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# PRESSURE PULSE ANALYSIS OF FLOW IN TUBING AND CASING OF GAS LIFT WELLS

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## ABSTRACT

Pressure pulse technology represents a new generation of well and pipe flow measurements. The technology is robust and cost effective. The use of pressure pulse technology for production testing, giving production rate of gas-liquid mixtures, has been demonstrated on several offshore platforms, and is available on commercial basis. The use of pressure pulse technology for flow condition analysis in production and injection wells is under development. Flow condition analysis can be used to detect and monitor changes in flow channel geometry (for example, formation of deposits) and to locate and quantify fluid entry/exit points downhole. Pressure pulse technology can be used on either the tubing-side or the casing-side of gas lift wells. A quick-acting valve is activated for 20-40 seconds and the pressure change measured at the wellhead, immediately up-stream for a tubing-side test and immediately down-stream for casing-side test. The pressure resulting pressure survey is then analyzed to determine the open/closed status of gas lift valves.

## INTRODUCTION

Pressure pulse technology is for on-demand measurements of production rate and wellbore condition analysis. With the advent of high-quality pressure transducers and computer-based data acquisition systems, it has become possible to make practical measurements of rapid pressure transients. The widespread use of quick-acting valves in the oil industry to open, close and control pipeline and wellbore flows, has made it possible to harness the information contained in rapid pressure transients when valves are activated. Pressure is one of the easiest parameters to measure in the production of oil and gas. It can be measured in pipelines, flowlines and wellbores; at wellheads, chokes, manifolds and separators.

In pressure pulse technology the pressure profile in a pipeline can be used to detect and monitor solid deposits. The pressure profile is obtained from pressure measurements at one location, immediately up-stream of a quick-acting valve. When the valve is activated, the up-stream pressure is measured, resulting in a pressure-time log. The pressure-time log is then converted into a pressure-distance log. The pressure-distance log gives the location and extent of deposits in a pipeline (Gudmundsson et al. 2001).

Pressure pulse technology can be used in gas lift wells for flow rate metering and flow condition analysis. For example, pressure pulse testing can be used to detect the open/closed condition of gas lift valves. A case study for such a gas lift well will be presented, for gas-liquid flow on the tubing-side and gas flow on the casing-side (in the annulus). Pressure pulse measurements are made at the wellhead; there is no need to enter the well (the technology is non-interventive).

## RAPID PRESSURE PULSES

When a quick-acting valve in a multiphase pipeline is activated, a pressure pulse will be generated. The pressure pulse will propagate both up-stream and down-stream of the quick-acting valve. The magnitude of the pressure pulse will be governed by the water-hammer equation, also called the Joukowsky equation:

$$\Delta p_a = r\, u\, a$$

where ρ (kg/m3) represents the fluid density, *u* (m/s) the fluid flowing velocity and *a* (m/s) the speed of sound in the fluid. The speed of sound in the fluid is equivalent to the propagation speed of the pressure pulse generated.

A typical pressure pulse technology set-up is shown in Figure 1a (flow is from left-to-right). It shows a quick-acting valve and two pressure transducers, A and B, up-stream of the valve. The pressure transients generated at locations A and B are shown in Figure 1b. The quick-acting valve generates a rapid increase in the pipeline pressure at locations A and B. The initial rapid pressure increase is the water-hammer, as given by the Joukowsky equation. The pressure pulse will arrive at location A before it arrives at location B. The time difference is the time-of-flight $\Delta t$ (s) which can be used to determine the speed of sound in the flowing gas-liquid mixture:

$$a = \Delta L_{AB} / \Delta t$$

A pressure pulse measurement on an injection line will have an inverted pressure pulse. The pressure pulse set-up is illustrated in Figure 1c (flow is from right-to-left). The pressure responses at locations A and B are shown in Figure 1d. The quick-acting valve generates a rapid decrease in downstream pipeline pressure. In most cases the fluid in an injection flowline will be single-phase gas or liquid. The speed of sound in a single phase fluid can easily be determined when a temperature measurement at the valve location is available. This will allow for a simplified set-up with only one pressure sensor. Pressure pulse measurements on the casing side of a gas lift well can be performed with such a simplified set-up.

A pressure pulse traveling up-stream (or down-stream) in a pipeline, will arrest (stop) the flow. The pressure pulse will travel at the in-situ speed of sound. In principle, when the pressure pulse has reached the end of the pipeline, the fluid velocity throughout will be reduced to practically zero.

The mass flow rate in a pipe of constant cross-sectional area *A* ($m^2$) can be obtained directly from the Joukowsky water-hammer equation, when the sound speed is also measured. The mass flow rate w (kg/s) is given by the expression

$$w = r \times u \times A$$

Therefore, provided the sound speed *a* (m/s) and the water-hammer pressure increase are known from measurements, the mass flow rate can be found directly from the relationship

$$w = \left(\Delta p_a\right) \frac{A}{a}$$

As the flow is brought to rest, the pressure loss due to wall friction will be made available. That is, the pressure drop due to gas-liquid mixture or single phase flow in the pipeline, will be released. This frictional pressure drop will propagate continuously to the quick-acting valve and can be measured and is often called line-packing. The gradual pressure change (pressure gradient) after the initial water-hammer in Figure 1b and Figure 1d is the line-packing.

Frictional pressure drop in pipes is governed by the Darcy-Weisbach equation:

$$\Delta p_f = (f/2)(\Delta L/d)\ r\, u^2$$

where $f$ (dimensionless) is the friction factor, $\Delta L$ (m) pipe length, $d$ (m) pipe diameter, $\rho$ (kg/m$^3$) fluid density and $u$ (m/s) fluid velocity. The $\Delta L$ is not the same distance as the $\Delta L_{AB}$ used to determine the speed of sound. Line-packing is used to split the measured mass rate into mixture density and average volumetric flow rate.

The speed of sound in homogeneous gas-liquid mixtures $a_M$ is given by the traditional Wood equation, expressed as:

$$a_M = (AB)^{-1}$$

where

$$A = [\alpha\rho_G + (1-\alpha)\rho_L]^{0.5}$$

and

$$B = \left(\frac{\alpha}{\rho_G\, a_G^2} + \frac{1-\alpha}{\rho_L\, a_L^2}\right)^{0.5}$$

where a (dimensionless) is the void fraction and the subscripts stand for $M$ (mixture), $G$ (gas) and $L$ (liquid). $a_G$ and $a_L$ are the speed of sound in gas and liquid, respectively.

An in-house computer program was used to estimate the speed of sound in the gas-oil mixture flowing at 60 bar and 90 bar in an offshore well. The results of the speed of sound calculations are shown in Figure 2 with void fraction from 0 to 1. The speed of sound in pure liquid is high and decreases dramatically with small amounts of gas. In the void fraction range 0.2-0.8 the sound speed remains relatively constant. As the void fraction increases from 0.8 to pure gas, the sound speed increases. Model calculations show that as the pressure increases, the sound speed in gas-liquid mixtures also increases.

## FIELD TESTS

Pressure pulse rate metering (production testing) has been tested on several offshore fields, including a long-term test on the Gullfaks B platform in 1999. The tests have demonstrated the feasibility of pressure pulse technology for rate metering, and have also shown that standard equipment can be used in the set-up.

Typical pressure pulse values in pipelines and oil producing wells will be in the range 2-10 bar, depending on fluid composition and flow rates (Gudmundsson et al. 2001). The pulse is attenuated as it travels up-stream from a quick-closing valve, and will typically be reduced to about 1-2 bar by the time it reaches the downhole inflow area. No negative effects have been observed on the reservoir during pressure pulse testing.

The valve closing time should be less than 2-3 seconds in order to create a distinct pulse. Available valve actuators can easily meet this requirement. In the Gullfaks measurements a standard 6" hydraulically operated ball valve with a modified actuator was used. The valve closing time was around 0.2 seconds. Existing wing valves have been made to close in 1-2 seconds by simple modifications to the hydraulic system.

## FLOW CONDITION ANALYSIS

The pressure profile obtained from pressure pulse measurements can be used to provide information about the flowing conditions of wells and pipelines. For example, pressure pulse testing can reveal the presence of solid deposits like scale. Deposits will change the frictional pressure drop in the affected interval both by changing the pipe roughness and by reducing the tubing diameter. This will show up as an increase in the line packing gradient in the affected region.

An in-house transient pressure simulator was used to calculate the pressure-time log for a pipeline with and without deposits. The simulation results are shown in Figure 3. The pressure-time log can be converted into a pressure-distance log. The pressure-distance log gives the location and extent of the deposits. The particular situation illustrated in Figure 3 can be analyzed using a stepwise procedure (Gudmundsson et al. 2001).

The transition from gas-liquid flow to single-phase flow will show up as a strong non-linear behaviour on the line packing curve. This is caused by the rapid increase in acoustic velocity of the gas-liquid mixture towards the bubble point. A pressure pulse recording from a North Sea well is shown in Figure 4. The bubble point is easy to locate from the pressure derivative plot, identified as a peak at about 11 seconds.

Pressure pulse records a transient pressure-time log. When this is combined with a well flow simulator and an acoustic velocity model, a flowing pressure with depth log is generated. Known locations of changes in diameter and other features are used to calibrate the depth log. This log represents a pressure survey of the well at a given instance in time. Pressure surveys can be used to adjust/calibrate fluid properties and flow models, and determine bottom hole flowing pressures. Pressure surveys are also used in gas lift wells to identify point(s) of gas injection.

Pressure pulse tests and measurements have been made in multiphase production wells on several platforms in the North Sea. Pressure pulse technology has been demonstrated to be cost-effective, flexible and highly-repeatable. The flexible nature of pressure pulse was demonstrated through a limited-installation test which was carried out on a North Sea well in 2001 (Gudmundsson et. al., 2001). The tests have shown that the theories expressed by the Joukowsky equation (water-hammer), the Darcy-Weisbach equation (line-packing) and the Wood equation (pressure wave propagation), are applicable in practical oil and gas production situations.

### GAS LIFT ANALYSIS

Computer codes that simulate the propagation of pressure pulses in wellbores and in the casing-tubing annulus can be used to illustrate the use of pressure pulse technology to detect injecting gas lift valves. Gas injection changes the fluid and flow properties in the well and in turn, the propagation and reflection characteristics of pressure pulses. This is illustrated through simulations on Well A, which is shown in Figure 5 (an example gas lift well). The well is fitted with three gas lift valves, located at 1100 m, 1750 m, and 2100 m respectively. The production enters the tubing at the bottom of the well, which is at 3500 m. Input data to the simulations are given in the following:

- Measured depth 3500 m
- Vertical well
- Tubing inside diameter 0.1005 m
- Produced oil 32 API gravity
- Gas gravity 0.85
- Water gravity 1.103
- Gas oil ratio (GOR) 50 $Sm^3/m^3$
- Wellhead pressure 50 bara
- Liquid production rate 400 $Sm^3/d$
- Water cut 50 %
- Gas injection rate 100 $MSm^3/d$
- Valve locations: 1100 m, 1750 m and 2100 m

## Flow on Tubing-Side

Gas lift analysis was carried out for Well A. A quick-acting valve at the wellhead was assumed to take 0.5 second to close. The pressure propagation was taken to be recorded at a fast sampling transmitter located immediately upstream of the quick-acting valve.

A commercial steady-state wellbore flow simulator was used to calculate the density profile, and an in-house acoustic velocity model provides the acoustic velocity profile. The mixture density, void fraction and acoustic velocity in Well A are shown in Figure 6 for gas injection through the valve at 1100 m depth. Even a small amount of gas changes the acoustic velocity. Below the bubble point, which is located at approximately 2800 m, the acoustic velocity increases only slightly with depth.

The pressure pulse and line packing simulation for three different cases are shown in Figure 7 (a, b and c). The gas injection rate is 100 MSm3/d (1.16 kg/s), and the liquid production rate is 400 Sm3/d (4.58 kg/s) in all simulations. The initial pressure increase from 50 bar to about 51.3 bar is the pressure pulse and the more gradual pressure increase after that is the line-packing pressure. The change in pressure appearing at approximately 17 seconds on the line packing curve in Figure 7a is the response from the gas lift valve injecting gas at 1100 meters. This is more clearly seen on the pressure derivative plot, which is shown together with the pressure response curve in Figure 7a. The drop in pressure at about 25 seconds is the pressure response from the bottom of the well. Deeper gas injection is recognized as a time-shift in reflection on the pressure derivative plot as indicated in Figure 7b and 7c. At higher gas injection rates the pressure pulse will dampen more. Field testing is needed to demonstrate the use of pressure pulse technology in gas lift operations.

Analysis of the line-packing pressures shown in Figure 7 makes it possible to assess the status of gas lift valves, and to identify which valves are injecting gas. Such analysis will include the measurement of flowrate by pressure pulse testing (Gudmundsson and Celius 1999).

## Flow on Casing-Side

Pressure pulse technology can be applied to the casing-side of a gas lift well by introducing the concept of hydraulic diameter in the frictional pressure loss calculation. Hydraulic diameter is the ratio of the cross-sectional area to the wetted perimeter. In a concentric annulus, it gives:

$$D_h = 2(a - b)$$

where *a* is the casing inside radius, and *b* is the tubing outside radius.

The equivalent diameter, $D_{eq}$ for a given annular space is defined as:

$$D_{eq} = 2\sqrt{a^2 - b^2}$$

Therefore, in a concentric annulus, the flow velocity will be the same, but the diameter in frictional loss term will be smaller, and the friction factor will be bigger as well.

Example Well A is also used in the simulations on the casing side. The gas is injected through the lowest valve at 2100 meters. Additional well data are given in the following:

- Casing inside diameter 0.1524 m, tubing outside diameter 0.1200 m
- Equivalent diameter 0.0939 m, hydraulic diameter 0.0324
- Gas gravity 0.85
- Gas injection pressure 150 bara
- Gas injection rate 100 $MSm^3/d$

The simulation set-up is shown in Figure 8. A quick-acting valve located close to the wellhead on the gas injection line was assumed to take 0.5 seconds to close. The pressure propagation is recorded at a fast sampling transmitter located immediately downstream of the quick-acting valve.

Input to the simulations is the density and acoustic velocity profiles in the annulus. Three cases were investigated. In the first case the annulus is filled with gas only (Figure 8a). The second case investigates a situation in which there is a liquid column just below the valve (Figure 8b). In the third case the liquid column starts at 500 meters below the valve (Figure 8c). In all simulations, the gas injection rate is the same and the moving pressure pulse is assumed not be change the flow rate through the valve.

The pressure pulse and the line packing simulation for all three cases are shown in Figure 9 (a, b and c). The initial pressure reduction from 150 bar to 149.5 bar is the pressure pulse and the more gradual pressure reduction after that is the line-packing pressure. The change in pressure appearing at approximately 19 seconds in all cases is the response from the active gas lift valve. This is more clearly seen on the pressure derivative plots, which show a distinct change at the point of gas injection. The drop in pressure at approximately 28 seconds in Figure 9a is the response from the bottom of the well. The liquid surface below the gas lift valve will reflect the pressure pulse, leaving a distinct "footprint" on the response curve. This is clearly seen in Figure 9b and c. If the liquid level is located immediately below the point of injection, the valve response and the gas-liquid surface response will coincide (Figure 9b). If the liquid surface is located some distance below the valve, the liquid response will be delayed compared to the gas injection response. The liquid surface shows up at approximately 23 seconds in Figure 9c. The bottom hole response appears at 26 seconds.

Analysis of the line packing pressures shown in Figure 9 makes it possible to identify the location of gas injection point(s). Pressure pulse measurements on the casing side will dampen the pulse less than on the tubing side. Field testing is needed to demonstrate the use of pressure pulse technology to asses the status of gas lift valves.

## CONCLUSIONS

- In pressure pulse flow condition analysis, a pressure-distance log is obtained from expert analysis of a measured pressure-time log. The analysis is based on understanding the nature of pressure pulse propagation in gas-liquid mixtures flowing in pipes, and the availability of specialized software for analysis of rapid pressure transients.
- An example was presented where flow condition analysis was used to detect and monitor deposits in a flowline/pipeline. The same methodology can be used to detect deposits in wellbores. Another example was presented where flow condition analysis was used to identify the depth to bubble point in a production well.
- Flow condition analysis can be applied to gas lift wells, by making pressure pulse measurements on the tubing-side (gas-liquid flow). An example was presented where the open/closed status of gas lift valve at 1100 m, 1750 m and 2100 m depth was determined. The simulated pressure pulse measurement took 30 seconds.
- Pressure pulse measurements can also be taken on the casing-side of gas lift wells. In principle, flow condition analysis for single-phase gas flow on the casing side is simpler than for gas-liquid flow on the tubing-side. A casing-side example was presented where the open/closed status of a gas lift valve at 2100 m depth was studied, with the liquid level at same depth, at 2600 m and 3500 m.
- The use of pressure pulse flow condition analysis in gas lift wells needs to be field tested and demonstrated.

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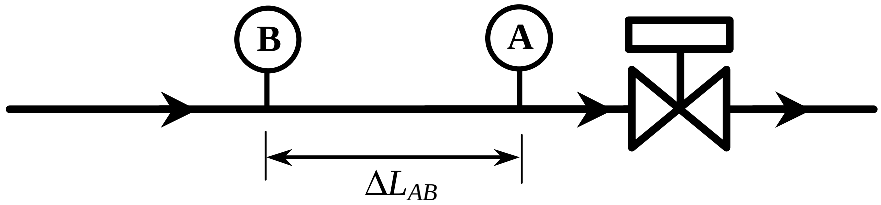



Figure 1a – Pressure pulse set-up for a pipeline, showing quick-acting valve and pressure transducers.

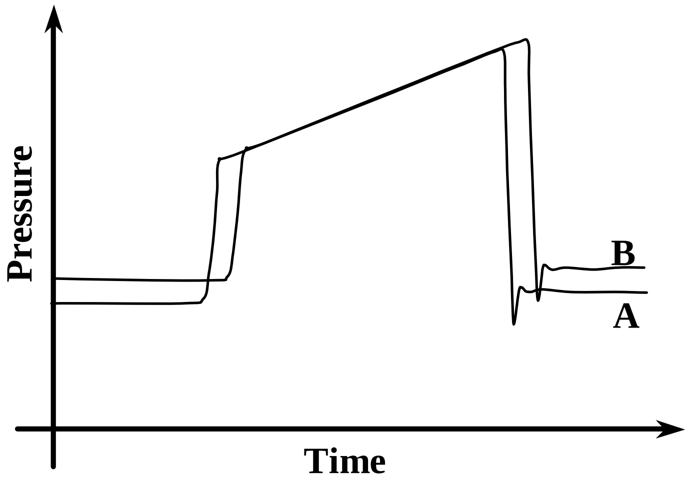



Figure 1b – Pressure pulse at locations A and B up-stream a quick-acting valve.

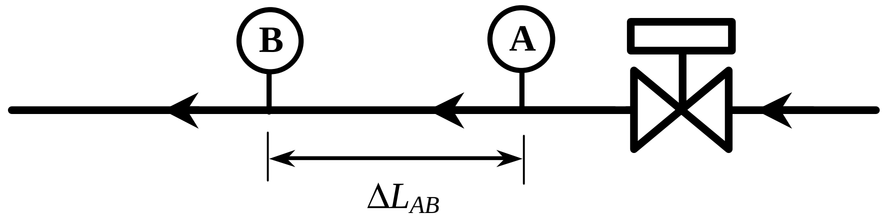



Figure 1c – Pressure pulse set-up for a gas injection line, showing quick-acting valve and pressure transducers.

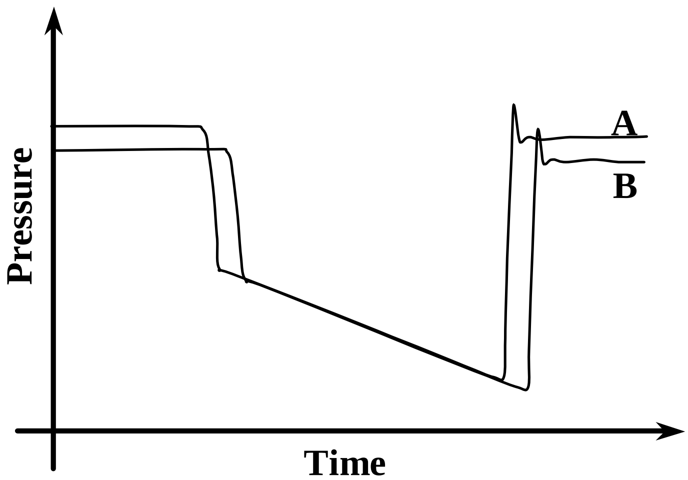



Figure 1d – Pressure pulse at locations A and B down-stream a quick-acting valve.

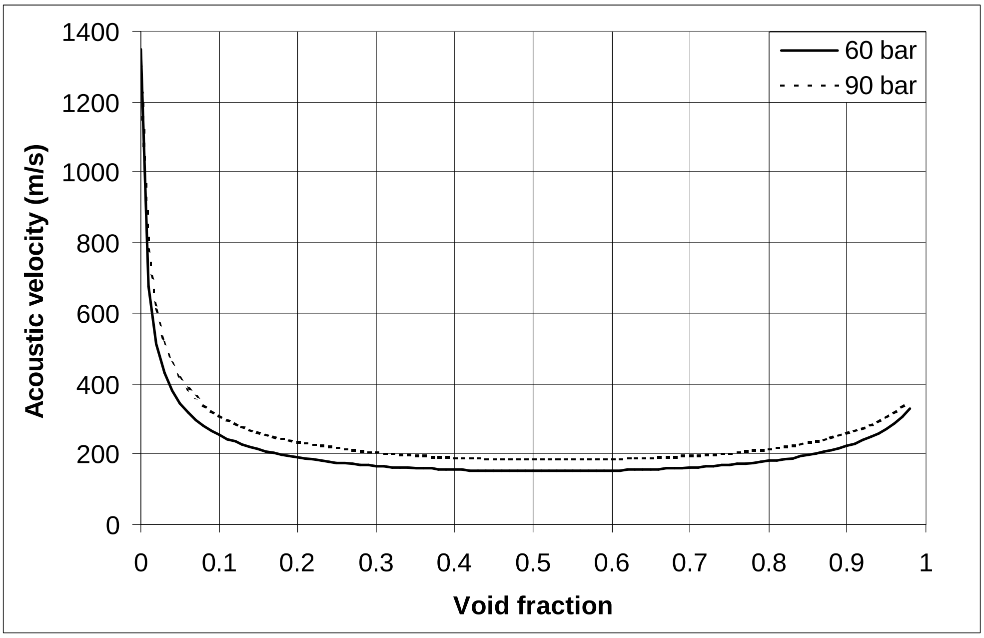



Figure 2 – Speed of sound (acoustic velocity) in North Sea production gas-oil mixture at 60 bar and 90 bar.

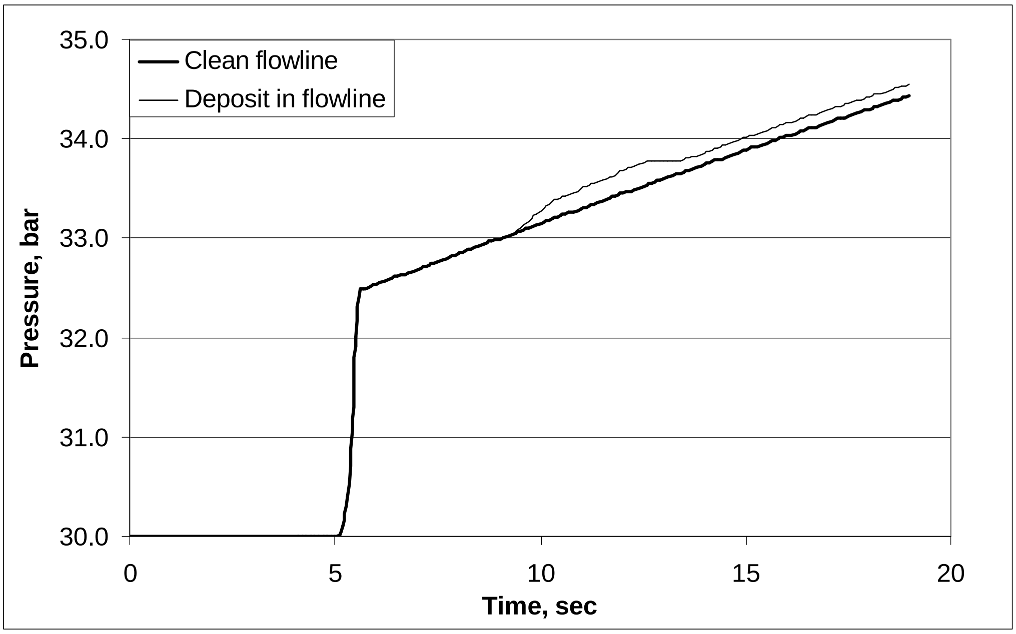



Figure 3 – Pressure pulse used to detect pipe deposits. Change in simulated response between pipe with deposits (thin-line) and clean tubing (solid-line) for the same flow rate.

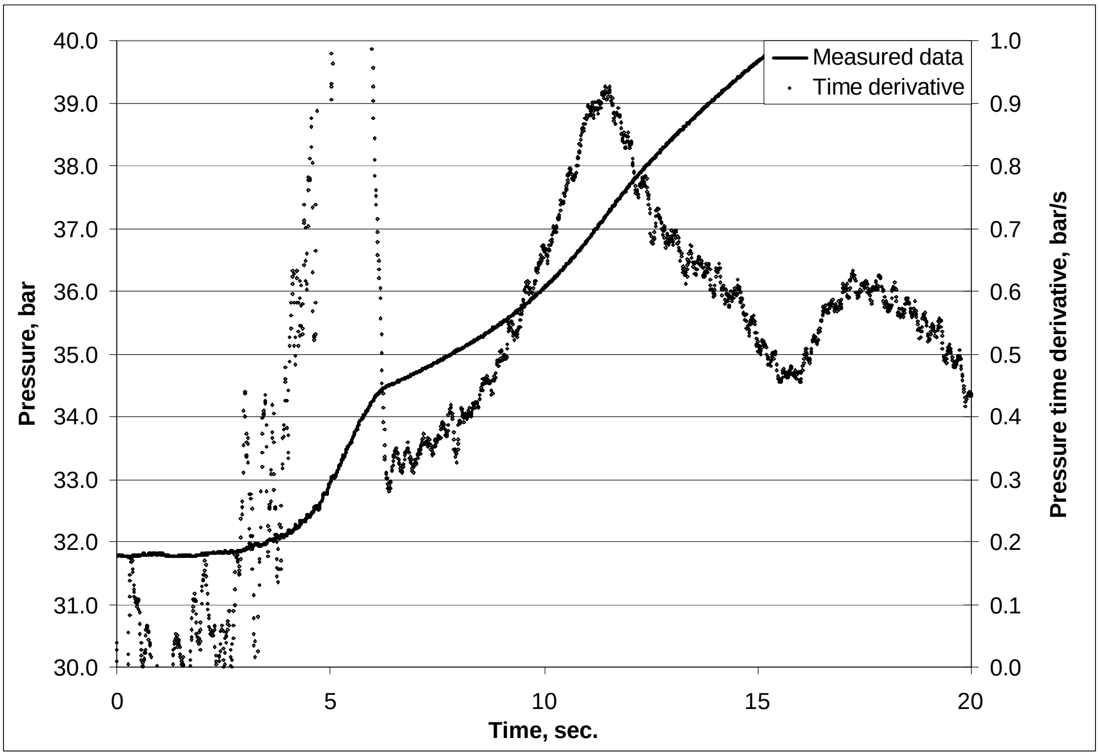



Figure 4 – Pressure pulse test on a North Sea well: The bubble point is the peak appearing at approximately 11 seconds on the pressure derivative curve.

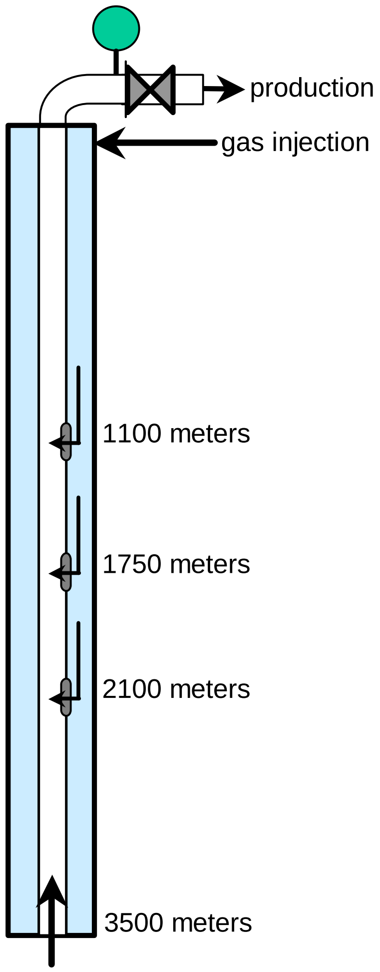



Figure 5 – Gas lift well used in pressure pulse simulations (well A)

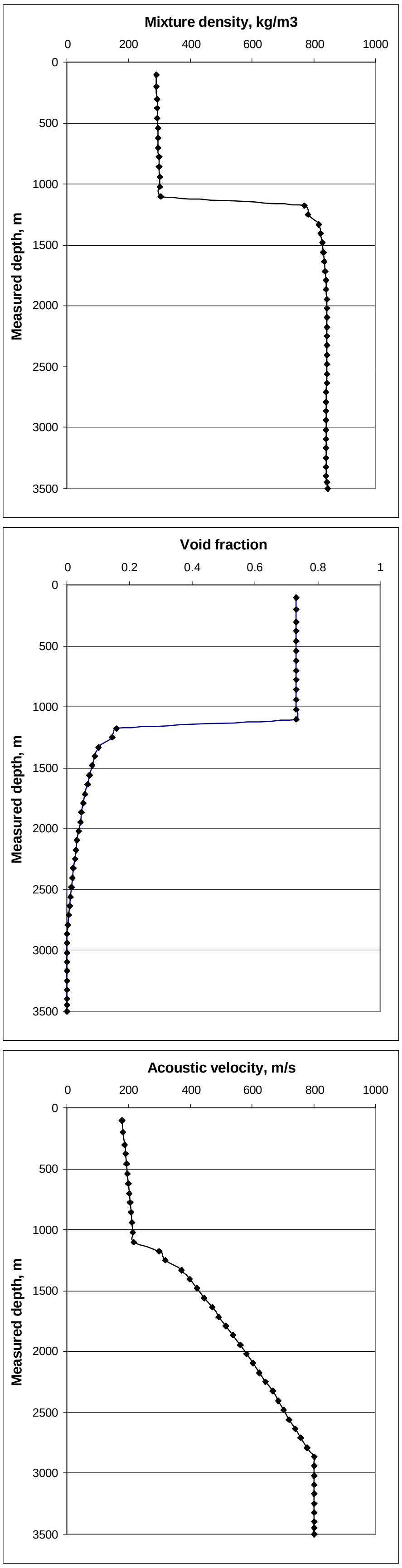
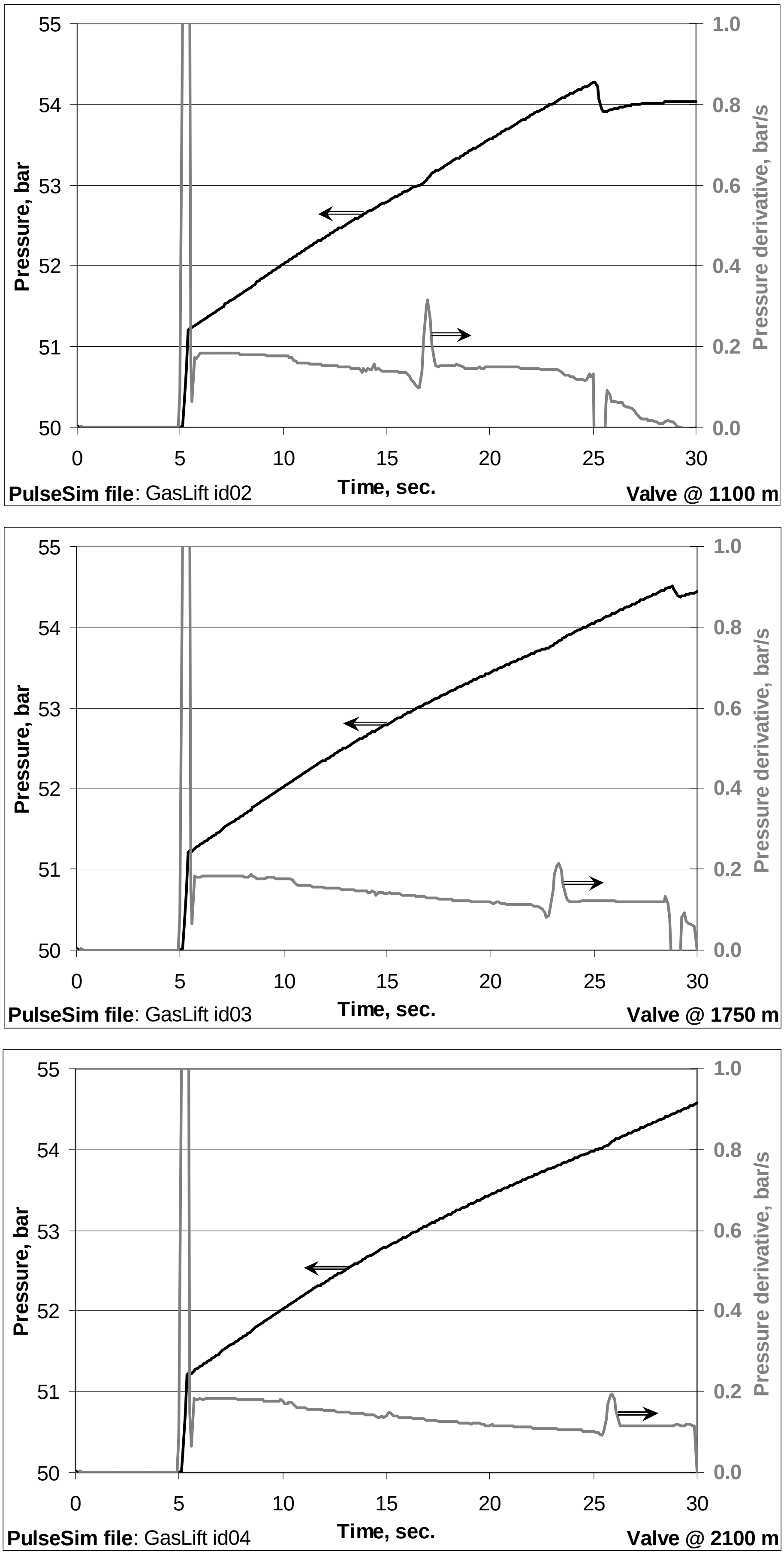



Figure 6 – Mixture density, void and acoustic velocity profiles in the tubing




(a) (b) (c)

Figure 7 – Simulation results for tubing-side (for three different valve locations)

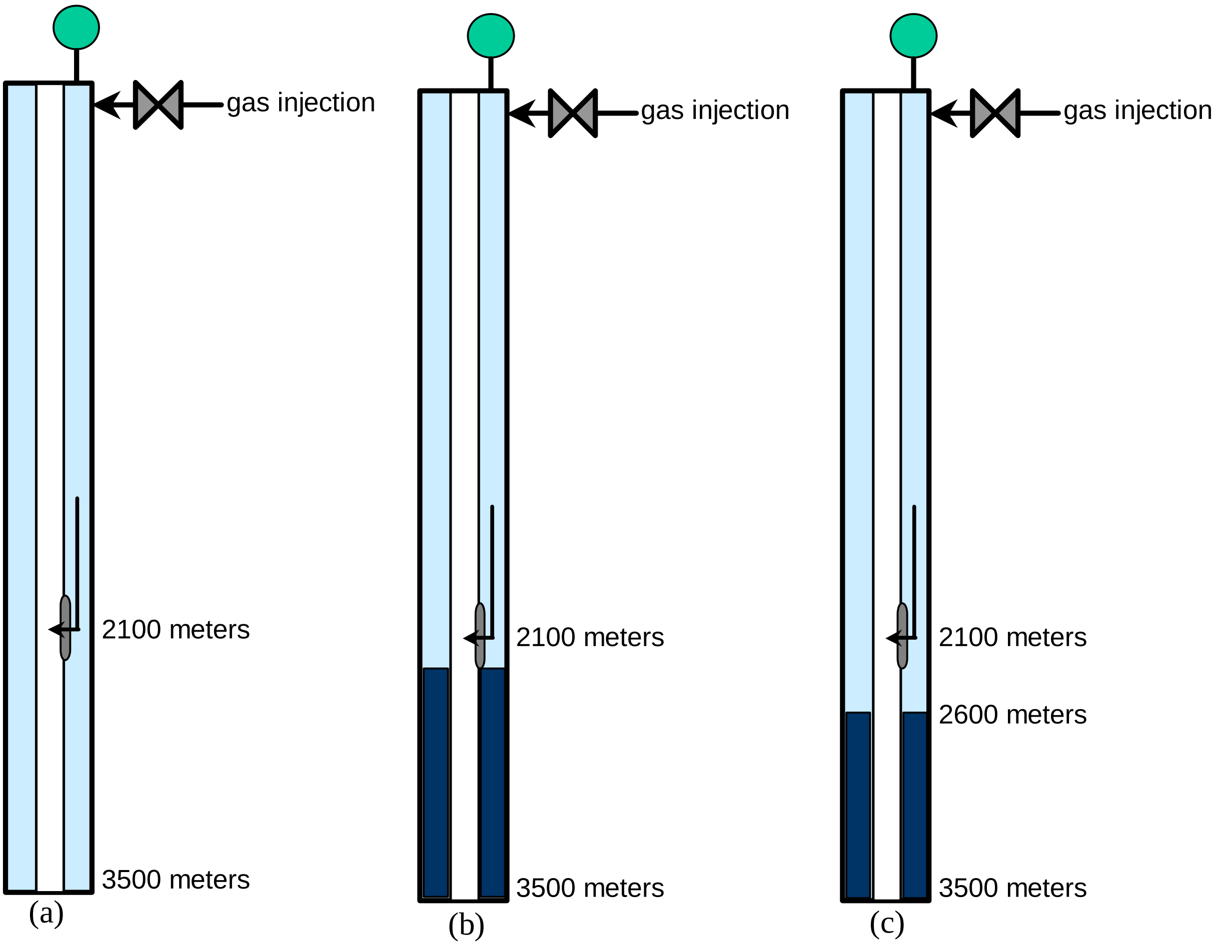


Figure 8 – Gas injection with three liquid level cases (well A)

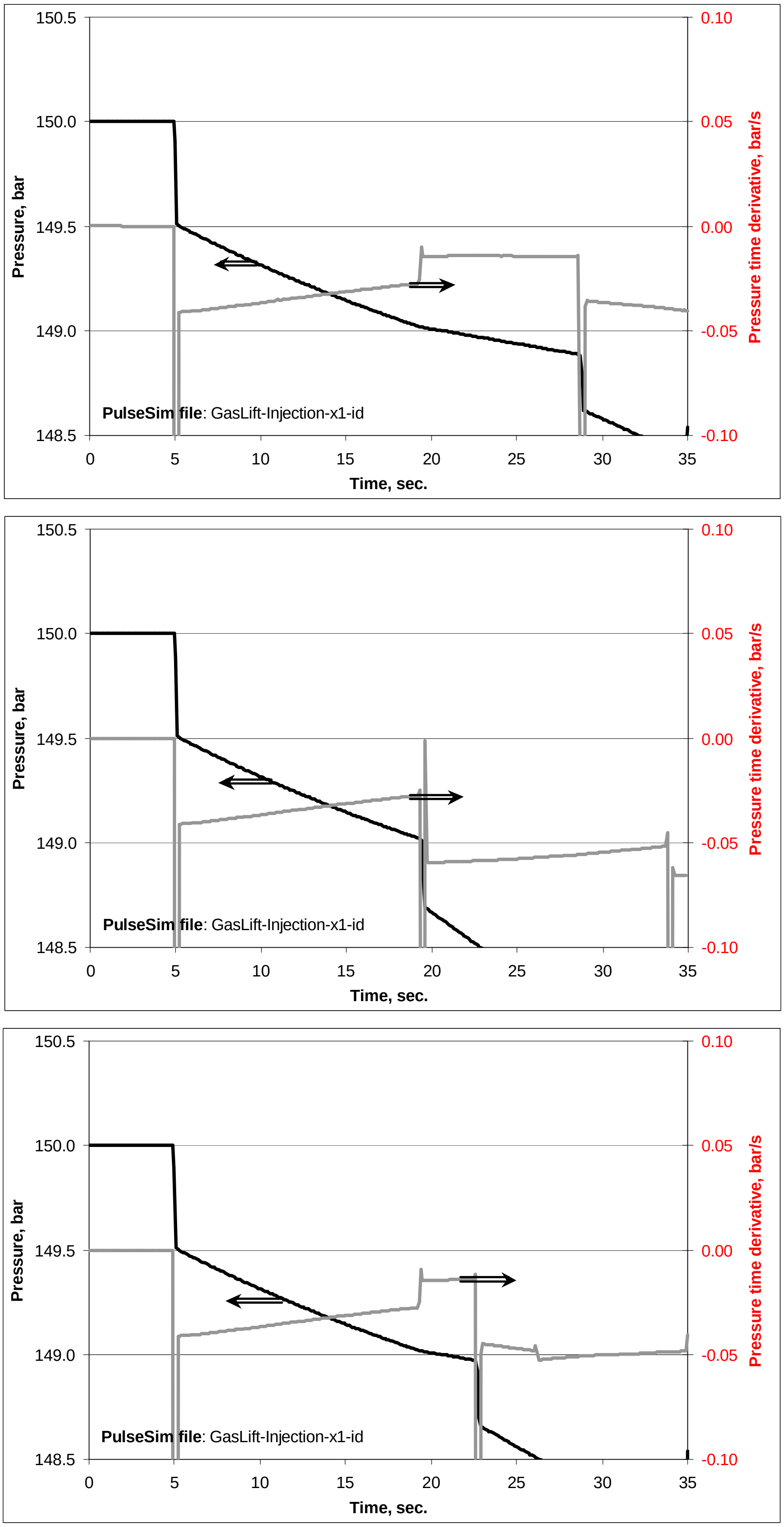



Figure 9 – Simulation results for casing side (for three different cases)