Well Test Analysis of Blood Pressure

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.

September 2011
DECLARATION OF OWN WORK

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

Signature:

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Names of supervisors: Professor Alain C. Gringarten, Professor Kim H. Parker
I would like to thank Professor Alain C. Gringarten and Professor Kim H. Parker from Imperial College of London for their help and guidance throughout the project. I would also like to thank my mum and friends for inspiring and supporting me.
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Well Test Analysis of Blood Pressure

Anzhela Glebova

Imperial College supervisors: Professor Alain C. Gringarten, Professor Kim H. Parker

Abstract

The cardiovascular system carries out one of the critical roles to maintain the functionality of the organism, which is transportation of the oxygen, nutrients, waste products, hormones and heat to and from tissues of the body in general. Fatal consequences may occur due to the failure of the circulatory system. Rapid heart contraction stimulates the blood flow. The right heart collects deoxygenated blood via the inferior and the superior vena cava and pumps it out to the lungs. Newly received oxygenated blood from the lungs is then pumped back to the body through the aorta. With each heartbeat 70-80 ml of blood is ejected from ventricles and the total volume of blood in the body is 3 – 7 litres, depending on the size of the person. The blood pressure is the pressure applied to the walls of the blood vessels and it varies from its maximum (during systole) to its minimum (during diastole) values.

Well test analysis of the blood pressure is a new research area that was firstly investigated by Mukhtar Sargaskayev (2009) and Shari Channa (2010). Deconvolution and log-log analysis were applied to the clinical data, in order to obtain an interpretation model that could describe the circulatory system behaviour. A number of similarities between reservoir and cardiovascular systems were found. The main correlations are that smaller arterial branches with capillaries refer to the porous media and transient pressure with the rate data could be measured in both systems. Lastly, it was discovered that larger arteries behave like vertical wells in a homogeneous reservoir with a constant pressure boundary exhibited at late times. However, early time behaviour of the derivative curve was overestimated and did not correspond to the actual volume of blood in the body. Therefore, the objectives of this paper are to verify previous work, obtain sensible log-log analysis parameters that could describe the circulatory system behaviour and analyze data from veins that were not taken into account before.

In the present study venous data is analysed and interpretation parameters are very similar to those from aortic data. Deconvolution and log-log analysis of the unit rate pressure drawdown are applied employing several software packages in order to validate the interpretation model selected and parameters obtained. Reasonable values of the wellbore storage coefficient are obtained and its dependence on the variation of the arterial cross-sectional area is shown. Permeability that is defined by the radial flow stabilization corresponds to the typical systemic resistance value. Since the volume of blood in the body is known, it is used to validate results obtained from log-log analysis.

Introduction and background

The blood circulates around the body due to the rapid contraction of the heart that acts as a pump. The circulatory system is one of the most crucial physiological systems, which is responsible for heat control and delivery of the essential components (oxygen, hormones, nutrients and waste products) to and from tissues of the human’s and other vertebrates’ bodies. It consists of the heart and blood vessels. The cardiovascular system can be divided into two main loops: pulmonary and systemic circulations. The pulmonary circulation is the circulation of the deoxygenated blood from the heart to the lungs and then back to the heart. The systemic circulation, in turn, involves the flow of the newly received oxygenated blood back to the body and the flow of oxygen-depleted blood back to the heart.

The circulatory system is a closed system, meaning that the blood never leaves its vessels. However, comparing cardiovascular and reservoir systems, several similarities can be found. On the one hand, larger arteries and veins behave as vertical wells, while smaller arterial branches and capillaries represent the porous media. Pressure response and velocities of the fluid flow can be measured from both systems.

Well test analysis is a technique that is based on the analysis of the transient pressure response versus elapsed time. It provides information on the well and reservoir conditions, allowing us to describe the ability of the fluid to flow through the reservoir and into the well. Mukhtar Sargaskayev (2009) and Shari Channa (2010) embarked on the use and application of well test analysis to the human body. Analyzing blood pressure response, it was found that larger arteries near the heart behave as vertical wells in a homogeneous reservoir. Early time behaviours of the pressure derivative exhibit wellbore storage and skin effect, while late time behaviours indicate a constant pressure boundary. Even though some log-log analysis parameters relevant to the cardiovascular system were obtained, early time behaviours represented unrealistic values of wellbore storage coefficient that is used to calculate the volume of the blood in the body and blood vessels.

The current research involves several stages, such as verification of the previously obtained results, investigating the early time behaviour of the blood pressure derivative and obtaining sensible log-log analysis parameters that could characterise the circulatory system. In order to validate input parameters that were used previously as well as the interpretation model selected
and the log-log analysis parameters obtained, the transient blood pressure and rate data are deconvolved and interpreted using the same methodology as was employed before. Moreover, different software packages were used and additional data are analyzed so as to examine and to prove results obtained from deconvolution and log-log analysis.

**Blood pressure and cardiac cycle**

The blood pressure is the pressure applied by the circulating blood to the walls of blood vessels and it is one of the critical physiological parameters that is required to assess the condition and functionality of the body. The term ‘blood pressure’ is mainly used as arterial pressure while venous pressure refers to the pressure in the right atria. Blood pressure varies with each heart beat from its maximum at the systole to its minimum at the diastole. The cycle of atrial and ventricular contraction is called the cardiac cycle (Levick J. R., 2010). Depending on the conditions of the inlet and outlet valves, four phases of each cardiac cycle can be distinguished. However, for the current research, only two main phases, namely systole and diastole, are considered. Pressure and volume fluctuations within different phases are shown in Figure 1. The diastole refers to the ventricular filling. The ventricle fills with blood due to the fact that ventricular pressure drops and, as soon as it is below the atrial pressure, inlet valve opens and allows the blood to flow into the ventricle. The systole, on the other hand, is the contraction of the heart muscle. As a result of the pressure difference between ventricular pressure and arterial pressure, outflow valves open and ejection starts. Both systole and diastole correspond to the build-up and drawdown flow periods found in well test analysis.

**Blood distribution and blood vessels**

The total volume of blood in a human body is 6-8% of the total weight, which is 3 – 7 litres, depending on the size of the person. Blood vessels are responsible for the transportation of the blood around the body and include arteries, veins and capillaries. Depending on the size, amount and elastic properties of walls, various blood vessels contain different volumes of blood. The blood volume distribution is illustrated in Figure 2.
Systemic arteries supply body tissues with oxygenated blood. Having elastic walls they transport the blood from the heart under a relatively high pressure. The aorta is the largest artery (up to 3 cm in diameter) and arterial pressure reaches its maximum during the ventricular ejection phase (systole). Originating from the ascending portion of the aorta are the right and left coronary arteries, which supply the heart with oxygenated blood (Rogers K., 2011). More than half of the coronary arterial system is embedded within the myocardium. During the systole, when coronary blood pressure reaches its minimum, those vessels are compacted and, consequently, blood flow stops. Therefore, coronary blood flow is primarily driven by the diastolic blood pressure. Oxygen saturation of blood decreases as the blood flows from the heart to the body via capillaries and arterioles. Oxygen-depleted blood returns to the heart through venules and veins. Peripheral veins and venules are thin-walled, contractile, voluminous vessels that contain about two-thirds of the blood pool (Levick J. R., 2010). Compared to the arterial, venous pressure is relatively small and the blood flow back to the heart is controlled by valves located in veins. Venous pressure reaches its maximum in late diastole of the cardiac cycle. Figure 3 shows the heart structure and placement of blood vessels arising from the heart.

**Methodology**

**Verification of previous work**

Aortic and coronary artery pressure and rate responses were first analyzed by Mukhtar Sargaskayev (2009) and Shari Channa (2010). In order to verify previous results, the current study adopts the same fluid properties, well parameters and methodology. Aortic pressures and rates that are used differ due to the unavailability of the past data, but measured at similar aortic sites. Throughout the current section deconvolution and log-log analysis results of only one aortic data set are shown. Appendix C describes verification of the previous results with the other data sets analysed in more detail.

The verification process involves the following steps:
1. Blood velocity data is smoothed and converted into blood flow rate.
2. Aortic pressure data is modified using Eq. 1 (where \( P_i \) stands for the arbitrary value that is higher than any value of \( P_{data} \)) in order to force data to follow the pressure-rate trend found in the reservoir.

\[
P_{\text{analysis}} = P_i - P_{\text{data}}
\]  

(1)

3. All data are divided into separate cardiac cycles.
4. Rates that correspond to build-up flow periods are assumed as zero.
5. Deconvolution is performed using TLSD software. Single flow periods and series of flow periods are deconvolved. Figure 4 and Figure 5 show deconvolved derivatives obtained throughout both studies, while Figure 6 and Figure 7 illustrate the pressure history match between the original and convolved pressure data.
Figure 4: Deconvolution of various sets of flow periods. Data set Ao_PROX (adapted from Channa, S., 2010)

Figure 5: Deconvolution of various sets of flow periods. Data set Ao_PROX (current research)

Figure 6: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set Ao_PROX (adapted from Channa, S., 2010)

Figure 7: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set Ao_PROX (current research)

Log-log analysis of the unit rate pressure drawdown is done using Kappa Engineering software. Input parameters used for the analysis are summarized in Table 1, while Figure 8 and Figure 9 illustrate analysis model of the unit rate pressure drawdown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Aorta</th>
<th>Coronary Artery</th>
</tr>
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<tr>
<td>Initial pressure</td>
<td>psia</td>
<td>1.6</td>
<td>2.18</td>
</tr>
<tr>
<td>Well (=artery) diameter</td>
<td>ft</td>
<td>0.095</td>
<td>0.0066</td>
</tr>
<tr>
<td>Reservoir thickness (=artery length)</td>
<td>ft</td>
<td>1.0</td>
<td>0.33</td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
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<td>0.9</td>
</tr>
<tr>
<td>Blood viscosity</td>
<td>cP</td>
<td>1.96</td>
<td>1.96</td>
</tr>
<tr>
<td>Total compressibility</td>
<td>psi(^{-1})</td>
<td>8E-5</td>
<td>8E-5</td>
</tr>
<tr>
<td>Formation volume factor</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir (=body) temperature</td>
<td>°F</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1: Input parameters used in previous study (Channa, S., 2010)

Figure 8: Log-log deconvolution plot. Data set Ao_PROX (Channa, S., 2010)

Figure 9: Log-log deconvolution plot. Data set Ao_PROX (current research)
It is confirmed that arteries seem to act as vertical wells with wellbore storage and skin in a homogeneous reservoir with the constant pressure boundary. Even though the model appears to be reasonable, some obtained parameters are unrealistic, for example wellbore storage coefficient leads to the overestimation of the volume of blood, and requires further investigation. Therefore, in order to obtain reasonable and realistic log-log analysis parameters and obtain sensible deconvolution results, the methodology and input parameters are revised and modified.

**Data reformulation**

Present research involves the analysis of the blood pressure and velocity data from various blood vessels. By inserting a thin and flexible tube (catheter) into a blood vessel, pressure and blood velocity measurements can be performed (Cardiac Catheterization). Aortic and coronary artery pressure measurements were taken from the human patients, while venous data came from dogs. Figure 10 schematically shows various measurement points where transient blood pressure and velocity data were acquired.

![Image of blood vessels]

**Figure 10: Multiple sites of measurements used for the analysis. Mammalian body (modified from Gray, H., 1918)**

Due to limitations of the software employed, noisiness of data and diverse input parameters used in medical and petroleum engineering industries, a number of modifications are applied to the data throughout the current research. Firstly, in order to perform well test analysis, blood velocities are converted into rates using Eq. 2 (where \( Q \) stands for the liquid rate, \( U \) – blood velocity and \( d \) – blood vessel diameter ) and shifted by +10 ms to account for processing delays to the Doppler ultrasound transducer. Secondly, pressure data are smoothed using MATLAB R2010a software to reduce small scale noise.

\[
Q = \frac{U \pi d^2}{4}
\]  

**Aortic data adjustment**

During the ventricular contraction phase most of the stroke volume of blood is ejected into arteries, which leads to the increase in the aortic blood pressure. Consequently, with the increase in blood flow rate, pressure in the aorta is pushed up. By contrast, in the oil and gas industry the pressure typically declines as the oil rate goes up. For the sake of analyzability and to maintain systole-diastole pressure response, rates are altered using Eq. 3, where \( Q \) is an arbitrary value that corresponds to the maximum value of \( Q_{data} \).

\[
Q_{analysis} = Q - Q_{data}
\]  

Figure 11 and Figure 12 show the effect of the applied modification. The systole corresponds to the build-up flow period that is used in well test analysis, while diastole corresponds to the drawdown.
Coronary artery and venous data adjustment

As was stated before, coronary blood flow is primarily impelled by the diastolic pressure. Therefore, no specific data modification is required and it corresponds to the typical pressure - rate response seen in well testing. At late ventricular filling phase the atrium contracts, pushing more blood into the ventricle and ventricular filling is now controlled by the venous pressure. Atrial contraction causes slight back-flow of the blood through veins and it pushes venous pressure to its maximum. Venous pressure and rate data do not require any alteration, as well as data from the coronary artery. However, venous blood flow rate and pressure values are rather small and it is not possible to use well test analysis software. Therefore, in order to be able to employ the software to process the data, maintaining systole and diastole pressure responses, venous rates are slightly increased using Eq. 4, where Q exhibits the absolute magnitude of the minimum venous blood flow rate.

\[ Q_{\text{analysis}} = Q + Q_{\text{data}} \]  

Figure 11 and Figure 12 demonstrate model pressure and rate responses obtained from the coronary artery and veins.

Flow period adjustment

Data obtained from the aorta, coronary artery and veins are split up into a number of flow periods. Interval between two consecutive peak pressure points is assumed to be separate cardiac cycle and rates corresponding to the pressure build-up are set to zero.

In order to perform deconvolution using TLSD software, pressure and rate data require further modification due to the restricted number of input flow periods and data points allowed. On the one hand, maintaining build-up flow periods, drawdown pressure data are reduced using Kappa Engineering software. On the other hand, blood flow rates are simplified using Kappa Engineering software and several flow periods are merged together. Lastly, the beginning and the end of each flow period are synchronized with the pressure data points. Figures 15 - 20 illustrate history plots of the actual pressure data and modified rates of all data sets analysed throughout the current research.
Deconvolution

Deconvolution is a very powerful tool to process pressure and rate data in order to obtain more pressure data to interpret with conventional techniques (Gringarten, A. C., 2010). Deconvolution is performed using both Kappa Engineering (Saphir) and TLSD software. Deconvolution is applied to modified and adjusted pressure and rate data. Various data sets are deconvolved, including single flow periods, a number of flow periods and the entire pressure history. Since the regularization parameter $\lambda$ should be carefully selected to not over-smooth the data but to minimize small-scale noise and since the deconvolution process is very responsive to the initial pressure $P_i$, suitable values of $\lambda$ and $P_i$ were selected. Deconvolution quality is assessed by the lack of late time oscillations on the deconvolved derivative; by the fact that different flow periods yield converging derivatives; by the consistency between the deconvolved derivative and possible interpretation models resulting from a conventional analysis of the data; and by the ability to generate a pressure history from the deconvolved derivative that matches the actual pressure history (Gringarten, A. C., 2010).
Log-log analysis
This study involved revision and alteration of the fluid (=blood) properties and well (=blood vessels) parameters used by Channa, S. (2010). Major changes are applied to the blood compressibility value and blood vessel length. Appendix D describes all refinements that are done in more detail. Modified input parameters are listed in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Aorta</th>
<th>Coronary Artery</th>
<th>Veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well (=artery) radius</td>
<td>ft</td>
<td>0.0475</td>
<td>0.0033</td>
<td>0.025</td>
</tr>
<tr>
<td>Reservoir thickness (=blood vessel length)</td>
<td>ft</td>
<td>5.0</td>
<td>0.33</td>
<td>3.28</td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Blood viscosity</td>
<td>cP</td>
<td>2.76</td>
<td>2.76</td>
<td>2.76</td>
</tr>
<tr>
<td>Total compressibility</td>
<td>psi</td>
<td>0.066</td>
<td>0.066</td>
<td>0.41</td>
</tr>
<tr>
<td>Formation volume factor</td>
<td>Rb/stb</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir (=body) temperature</td>
<td>°F</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2: Input parameters (present study)

Selecting an interpretation model is a very critical process. If an inappropriate interpretation model is selected, it leads to misrepresentation of the reservoir characteristics and in our case the cardiovascular system characteristics. Log-log analysis is performed using different software packages, such as Interpret 2010 and Kappa Engineering software (Saphir).

Results
Deconvolution is performed using TLSD and Kappa Engineering (Saphir) software. The default value of λ is applied to the deconvolution of single and pairs of flow periods, while for the entire pressure history it is increased by the factor of 100. Throughout this section only aortic Ao_PROX, coronary artery CX and venous IVC data sets are presented. Analysis of the additional data sets is discussed in Appendices E, F and G. Deconvolved derivatives, resulting from the deconvolution of the entire pressure history, the final and penultimate flow periods, consecutive and separated pairs of build-ups, show similar trend at late times and are illustrated in Figure 21. Figure 22 demonstrates pressure change and derivative corresponding to the unit-rate pressure drawdown convolved from the deconvolved derivative, obtained from the deconvolution of all flow periods using Kappa Engineering software. Satisfactory pressure history match is obtained employing both Kappa Engineering and TLSD software and it is displayed in Figure 23 and Figure 24. The fractional pressure difference is within the acceptable limit of ±10%. However, for the aortic data set (Ao_PROX), the match obtained from Saphir software is not stable at early times.

Figure 21: Deconvolved derivatives. Data set Ao_PROX (TLSD)

Figure 22: Log-log deconvolution plot resulted from deconvolution of the entire pressure history. Data set Ao_PROX (Kappa Engineering, Saphir)
Deconvolution transforms variable-rate pressure data into a constant-rate initial drawdown with the duration equal to the total duration of the test (Gringarten, A. C., 2010). In order to select the interpretation model that could describe the cardiovascular system conditions, unit rate pressure drawdown is first used for analysis. Figure 25 and Figure 26 show the match between the simulated model and pressure change with the derivative obtained from the unit rate pressure drawdown. The derivative curve resulted from the unit rate pressure drawdown, which is obtained from deconvolution employing both TLSD (Figure 25) and Kappa Engineering software (Figure 29), exhibits a unit-slope straight line at the early time that is followed by a slight hump, stabilization at the middle time and finally negative slope at the late time. The middle time behaviour of the derivative in Figure 25 is not clear and is affected by the noisiness of data, while in Figure 29 the radial flow stabilisation is observable. Therefore the level of the stabilisation is roughly assumed referring to the derivative obtained from the deconvolution of the entire pressure history using Kappa Engineering software (Figure 29). Consequently, the selected analysis model is: vertical well with wellbore storage and skin in a homogeneous reservoir with the constant pressure boundary, which corresponds to the previous research findings. Figure 29 and Figure 30 illustrate log-log analysis resulting from the deconvolution of the entire pressure history using the only Kappa Engineering software for both deconvolution and analysis processes. All obtained parameters are summarized in Table 3. In addition to the known uncertainty ranges, such as 20% for the permeability and the wellbore storage constant and ±0.3 for the skin factor (Azi, A. C., 2008), the variation of calculated parameters magnitudes shown in Table 3 result from the use of several software packages as well as from the imperceptible stabilisation of the pressure derivative curve. Therefore, permeability is within 20 - 40%, skin is within ±0.5 - ±2.0 and wellbore storage coefficient is within 24 – 50%. The skin factor does not exceed the magnitude of 4 and the wellbore storage value reflects the real volume of the blood within the blood vessel, which can be calculated from Eq. 5, where $c_t$ stands for the sum of the compressibility of the blood and arterial walls distensibility.

$$V_{blood} = \frac{C}{c_t} \quad (5)$$
Well Test Analysis of Blood Pressure

Figure 27: History pressure match between unit rate pressure drawdown and simulated model. Data set Ao_PROX (Interpret)

Figure 28: History pressure match between unit rate pressure drawdown and simulated model. Data set Ao_PROX (Kappa Engineering, Saphir)

Figure 29: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history. Data set Ao_PROX (Kappa Engineering, Saphir)

Figure 30: Pressure history match between the actual and simulated data. Data set Ao_PROX (Kappa Engineering, Saphir)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Aortic data</th>
<th>Coronary artery data, CX</th>
<th>Venous data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ao_PROX</td>
<td>Ao_00</td>
<td>Ao_45</td>
</tr>
<tr>
<td>Initial pressure, $P_i$</td>
<td>psia</td>
<td>2.47</td>
<td>2.4</td>
<td>2.45</td>
</tr>
<tr>
<td>Permeability, $k$</td>
<td>min</td>
<td>mD</td>
<td>31,100</td>
<td>40,600</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td></td>
<td>45,000</td>
<td>67,600</td>
</tr>
<tr>
<td>Skin, $S$</td>
<td>min</td>
<td></td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td></td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Wellbore storage, $C$</td>
<td>min</td>
<td>Bbl/psi</td>
<td>1.7E-4</td>
<td>3.0E-4</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td></td>
<td>2.0E-4</td>
<td>3.7E-4</td>
</tr>
<tr>
<td>Blood volume, $V_{\text{blood}}$</td>
<td>min</td>
<td>L</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td></td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 3: Summary of the results

Coronary artery analysis results

Coronary artery analysis provides results that are similar to the aortic and they are illustrated in Figure 31 - Figure 40 and Table 3.
Figure 31: Deconvolved derivatives. Data set CX (TLSD)

Figure 32: Log-log deconvolution plot resulted from deconvolution of the entire pressure history. Data set CX (Kappa Engineering, Saphir)

Figure 33: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history. Data set CX (TLSD)

Figure 34: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history. Data set CX (Kappa Engineering, Saphir)

Figure 35: Log-log match between simulated data and data resulted from the unit rate pressure drawdown. Data set CX (Interpret)

Figure 36: Log-log match between simulated data and data resulted from the unit rate pressure drawdown. Data set CX (Kappa Engineering, Saphir)

Figure 37: History pressure match between the unit rate pressure drawdown and simulated model. Data set CX (Interpret)

Figure 38: History pressure match between the unit rate pressure drawdown and simulated model. Data set CX (Kappa Engineering, Saphir)
Venous analysis results

Analysis of the venous pressure and rate responses, that were not analyzed previously, is illustrated in Figure 41 - Figure 50 and Table 3 and achieved results resemble the aortic results.

Figure 39: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history. Data set CX (Kappa Engineering, Saphir)

Figure 40: Pressure history match between the actual and simulated data. Data set CX (Kappa Engineering, Saphir)

Figure 41: Deconvolved derivatives. Data set IVC (TLSD)

Figure 42: Log-log deconvolution plot resulted from deconvolution of the entire pressure history. Data set IVC (Kappa Engineering, Saphir)

Figure 43: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history. Data set IVC (TLSD)

Figure 44: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history. Data set IVC (Kappa Engineering, Saphir)
Well Test Analysis of Blood Pressure

Figure 45: Log-log match between simulated data and data resulted from the unit rate pressure drawdown. Data set IVC (Interpret)

Figure 46: Log-log match between simulated data and data resulted from the unit rate pressure drawdown. Data set IVC (Kappa Engineering, Saphir)

Figure 47: History pressure match between the unit rate pressure drawdown and simulated model. Data set IVC (Interpret)

Figure 48: History pressure match between the unit rate pressure drawdown and simulated model. Data set IVC (Kappa Engineering, Saphir)

Figure 49: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history. Data set IVC (Kappa Engineering, Saphir)

Figure 50: Pressure history match between the actual and simulated data. Data set IVC (Kappa Engineering, Saphir)

Discussion

Deconvolution

As was stated before, deconvolution is carried out employing two different software packages, namely TLSD and Kappa Engineering (Saphir). Saphir software does not detect pressure and rate data of small magnitude, such as for example venous data, which leads to the need for the alteration of the real data acquired. Furthermore, the shape of the deconvolved derivative obtained via Kappa Engineering software is highly affected by the reference group selected. TLSD software, in turn, is limited in the number of flow periods and pressure data points that can be loaded for the further deconvolution process. However, if regularisation parameter is carefully selected, deconvolution results are visualised clearly without small scale oscillations and
allow identifying the initial pressure value. Nevertheless, results achieved using both software reasonably well correspond each other.

**Input parameters**

The reservoir thickness (=blood vessel length) influences the level of the radial flow stabilization and consequently the permeability-thickness product $k_h$ that is identified from the log-log analysis. Since the circulatory system is a very complex system and blood vessels such as arteries and veins are multiply branched, the effective length is taken as the entire body length. However, the net length of the blood vessels directly affects the permeability value and it should be carefully selected. Moreover, the effective wellbore (=blood vessel) radius, that impacts the calculated skin factor, requires further investigation due to the fact that it is not a uniform value and by taking into account smaller branches it could be significantly increased.

Throughout the current study, the compressibility term is recalculated referring to the distensibility of the arterial walls, due to the fact that arteries have elastic walls, which are very responsive to the pressure fluctuations. Consequently, assuming that only a single-phase fluid is present, the wellbore storage is calculated by the combined compressibility, which is the sum of the blood and blood vessel walls compressibility.

**Wellbore storage**

The total volume of blood in a mammalian body is $6 – 8\%$ of the total weight. On the one hand, aortic and coronary artery data are taken from human patients and estimated blood volume is $3 – 4$ litres. On the other hand, venous data are obtained from dogs, for which estimated total volume of blood is $1 – 3$ litres, depending on the size. Continuously re-circulating blood is distributed all over the body and, referring to Figure 2 and input parameters that are used for the log-log analysis, the aorta can contain $0.3 – 0.4$ litres of blood, while the coronary artery: $0.003 – 0.004$ litres and veins: $0.6 – 2.1$. 

The blood volume can be calculated from Eq. 5 and it reflects the wellbore storage coefficient that could be obtained from the log-log analysis and that is indicated by a unit-slope straight line on the derivative at the early times. In the petroleum industry, if a single-phase fluid is present, wellbore storage is defined by the product of the fluid compressibility and wellbore volume. Arterial walls are elastic, sensitive to the pressure change and they adjust the blood vessel’s inner diameter (and consequently the volume that can be stored) via the contraction of the muscular layer. Thus, calculating the wellbore storage coefficient corresponding to the blood vessel, the distensibility of the arterial walls is taken into consideration. Obtained values of the wellbore storage coefficient and consequently calculated volume of the blood match the real volumes that blood vessel can store, therefore validating the analysis.

**Permeability and skin**

Regarding to the reservoir system, permeability is the ability of the rock to transmit the fluid and it can be found from the log-log analysis by the radial flow stabilization. In other words, permeability indicates the ease of the fluid to flow. On the contrary, in a human’s body, the difficulty of the blood flow is measured and it is called resistance. Resistance is the difference in mean pressure needed to drive one unit of flow (Levick, J. R., 2010) and it can be found from Darcy’s law, Eq. 6.

\[ Q = \frac{\Delta P}{R} \]  

(6)

Permeability can also be found from Darcy’s law, Eq. 7.

\[ Q = \frac{kA \Delta P}{\mu L} \]  

(7)

Correlating resistance $R$ and permeability $k$, it is found that they are inversely proportional, Eq. 8.

\[ k = \frac{\mu L}{RA} \]  

(8)

Applying a typical systemic circulation resistance of $0.02$ mmHg min/ml and the input parameters used for log-log analysis to Eq. 8, the estimated value of the permeability for the aorta is $30,000 - 50,000$ mD, while for the venous data – $70,000 - 110,000$ mD. The permeability obtained from well test analysis has very similar magnitudes, which are $30,000 - 70,000$ mD for the aorta and $40,000 - 60,000$ mD for veins.

The skin factor in well testing indicates whether the fluid flow into the well was restricted or stimulated by any means. A damaged well is characterized by a positive skin factor, while stimulated – by negative. The skin is defined by the pressure drop between the original reservoir permeability zone and changed permeability zone. Analysis of the blood pressure behaviour from multiple aortic and veins sites demonstrate relatively small positive skin values.

Both permeability and skin could be used as indicators of any restriction to the blood flow that may cause number of heart diseases. However those parameters are of a big uncertainty that is up to 40% for the permeability and up to ±2 for the skin
factor. The first reason for that is the noisiness of the data and at the middle time the radial flow stabilisation level on the derivative is not clear. The second reason is not uniform values of the arterial length and diameter, which require further investigation.

Conclusions and suggestions

Previous study carried out by Channa, S. (2010) suggested that larger arteries behave as vertical wells in a homogeneous reservoir with a constant pressure boundary. However early times behaviour was of a big uncertainty exhibiting overestimated values of the wellbore storage coefficient leading to the unrealistic volume of the blood in the human body.

Current research is mainly concentrated on obtaining sensible and realistic log-log analysis parameters that could describe the circulatory system and also on the correlation between obtained output variables and human body. Analysis of the aortic, coronary artery and additional veins data yield comparable results. Wellbore storage coefficient extracted from the early times behaviour exhibits reasonable values, and, calculating the blood volume, the total compressibility value (including the effect of the distensibility) is taken into account. The middle time behaviour and the blood vessel dimensions are not certain and consequently permeability and skin factors are not well defined. Therefore, those parameters are within a relatively wide range, such as 20 - 40% for the permeability and ±0.5 - ±2 for the skin factor. Nevertheless, calculated from log-log analysis values correspond to the typical systemic resistance measured in a human body.

If uncertainties related to the well test analysis of the blood pressure are minimized, this new technique could be very useful in a medical world in order to diagnose various heart diseases that result from the failure of the circulatory system. For example, thickening of the coronary artery walls due to the accumulation of atheromatous plaques may cause coronary heart disease, which affects the heart supply with oxygenated blood and yields to the chest pain or even heart attack. The rate of cardiovascular diseases, that involve the heart itself and blood vessels (atherosclerosis and hypertension), is very high and it is continuously increasing. When the heart problem is identified, the underlying origin, progressing over years, is significant. Therefore, detecting the symptoms at the early stages is vital. The future research related to the current project could be concentrated on the investigation of the effect of the arterial effective radius and length, to minimize uncertainties in permeability and skin factor. The middle time behaviour could also be studied in more details for the purpose of bringing more understanding and correlation between the resistance and permeability values. Lastly, in order to investigate how diverse diseases affect the blood circulation and consequently log-log analysis variables, it would be useful to test more patients knowing their parameters, such as for instance weight, height and disease.
**Nomenclature**

- \( \mu \) Blood viscosity, cP
- \( A \) Cross-sectional area, \( \text{ft}^2 \)
- \( C \) Wellbore storage coefficient, bbl/psi
- \( c \) Wave speed, \( \text{ft/D} \)
- \( c_t \) Total compressibility, \( \text{psi}^{-1} \)
- \( d \) Diameter of blood vessels, ft
- \( D \) Distensibility, \( \text{psi}^{-1} \)
- \( k \) Permeability, \( \text{mD} \)
- \( kh \) Permeability-thickness product, \( \text{mD ft} \)
- \( L \) Blood vessel length, ft
- \( P_{\text{analy}} \) Pressure used for analysis, psia
- \( P_{\text{data}} \)Measured pressure, psia
- \( P_i \) Initial pressure, psia
- \( Q \) Blood flow rate, bbl/D
- \( Q_{\text{analy}} \)Blood flow rate used for the analysis, bbl/D
- \( Q_{\text{data}} \) Measured blood flow rate, bbl/D
- \( R \) Resistance, psi D/bbl
- \( r \) Well (=blood vessel) radius, ft
- \( S \) Skin factor
- \( U \) Measured blood velocity, \( \text{ft/D} \)
- \( V_{\text{blood}} \) Volume of blood, L
- \( \lambda \) Regularization parameter for deconvolution (TLSD software)
- \( \rho \) Blood density, \( \text{lb/ft}^3 \)

**References**


APPENDICES

APPENDIX A - Critical literature review

Anatomy of the human body (1918)

Chapters 5, 6 and 7

Authors: Gray, H., edited by Lewis, W. H.

Contribution to the understanding of well test analysis of the blood pressure:

Describes the cardiovascular system and details the blood circulation around the body. Furthermore, the structure and functionality of the blood vessels are presented.

Objectives:

The main objective of this book is to give an understanding of the anatomy and internal processes of the human body.

Methodology:

Each chapter describes particular organ and related to it processes within the organism.
Imperial College MSc Petroleum Engineering Thesis (2009)

Well test analysis of blood pressure

Authors: Sargaskayev, M.

Contribution to the understanding of well test analysis of the blood pressure:

The first attempt to use petroleum engineering technique, called well test analysis, and software to analyse the cardiovascular system behaviour and conditions.

Objectives:

The main objectives of this paper are to analyse blood pressures and velocities applying well test analysis methods and to find the interpretation model that corresponds to the circulatory system.

Methodology:

Clinical blood pressure and rate data, measured at multiple arterial sites, is deconvolved employing Kappa Engineering software in order to convert data into the unit-rate pressure drawdown to obtain more data available for the interpretation. Further log-log analysis is performed in order to investigate the flow regimes and to obtain sensible interpretation model and parameters.

Conclusions:

Proposed, that larger arteries behave as vertical wells in a homogeneous reservoir. However, late time behaviour is uncertain and no reasonable log-log analysis parameters are achieved.
SPE 134534 (2010)

Practical use of well test deconvolution

Authors: Gringarten, A. C.

Contribution to the understanding of well test analysis of the blood pressure:

Deconvolution process is used to transform multi-rate blood pressure data into a single drawdown at a constant rate with the duration of the entire test in order to get more data available for the interpretation and clarify the boundary effect.

Objectives:

The main objectives of this paper are to illustrate various cases where deconvolution can be used; to demonstrate the methodology of the deconvolution process; benefits that could be achieved applying that powerful tool; and to provide recommendations on the ways of obtained results verification.

Methodology:

Deconvolution algorithm is applied to the various cases; single build-ups as well as different sets of build-ups and entire pressure history are deconvolved; the unit-rate pressure drawdown, which is convolved from deconvolved derivative, is then analysed in a conventional way; the resulting model is applied to the actual pressure data with adopted rates.

Conclusions:

Deconvolution allows seeing boundaries that were not seen by individual flow periods due to the fact that it converts variable-rate pressure data into a single rate drawdown with the duration equal to the entire test duration, therefore, more pressure data that can be analyzed is obtained. In addition, by deconvolving and adapting entire rate history, inaccurate rates can be corrected and missing rates can be detected.
An introduction to cardiovascular physiology (2010)

Authors: Levick, J. R.

Contribution to the understanding of well test analysis of the blood pressure:
Details the cardiovascular system and outlines properties and the structure of the heart and blood vessels. Some parameters related to the blood vessels and circulatory system in general, which are used for the interpretation and verification of the results obtained from the log-log analysis, are adopted from this book.

Objectives:
The main objectives of this book are to describe the cardiovascular system in details, including the structure, functionality and responses in both normal and pathological situations.

Methodology:
Starting from the overview of the cardiovascular system in general each following chapter is concentrated on the particular component of the circulatory system and processes related to it with the description of the methodology of the measurements that can be performed and various aberrations due to the pathologies.
Well test analysis of blood pressure

Authors: Channa, S.

Contribution to the understanding of well test analysis of the blood pressure:

Deconvolution and log-log analysis of the blood pressure are performed and suggested an interpretation model.

Objectives:

The main objectives of this paper are to interpret clinical data from the aorta and the coronary artery and to obtain reasonable parameters that correspond to the cardiovascular system.

Methodology:

Clinical blood pressure and rate data, measured at multiple arterial sites, is deconvolved employing TLSD software to obtain more data available for the interpretation and to clarify the boundary effect. Further log-log analysis of the unit-rate pressure drawdown is performed in order to investigate flow regimes and to obtain reasonable interpretation model with its parameters that correspond to the cardiovascular system.

Conclusions:

Suggested, that larger arteries near the heart behave as vertical wells in a homogeneous reservoir with the constant pressure boundary effect at late time. However, early time behaviour is uncertain and the volume of the blood that is calculated from the wellbore storage coefficient is overestimated. Thus, further research is needed.
The cardiovascular system (1918)

Authors: Rogers, K.

Contribution to the understanding of well test analysis of the blood pressure:

This book describes the structure and various functions of the heart and blood vessels. In addition, multiple heart and blood vessels diseases are presented with possible reasons for those pathologies.

Objectives:

The main objectives of this book are to present various diseases related to the cardiovascular system; to show the progress of the cardiology; and to emphasize the importance of the further investigations in the cardiology in order to achieve a better understanding of the mechanisms of the cardiovascular pathologies and to identify the reasons for those diseases.

Methodology:

Starting from the heart and blood vessels description, each following chapter is concentrated on the either congenital or acquired diseases that may occur within the circulatory system.
## APPENDIX B - Milestones

### MILESTONES IN WELL TEST ANALYSIS OF BLOOD PRESSURE STUDY

<table>
<thead>
<tr>
<th>Paper n°</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPE 102079</td>
<td>2006</td>
<td>“From Straight Lines to Deconvolution: The Evolution of the State of the Art in Well Test Analysis”</td>
<td>Alain C. Gringarten</td>
<td>In addition to the review of the development of the well test analysis techniques, this paper outlines details and methodologies of the analysis process and ways to verify obtained results.</td>
</tr>
<tr>
<td>MSc Petroleum Engineering Thesis</td>
<td>2009</td>
<td>Well Test Analysis of Blood Pressure</td>
<td>Mukhtar Sargaskayev</td>
<td>First attempt to apply well test analysis to investigate the blood pressure behaviour.</td>
</tr>
</tbody>
</table>
APPENDIX C – Revision of previously obtained results

As was stated before, in order to verify previous results, the current study adopts the same fluid properties, well parameters and methodology, while aortic pressures and rates that are used differ due to the unavailability of the past data, but measured at the similar aortic sites. Deconvolution is performed using TLSD software. Single flow periods and series of flow periods are deconvolved, which are the final build-up, the penultimate build-up, two consecutive build-ups, two separated build-ups and the entire pressure history. On the one hand, the default value of \( \lambda \) is applied to the deconvolution of single and pairs of flow periods. On the other hand, for the entire pressure history it is increased by the factor of 100. Figure C-1, Figure C-2, Figure C-7 and Figure C-8 illustrate deconvolved derivatives obtained from both studies, while corresponding pressure history matches between the original and convolved pressures are shown in Figure C-3, Figure C-4, Figure C-9, Figure C-10. The arbitrary values of \( P_i \), which were used to modify pressure data throughout the previous research, seem to be underestimated and yield reconvolved pressure data fall to negative values.

Log-log analysis of the unit rate pressure drawdown is done using Kappa Engineering software and correlation between the previous study and results obtained during verification phase of the present study are presented in Figure C-5, Figure C-6, Figure C-11 and Figure C-12 and Table C-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Previous study</th>
<th>Present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial pressure, psia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Ao} _\text{PROX} )</td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>( \text{Ao} _00 )</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>( \text{CX} )</td>
<td>2.2</td>
<td>2.25</td>
</tr>
<tr>
<td>Skin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>min</td>
<td>3.0</td>
<td>8.0</td>
</tr>
<tr>
<td>max</td>
<td>9.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Volume of blood, L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>min</td>
<td>145</td>
<td>140</td>
</tr>
<tr>
<td>max</td>
<td>245</td>
<td>200</td>
</tr>
</tbody>
</table>

Table C-1: Summary of the results obtained during verification process

Arteries seem to act as vertical wells with wellbore storage and skin in a homogeneous reservoir with the constant pressure boundary. Even though the model appears to be reasonable, some obtained parameters are overestimated and do not correspond to the characteristics of the cardiovascular system.
Data set Ao_00:

Figure C-1: Deconvolution of various sets of flow periods. Data set Ao_00 (adapted from Channa, S., 2010)

Figure C-2: Deconvolution of various sets of flow periods. Data set Ao_00 (current research)

Figure C-3: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set Ao_00 (adapted from Channa, S., 2010)

Figure C-4: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set Ao_00 (current study)

Figure C-5: Log-log deconvolution plot. Data set Ao_00 (Channa, S., 2010)

Figure C-6: Log-log deconvolution plot. Data set Ao_00 (current research)
Data set CX:

Figure C-7: Deconvolution of various sets of flow periods. Data set CX (adapted from Channa, S., 2010)

Figure C-8: Deconvolution of various sets of flow periods. Data set CX (current research)

Figure C-9: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set CX (adapted from Channa, S., 2010)

Figure C-10: Pressure history match, resulted from the deconvolution of the entire pressure history. Data set CX (current study)

Figure C-11: Log-log deconvolution plot. Data set CX (Channa, S., 2010)

Figure C-12: Log-log deconvolution plot, data set CX (current research)
APPENDIX D – Revision of input parameters

Well radius:

Well radius is the radius of the blood vessel. Thus, it is approximated as:

- \( r_{\text{aorta}} = 0.015 \text{ m} = 0.0475 \text{ ft}; \)
- \( r_{\text{coronary artery}} = 0.001 \text{ m} = 0.0033 \text{ ft}; \)
- \( r_{\text{veins}} = 0.008 \text{ m} = 0.025 \text{ ft}. \)

Reservoir thickness:

Reservoir thickness is assumed as the body length for the aorta and veins due to the fact that, continuously branching, those blood vessels are extended throughout the entire body. Therefore:

- Length of the aorta = 1.5 m = 5.0 ft.
- Length of the coronary artery = 0.1 m = 0.33 ft.
- Length of the veins = 1 m = 3.28 ft.

Porosity:

Porosity is assumed as 0.9 due to the fact that blood flows through blood vessels where there are no actual pores presented.

Blood viscosity:

The blood viscosity is approximated as four times of the viscosity of water. At 37° C, water viscosity, in turn, is 0.69 cP. Therefore, the blood viscosity is roughly 2.76 cP.

Compressibility:

- The compressibility of the blood is similar to the compressibility of water and equals 3E – 6 psi\(^{-1}\).

- Calculating the total compressibility, the distensibility of the blood vessel walls is taken into account due to the fact that arterial walls are very elastic and responsive to the pressure variance. The distensibility is the change of the cross-sectional area with the change in pressure and it can be calculated from the following equation (where D stands for the distensibility, c – wave speed, which is 10 ms\(^{-1}\) for the aorta and 4 ms\(^{-1}\) for veins, and \( \rho \) – blood density, which is 1050 kg m\(^{-3}\)):
\[ D = \frac{1}{\rho c^2} \]

- Owing to the fact that blood compressibility is negligibly small comparing to the distensibility of the arterial walls, total compressibility is approximated as 0.066 psi\(^{-1}\) for the aorta and 0.41 psi\(^{-1}\) for veins.

**Formation volume factor:**

Circulatory system is the closed system and the blood never leaves blood vessels. Thus, the formation volume factor is 1 Rb/stb.

**Reservoir temperature:**

Reservoir temperature is the temperature of the body, which is 37° - 38° C.
APPENDIX E - Analysis results for data set Ao_00

Deconvolved derivatives shown in Figure E-1 do not converge together, nonetheless, they have similar trend. The derivative curve resulted from the unit rate pressure drawdown, which is obtained from deconvolution employing both TLSD (Figure E-5, Figure E-6) and Kappa Engineering software (Figure E-2), exhibits a unit-slope straight line at the early time that is followed by a slight hump, stabilization at the middle time and finally negative slope at the late time. The middle and late times behaviour of the derivative in Figure E-5 and Figure E-6 is not clear and is affected by the noisiness of data, while in Figure E-2 the derivative curve stabilizes.

Figure E-1: Deconvolved derivatives (TLSD)

Figure E-2: Log-log deconvolution plot resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure E-3: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (TLSD)

Figure E-4: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)
Figure E-5: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Interpret).

Figure E-6: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Kappa Engineering, Saphir).

Figure E-7: History pressure match between the unit rate pressure drawdown and simulated model (Interpret).

Figure E-8: History pressure match between the unit rate pressure drawdown and simulated model (Kappa Engineering, Saphir).

Figure E-9: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir).

Figure E-10: Pressure history match between the actual and simulated data (Kappa Engineering, Saphir).
APPENDIX F – Analysis results for data set Ao_45

Figure F-1: Deconvolved derivatives (TLSD)

Figure F-2: Log-log deconvolution plot resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure F-3: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (TLSD)

Figure F-4: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure F-5: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Interpret)

Figure F-6: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Kappa Engineering, Saphir)
Figure F-7: History pressure match between the unit rate pressure drawdown and simulated model (Interpret)

Figure F-8: History pressure match between the unit rate pressure drawdown and simulated model (Kappa Engineering, Saphir)

Figure F-9: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure F-10: Pressure history match between the actual and simulated data (Kappa Engineering, Saphir)
APPENDIX G – Analysis results for data set SVC

Figure G-1: Deconvolved derivatives (TLSD)

Figure G-2: Log-log deconvolution plot resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure G-3: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (TLSD)

Figure G-4: Pressure history match between actual and convolved pressure data, resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure G-5: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Interpret)

Figure G-6: Log-log match between simulated data and data resulted from the unit rate pressure drawdown (Kappa Engineering, Saphir)
Figure G-7: History pressure match between the unit rate pressure drawdown and simulated model (Interpret)

Figure G-8: History pressure match between the unit rate pressure drawdown and simulated model (Kappa Engineering, Saphir)

Figure G-9: Log-log deconvolution plot showing the match between the interpretation model and data resulted from deconvolution of the entire pressure history (Kappa Engineering, Saphir)

Figure G-10: Pressure history match between the actual and simulated data (Kappa Engineering, Saphir)