shut-in period are available for the analysis in addition to the production history. The well test measurements are summarized in Fig. 6. The basic properties of the field case are given in Table 3.

The conventional MB technique (without using this work Step 1) was applied to the buildup data. The results are shown in Fig. 7.a where the blue circles represent the resulting WBS-free profile and the red circles show the buildup field data on the log–log plot. The resultant pressures in this figure correspond to 1500 STB/D (the effective change in flow rate from 1500 STB/D drawdown to zero rate at buildup period). As shown in Fig. 7.a, the direct deconvolution method (MB) was not successful in removing the noise in the data. In addition, the MB deconvolved signal shows downward deviation at the end of the pressure derivative, which may indicate possible boundary effects. This behavior does not match the interpretation given by the original paper [27]. The original paper concludes that the appropriate interpretation model is infinite reservoir. It is believed that this downward derivative behavior is caused by slight errors present in the field measurements (since conventional WBS-removal methods are sensitive to noise).

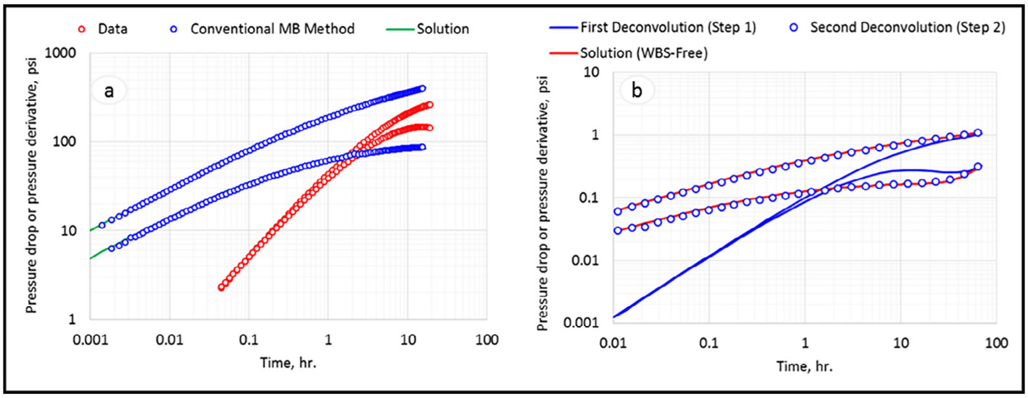

Fig. 3. Results of (a) conventional material balance (MB) method of the first flow period, and (b) developed approach - simulated example 1.

Table 2
Analysis of the simulated examples.

	Permeability, md	Skin factor, unitless	r_e, ft
Example 1	18.9 (5.5% error)	−5.2 (4% error)	895 (0.5% error)
Example 2	56.5 (5.8% error)	−6.13 (2.17% error)	1000 (no error)

Applying this work approach gives the results shown in Fig. 7.b. In this figure, the blue line shows the results after applying von Schroeter algorithm (Step 1) to field data and the blue circles represent the results of the conventional MB method (Step 2) applied on data after Step 1. The red solid line represents the WBS-free pressure profile after interpreting the data in Step 2. The pressure data in this figure are equivalent to constant unit flow rate. The data after Step 2 calculations shows that the derivative is flat, indicating infinite acting reservoir model (which matches the geological information in the original paper interpretation). The results of the original paper interpretation and this work interpretation are compared in Table 4.

As shown in Fig. 7, this paper approach results in a smooth signal (after the application of Step 1). Using conventional WBS-removal techniques (without Step 1) would have resulted in wrong reservoir model selection and wrong parameters. The approach also gives three additional log cycles of the WBS-free data. This additional data shows the clear development of the flat derivative.

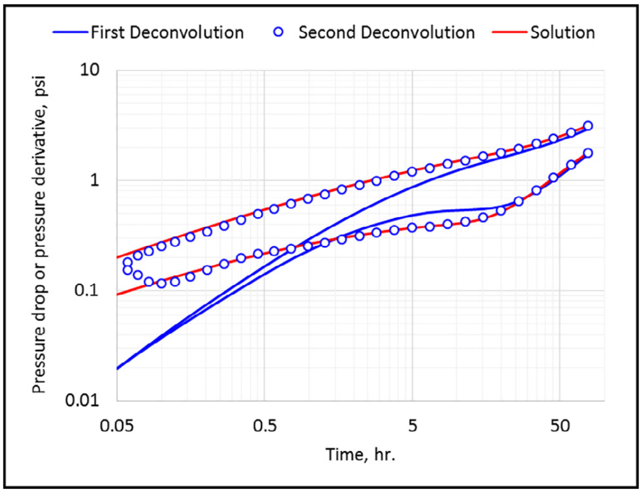

Fig. 5. Approach results - simulated example 2.

5. Discussion

The approach developed here has several advantages over the direct approaches for the removal of WBS effects. This developed technique can construct pressure signal extended over the entire test duration (both the drawdown and buildup periods) and reduce

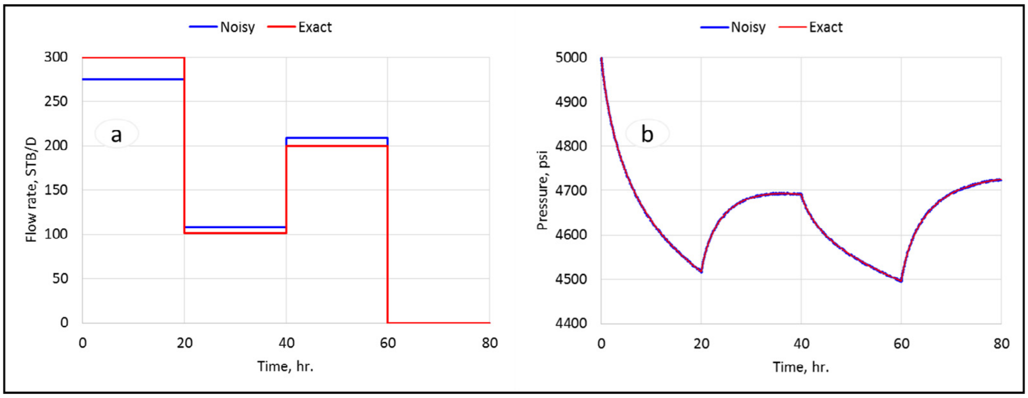

Fig. 4. Well test data - simulated example 2.

data noise. In addition, the rate measurements are corrected, the initial pressure value is recovered (if unknown), and the derivative is smoothed.

The approach presented here is a two-step approach. In the first step, any of the recent stable deconvolution algorithms [19,28,29] can be used. The second step uses any of the direct WBS-removal methods.

Depending on the choice of deconvolution methods in the two steps, the assumptions and limitations of each method will migrate to the proposed technique in this paper. The most successful examples cited here are those which employ von Schroeter algorithm for the first deconvolution step and material balance direct deconvolution for the second step. von Schroeter algorithm assumes that the measured well test data are affected by constant WBS and constant skin factor. von Schroeter algorithm may fail to process the data if variable WBS or variable skin factor is present. In addition, von Schroeter algorithm assumes that the measured flow rates follow a stepwise function. Therefore, the algorithm may experience some difficulties in processing smoothly changing flow rate profile. The material balance deconvolution method is a direct method and sensitive to errors in pressure and rate data. The results from material balance deconvolution could be with no value if there is some noise in pressure or rate data. Therefore, the successful implementation of the second deconvolution requires that von Schroeter algorithm (or any other stable algorithm used for Step 1) is successful in noise removal.

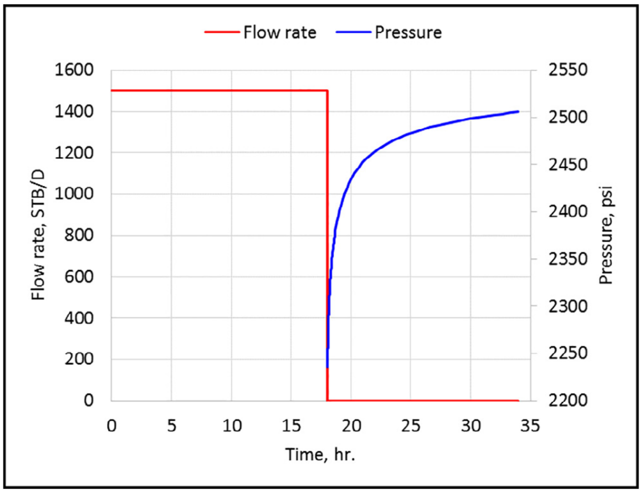

Fig. 6. Well test data – field case.

The developed two-step method assumes also that the linear diffusion equation is the governing equation for the fluid flow in the reservoir. Therefore, the method is applicable to single-phase oil/water problems. In case of nonlinearity (e.g. gas or multiphase flow cases), deconvolution requires different considerations. The linearization of such flow equations using pseudo-transform functions [30,31] may be required in case of gas or multi-phase flow.

The variable WBS or variable skin factor cases are not investigated using the method presented in this paper. Levitan (2005) [29] discussed this issue of inconsistent pressure transient data (variable WBS or skin factor). The impact of such inconsistent data sets on results from the developed technique are not considered in this study.

6. Conclusions

This work developed a technique to eliminate WBS-effects in well test data. This technique incorporates the stable deconvolu-

Table 3
Basic properties of the field example.

Thickness, ft.	Porosity, %	B_o, bbl/STB	Viscosity, cp	Total compressibility, psi^{-1}	Wellbore radius, ft
73	20	1.3	0.5	1×10^{-5}	0.401

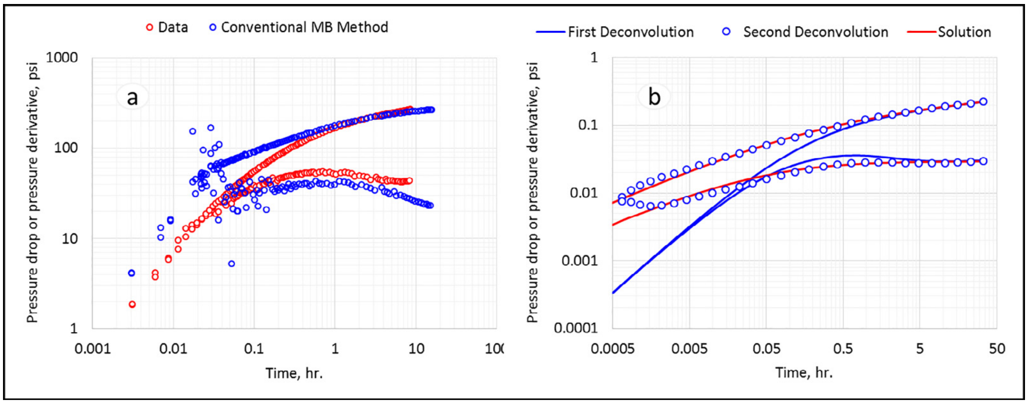

Fig. 7. Results of (a) conventional material balance (MB) method, and (b) developed approach– field case.

Table 4
Results of the field example.

	Reservoir	Boundary	Permeability, md	Skin
This work	Homogenous	Infinite	21.40	−3.60
Bourdet et al. (1983) analysis	Homogenous	Infinite	22.32	−3.50

tion algorithms and the direct WBS-removal methods. The following conclusions can be drawn:

1. The technique introduced can viably eliminate WBS-effects and reveal the undistorted pressure signal in cases where many direct deconvolution techniques fail.
2. This technique has several advantages over the previous techniques. It is a fast and stable technique and has the capacity to stretch the undistorted pressure signal over the entire test duration (drawdown and buildup periods combined) and to handle noisy data.
3. This work uses the advantage of robust deconvolution algorithms (e.g. von Schroeter technique) to minimize error-level in the pressure signal to achieve stable WBS-removal process.
4. The first step of this paper technique can be completed by any of the rigorous deconvolution algorithms (von Schroeter algorithm has been utilized here). The material balance WBS-removal method is recommended to be used in the second step of the technique.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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