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Gas-Liquid Metering Using Pressure-Pulse Technology

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Abstract

The Pressure-Pulse multiphase metering method is described. The combined effects of water-hammer and speed of sound in gas-liquid mixtures are used to measure the mass flow rate. Through continuity the mass flow rate at the wellhead is the same as the mass flow rate downhole and at standard conditions, making the Pressure-Pulse method suitable for routine production testing and allocation measurements. The method is highly repeatable. Offshore testing of the water-hammer effect and the speed of sound in gas-liquid mixtures, demonstrates the feasibility of the Pressure-Pulse method in petroleum production operations.

Introduction

Multiphase metering in oilfield operations is of considerable interest in the petroleum industry. However, widespread use of multiphase metering has been hampered by the availability of proven technology at reasonable costs. Oil companies have been hesitant to invest in expensive meters with limited track record. The search for robust metering technology at reasonable costs, therefore, continues in the oil industry.

As the development of multiphase meters advances, the applications found suitable for each metering technology are emerging. For example, a multiphase metering package consisting of several different instruments, may find uses on mobile units (trucks) brought on location for a specific job. The instruments are standard and accessible for calibration and maintenance. At the other end of the spectrum, a compact and integrated multiphase meter, without the need for extensive calibration, may find uses in sub-sea applications.

A robust and low-cost method for multiphase metering has been developed by Gudmundsson (1998), called the Pressure-Pulse method. The method is based on the propagation properties of pressure waves in gas-liquid media. Waves generated in gas-liquid mixture flowing in a pipe will propagate as pressure pulses. The speed of propagation is the speed of sound in the gas-liquid mixture. The practical sides of the Pressure-Pulse method are presented in Appendix A.

The Pressure-Pulse method has been tested on the Gullfaks A and Gullfaks B platforms in the North Sea, also on the Oseberg B platform. Experimental results and modelling results from some of the tests have been presented by Falk and Gudmundsson (1999a, 1999b). The multiphase metering aspects of the offshore production tests will be presented in this paper, in particular the water-hammer effect and the speed of sound in gas-liquid mixtures.

Water-Hammer and Line-Packing

The Pressure-Pulse method is based on the combined effects of the water-hammer measured in a gas-liquid flow when a valve is closed quickly, the line line-packing of the flow and the sound speed of the mixture in the pipeline. The Pressure-Pulse method can be used in pipelines, flowlines and wellbores.

The closing of a quick-acting valve will generate a pressure increase up-stream of the valve, called the water-hammer, given by the Joukowsky equation

$$\Delta p_a = \rho \, a \, u \quad \text{.......} \quad (1)$$

where Δp_a (Pa) is the water-hammer, ρ (kg/m3) the fluid density, a (m/s) the speed of sound in the fluid and u (m/s) the homogeneous fluid velocity. The pressure increase Δp_a is the pressure pulse generated when a quick-acting valve is closed. Water-hammer phenomena are presented in detail by Fox (1989), Thorley (1991), Watters (1984) and Wylie and Steeter (1993), primarily for single-phase liquid systems, but also for gas bubbles in liquids.

A valve is defined as quick-acting if it closes before a pressure pulse is reflected back from up-stream or down-stream. The water-hammer pressure increase is independent of the time it takes a quick-acting valve to close; provided the valve closes before reflections arrive from up-stream or down-stream. If there are reflections before the valve has closed, the pressure increase on closing will be affected. The closing behaviour of a quick-acting valve is illustrated in **Fig. 1**, the closing time increasing from left-to-right, as shown by arrow.

The shape of the pressure increase during valve closure depends on the pressure-loss coefficient of the valve. The pressure increase does not change much until a valve has closed about 80%. Most of the pressure increase measured in the Pressure-Pulse method, therefore, will arise while the valve closes from 80% to 100%. This fact has the practical significance that a valve that closes in 2 seconds, will generate most of the pressure pulse in the last 0.4 second.

When a quick-acting valve has been closed, the up-stream pressure continues to increase with time, as shown in **Fig. 2**. This pressure increase is called the line-packing of the pipeline. In Fig. 2 the line-packing increases upwards as shown by the arrow. In liquid-only flow the line-packing represents the frictional pressure drop with distance in the pipeline (the frictional pressure gradient). The frictional pressure drop is made available when the flow stops in the pipeline. The Darcy-Weisbach equation represents the frictional pressure drop in steady-state turbulent pipe flow

$$\Delta p_f = \left(\frac{f}{2}\right)\left(\frac{L}{d}\right)\rho u^2 \quad (2)$$

where f (-) is the friction factor, L (m) the pipeline length, d (m) the pipeline diameter, ρ (kg/m3) the fluid density and u (m/s) the fluid flow velocity. In Fig. 2 the pipeline length ΔL (m) can be replaced by $2 \times a \times \Delta t$, where Δt (s) is the time from the completion of valve closure.

Line packing in gas-liquid flow is more complicated than in liquid-only flow. In addition to the frictional pressure gradient, it contains also the increase in water-hammer with up-stream distance. In fluid flow he up-stream pressure increases, and hence the mixture density and speed of sound increase with distance. A hypothetical valve placed at an increasing up-stream distance, will experience an increasing water –hammer with distance. In vertical gas-liquid flow in production wells, the pressure increases with dept and hence the water-hammer increases with depth.

Sound Speed in Gas-Liquid Mixtures

The water-hammer and line-packing effects were presented above. The third effect that makes up the Pressure-Pulse method is the propagation speed of a pressure pulse in the gas-liquid mixture flowing in a pipe.

The speed of sound in gas-liquid mixtures is much lower than the speed of sound in the individual phases. Experiments and model calculations for air-water mixtures flowing in pipes at near-atmospheric pressures were reported by Gudmundsson et al. (1992) and Dong and Gudmundsson (1993). The work showed that the speed of sound for void fraction in the range 0.2-0.8 was in the range 30-40 m/s for line pressure in the range 1.4-1.6 bara. The work showed also that a homogeneous speed of sound model gave a good match with the experimental results.

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

$$a = \frac{1}{A \times B}, \quad (3)$$

where

$$A = \left[\alpha\rho_G + (1-\alpha)\rho_L\right]^{0.5}, \quad (4)$$

$$B = \left[\left(\frac{\alpha}{\rho_G\, a_G^2}\right) + \left(\frac{1-\alpha}{\rho_L\, a_L^2}\right)\right]^{0.5}, \quad (5)$$

and α (-) the void fraction, and the subscripts G and L indicating gas and liquid, respectively. Experiments by Falk et al. (1999) and work reported by Nakoyakov et al. (1993) confirm the applicability of Wood's equation to the speed of sound in well mixed gas-liquid flows. Kieffer (1977) provides data and models for speed of sound in water-air and water-steam mixtures.

A computer program developed by Dong and Gudmundsson (1993) was used to estimate the speed of sound in the gas-oil mixture flowing at 60 bar and 90 bar in an offshore well on the Gullfaks B platform. The wellhead pressure was about 90 bar and the separator pressure about 60 bar. For two-phase mixtures the computer program gives the same result as the Wood equation. The results of the speed of sound calculations are shown in **Fig. 5** 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. The observation that the sound speed in gas-liquid mixtures is lower than the sound speed in either liquid-only or gas-only is important in the Pressure-Pulse method. It means that pipe distances of 5-15 can be used to determine the sound speed.

The speed of sound a (m/s) in gas-liquid mixtures depends on the wave frequency; the frequency f (Hz) of the pressure pulse (Karplus, 1958). High-frequency waves have greater speed than low-frequency waves. The frequency, the wavelength λ (m) and speed of sound are given by the relationship

$$a = \lambda \mathrm{f} \quad (6)$$

Higher-frequency waves disperse and attenuate rapidly in gas-liquid mixtures. The minimum wavelength in a 6 inches diameter pipeline will be about 5-times the pipe diameter; that is, about 0.75 m. For a sound speed of 150 m/s the maximum frequency will be about 200 Hz. This compares with 20-20,000 Hz for audible sound. The dominant frequency in low-pressure air-water flow in pipelines has been shown to be in the range 1-10 Hz (Dong and Gudmundsson 1993). Similar results were reported by Falk (1998). Therefore, pressure waves in gas-liquid flow are infrasonic (lower frequency than audible sound). General considerations say that waves will pass through structures if the wavelength is larger than the structure. If the structure is a bubble or a slug in gas-liquid flow, a pressure pulse needs to have a wavelength greater than the size of the bubble and slug to propagate through the gas-liquid flow.

Pressure-Pulse Metering

The Pressure-Pulse gas-liquid metering method was developed by Gudmundsson (1998) and has been described by Celius et al. (1999). The practical aspects of the Pressure-Pulse method are presented in Appendix A. The method is based on the combined effects of water-hammer and line-packing, plus the measurement of sound speed in the flowing gas-liquid mixture. The water-hammer is measured as indicted in Fig. 1 and the line-packing as indicated in Fig. 2.

The speed of sound in the Pressure-Pulse method can be measured using the set-up shown in **Fig. 3**. The figures shows two pressure transducers, A and B, and a quick-acting valve installed in a flowline down-stream of the wellhead of a production well. The pressures measured at the two pressure transducers are shown schematically in **Fig. 4**. Transducer A is located immediately up-stream of the quick-acting valve and transducer B at some known distance L_{AB} (m) further up-stream. The valve-generated pressure pulse will be detected first at transducer A and then later at transducer B.

The water-hammer pressure increase during the closing of the quick-acting valve and the line-pressure pressure gradient from up-stream of the valve are shown in Fig. 4. After a while the quick-acting valve is opened and the pressures measured at locations A and B fall back to their original value; that is, the well is back on-stream. The Pressure-Pulse cycle will take a few seconds. The water-hammer and the line-packing gradient can be measured directly from the Pressure-Pulse diagram in Fig. 4.

The measurement of the pressure pulses at A and B make it possible to obtain the sound speed in the gas-liquid mixture flowing in the pipe between the two locations. The pressure pulse travels up-stream through the gas-liquid mixture at the speed of sound, minus the flowing velocity. However, the flowing velocity u (m/s) is much smaller than the sound speed a (m/s). The pressure pulse travel time (time-of-flight) from A to B can be determined by several methods, including direct reading from the Pressure-Pulse diagram in Fig. 4. The cross-correlation of the two pulses can also be used to determine the time-of-flight.

A valve is termed quick-acting if it closes completely before pressure waves (pulses) are reflected from up-stream or down-stream. If a valve closes in 1 s and the sound speed is 150 m/s, reflections generated at distances greater than 75 m will not detected at the valve location. Near the end of the valve closing process the gas-liquid mixture velocity in the valve will approach the speed of sound and pressure reflections from down-stream to up-stream will be reduced. In general, when the down-stream pressure is 50% of the up-stream pressure, gas-liquid flow through a restriction (valve) will be choked.

The water-hammer effect and the sound speed in gas-liquid mixtures are reported in this paper. The line-packing effect is the subject of on-going testing on the Gullfaks B platform in the North Sea.

Mass and Volume Flow Rates

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

$$G = \rho \times u \quad (7)$$

where ρ (kg/m3) is the gas-liquid mixture density and u (m/s) the mixture average velocity. The mass flow rate m (kg/s) is given by the expression

$$m = G \times A \quad (8)$$

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

$$m = (\Delta p_a)\frac{A}{a} \quad (9)$$

The continuity principle dictates that the mass flow rate at the quick-acting valve is the same as the mass flow rate at other locations, including: downhole, separator and stock-tank. It means that the mass flow rate m (kg/s) measured in the Pressure-Pulse method is exactly the same as the mass flow rate entering a wellbore in the pay-zone.

Flow rates in the petroleum industry are traditionally expressed in volumetric flow rates. The formation volume factors of oil, gas and water are used to determine the volumetric flow rates at various pressures and temperatures. The mass flow rate of oil and the volumetric flow rate of oil are connected through the relationship

$$m_o = q_o \times \rho_o \quad (10)$$

The volumetric flow rate of oil is related to the formation volume factor B_o as follows

$$q_o(p,T) = q_o \times B_o(p,T) \quad (11)$$

where the symbols (p,T) indicate the effects of pressure and temperature; for example, from reservoir conditions to stock-tank conditions. If the symbols (p,T) are not used the variables refer to standard conditions. The density of oil is given by the relationship

$$\rho_o(p,T) = [\rho_o + \rho_g \times R_s(p,T)] \times [B_o(p,T)][B_o(p,T)]^{-1} \quad (12)$$

where $R_s(p,T)$ expresses the amount of dissolved gas at any pressure and temperature in terms of Sm3 gas per Sm3 of oil. The volumetric flow rate of gas is usually related to its formation volume factor B_g (p,T) as follows

$$q_g(p,T) = q_g \times B_g(p,T) = q_o[R - R_s(p,T)] \times B_g(p,T) \quad (13)$$

where R is the GOR (gas/oil ratio) of the oil at standard conditions.

Based on the above, the PVT-data required to determine the volumetric flow rate of oil at any pressure and temperature, including standard conditions, are $B_o(p,T)$, $B_g(p,T)$ and $R_s(p,T)$. These must be known only when the mass flow rate needs to be converted to volumetric rate. If the oil produced contains liquid water, the watercut WC (%) needs also to be known, and the formation volume factor of produced water.

Field Testing of Water-Hammer

Early field testing of the Pressure-Pulse method was on the Gullfaks A platform in the North Sea (Gudmundseth et al. 1995). An oil production well operating with a wellhead pressure in the range 130-140 bar and a wellhead temperature in the range 50-60 C was tested. The well had a constant watercut WC of about 7% and a gas/oil ratio GOR of about 114 Sm3/m3 during the testing period. Complete PVT-analyse was available of the oil produced. An off-the-shelf 0-200 bar pressure transducer was installed at the wellhead immediately up-stream of the wing-valve. The transducer operated at 1 kHz and was connected to a data acquisition system operating at 10 kHz maximum.

The field testing of the oil well on Gullfaks A was carried out by closing the wing-valve quickly and measuring the pressure increase at the wellhead. The down-stream process was not affected by the rapid shut-in of the production well. Six tests were carried out at two flow rates, at the conditions shown in **Table 1**. The wellhead pressure and temperature were 131 bar and 60 C for the higher flow rate (tests 1-3) and 138 bar and 51 C for the lower flow rate (tests 4-6). The flow rate q (m3/d) in Table 1 is the total flowrate (q_o + q_w + q_g) determined from test separator measurements.

The pressures measured at the wellhead in the Gullfaks B well for the six tests are shown in **Fig. 6.** Note that the initial pressures are 2-3 bar lower than the well-head pressures given in Table 1, representing the difference in pressure measured by other transducers at the actual well-head to the 0-200 bar pressure transducer used in the testing. The pressure before shut-in is given by the horizontal line, the water-hammer by the sudden pressure increase when the wing-valve was closed, and subsequently the gradually increasing line-packing pressure (gradient). Six pressure curves are shown in Fig. 6: three curves for the higher flow rate and three curves for the lower flow rate. Each set of the curves is practically identical, suggesting that Pressure-Pulse measurements are highly repeatable. The water-hammer pressures measured in the six tests are shown in Table 1.

The pressures in Fig. 6, exhibit the water-hammer and the line-packing, and terminate at a pressure in the range 144-145 bar. This pressure is the wellhead pressure after 10-20 seconds. The wing-valve could not be opened in the particular tests on Gullfaks A. Therefore, the sound speed in the flowing gas-liquid mixture could not be determined using cross-correlation.

For the six tests the mixture density and average flow velocity were estimated from the test separator measurements and PVT-data. The inner diameter of the pipe (well tubing up-stream of wing-valve) was 5-1/8 inch. The speed of sound in the oil-water-gas mixture at wellhead conditions was estimated assuming a homogeneous mixture as in Wood's equation (Dong and Gudmundsson 1993). The theoretical water-hammer pressures from Joukowsky's equation are shown in Table 1 along with the measured water-hammer pressures.

The water-hammer results in Table 1 are plotted in **Fig. 7** to compare the measured to the theoretical. The measured water-hammer values are lower than the theoretical values. On average, the measured values are 3.4% lower for the higher flow rates and 6.9% for the lower flow rates. A line parallel the 45-degrees line can be drawn to represent the measured water-hammer values (the percentage error decrease with increasing pressure values). This suggests that the measured values are systematically lower than the theoretical values. It should be borne in mind that the flow rate accuracy of test separators on offshore platforms is limited to 5-10%.

Field Testing of Sound Speed

In the Pressure-Pulse method the sound speed can be determined from cross-correlation of two pressure signals from locations A and B, as indicated in Fig. 4. Recent testing of the Pressure-Pulse method on the Gullfaks B platform has resulted in measurements that make this possible (Falk and Gudmundsson, 1999b).

An oil production well operating with a wellhead pressure of 64 bar, a separator pressure of 60 bar and a separator temperature of 55 C was tested. The well had a constant GOR (gas/oil ration) of 53.4 and a constant WOR (water/oil ratio), both at separator pressure. Complete PVT-analyse of the oil produced was available. The flow rates of the produced phases at standard conditions were 325 Sm3/d oil, 17,363 Sm3/d gas and 416 Sm3/d water.

A manually operated ball valve was placed about 10 m up-stream of the test separator and 85.2 m down-stream of the wellhead. The effective closing time and opening time were each about 0.5 s. Pressure transducers were placed up-stream of the ball valve at 1.85 m (transducer A) and the wellhead (transducer B). Therefore, the distance between the transducers was 83.35 m. Distances of 5-15 m are planned in practical Pressure-Pulse applications (see Appendix A). Off-the-shelf 0-200 bar pressure transducers for 1 kHz were used and connected to a data acquisition system operating at 50 kHz maximum.

The recording of the pressure signals at locations A and B lasted about 20 s, with a sampling frequency of 700 Hz. The flow was stabilised and the ball valve closed some seconds after registration (data acquisition) started and then opened about 10 s later. The time-of-flight of the pressure pulse was found from cross-correlation of the pressure signals at locations A and B. The signals were 50 Hz low-pass filtered before cross-correlation. The results from 8 tests are shown in **Table 2.** The mean (average) value of the sound speed was 170.2 m/s with a standard deviation of 3.6 m/s or 2.1%. The test demonstrated the feasibility of using cross-correlation to determined the sound speed.

Conclusions

- The speed of sound in gas-liquid mixtures is much lower than the sound speed in the individual components. The sound speed in homogeneous gas-liquid mixtures flowing in oil wells is described by Wood's equation. Sound speeds in the range 150-200 m/s are typical for production wells in the North Sea.
- The combined effects of water-hammer and line-packing and speed of sound make up the Pressure-Pulse multiphase metering method, for production and allocation testing. The water-hammer effect and sound speed have been tested. The line-packing effect is the subject of on-going tests on the Gullfaks B platform.
- The Pressure-Pulse method makes possible the measurement of mass flow rate of gas-liquid mixtures in wellbores and flowlines. The mass flow rate at the wellhead is the same as the mass flow rate at other locations. Volumetric flow rates can be calculated using PVT-data.
- The mass flow rate was tested offshore in one well at two rates, showing a good match between theoretical and measured water-hammer. The Pressure-Pulse method is highly repeatable.
- The speed of sound in the gas-liquid mixture flowing in one offshore oil well was tested, demonstrating the feasibility of using cross-correlation in such determinations.

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References

Celius, H.K., J.S. Gudmundsson and K. Korsan (1999): The Pressure-Pulse Method for Multi-Phase Metering, IBC Conf. Field Applications & New Technologies for Multiphase Metering, Aberdeen, February, 10 pp.

Dong, L. and Gudmundsson, J.S. (1993): Model for Sound Speed in Multiphase Mixtures, Proc. 3rd Lerkendal Petroleum Engineering Workshop, Norwegian Institute of Technology, Trondheim, 19-29.

Falk, K. (1998a): Experimental Work on Pressure Pulse Propagation in Horizontal Gas/Liquid Flow, Technical Report, Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology, Trondheim.

Falk, K. (1998b): Rapid Pressure Waves Through Gas-Liquid Flow in Wells and Pipelines, SPE 52060, EUROPEC, The Hague, 20-22 October, 7 pp.

Falk, K., Hervieu, E. and Gudmundsson, J.S. (1999): Pressure Pulse and Void Fraction Propagation in Two-Phase Flow: Experiments for Different Flow Regimes, Proc., 2nd International Symposium on Two-Phase Flow in Modelling and Experiments, May 23-26, Pisa, 8 pp.

Falk, K. and Gudmundsson, J.S. (1999a): Pressure Pulse in Multiphase Wells: Offshore Testing and Modelling, 9th International Conference Multiphase-99, Cannes, 16-18 June, 10 pp.

Falk, K. and Gudmundsson, J.S. (199b): Multiphase Pressure Pulses for Quick-Acting Valves: Offshore Testing, SPE 56525, Annual Technical Conference and Exhibition, Houston, 3-8 October, 11 pp.

Fox, J.S. (1989): Transient Flow in Pipes, Open Channels and Sewers, Ellis Horwood Limited.

Gudmundseth, U., Gimmestad, O. and Gudmundsson, J.S. (1995): Pressure Pulse 95 – Offshore Gas/Liquid Metering, Technical Report, Department of Petroleum Engineering and Applied Geophysics, Norwegian Institute of Technology, Trondheim.

Gudmundsson, J.S. (1998): Method for Determination of Flow Rate in a Fluid, U.S. Patent No. 5,741,978.

Gudmundsson, J.S., Dong, L. and Rødøy, F. (1992): Two-Phase Flow Metering by Pressure Pulse Propagation, SPE 24778, 67th Annual Technical Conference and Exhibition, Washington, D.C., October 4-7, 10 pp.

Karplus, H.B. (1958): The Velocity of Sound in a Liquid Containing Gas Bubbles, U.S. Atomic Energy Commission, Technical Report COO-248, 22 pp.

Kieffer, S.W. (1977): Sound Speed in Liquid-Gas Mixtures: Water-Air and Water-Steam, J. Geophysical Research, Vol. 82, No. 20, 2895-2904.

Thorley, A.R.D. (1991): Fluid Transients in Pipeline Systems, P. & L. George Ltd.

Watters, G.Z. (1984): Analysis and Control of Unsteady Flow in Pipelines, Butterworths.

Wood, A.B. (1941): A Textbook of Sound, G. Bell and Sons.

Wylie, E.B. and Streeter, V.L. (1993): Fluid Transients in Systems, Prentice-Hall.

Appendix A – Pressure-Pulse in Practice

Applications. Important applications of the Pressure-Pulse method are production and allocation testing, flow rate measurements in general in wells, flowlines and pipelines. Pressure-pulse measurements can be useful in gas lift optimisation activities.

Mass rate. The mass flow rate is determined with an accuracy comparable with test separator readings, and with good reproducibility. The mass rate may in some cases be sufficient information to allocate production to wells and manifold flowlines. In combination with other information, for example wellhead and bottomhole pressure and temperature, the mass rate is used to determine the well stream composition through model calculations.

Line packing. The line packing contains information about friction and compressibility in the flowing stream. Such information is used to estimate the average density and volumetric flow rate of the stream. When water-cut is known, this will give the characterisation of the phases. Combined with PVT-data (model) and a wellflow model, a more detailed assessment of the stream composition is obtained.

Operation. A quick-acting valve is closed in 2-4 seconds and kept closed for 4-8 seconds and reopened (whole cycle, 8-16 seconds). The pressure increase will be in the range 2-6 bar. Because of the small pressure increase and short duration, neither well inflow nor down-stream process conditions are disturbed.

Equipment. The Pressure-Pulse method requires one quick-acting valve and 2-3 pressure transducers (depending on configuration, up-stream or down-stream sound speed). A pipe section length of 5-15 m between the transducers is used. Standard valves and transducers are used and mounted directly on the pipe.

Operating envelope. The Pressure-Pulse method has been tested for in-situ void fractions in the range 0.15-0.50. It is expected that accuracy will also be acceptable at higher void fractions. The method is suitable for all pipe diameters. Flow rate and pipe diameter together determine the operating envelope.

References. The Pressure-Pulse method has been tested on one well on Oseberg B, one well on Gullfaks A and several wells on Gullfaks B.

Table 1 – Comparison of theoretical and measured water-hammer at wellhead conditions from field testing on Gullfaks A. Flow rate, mixture density and mixture average flow velocity based on PVT-data and test separator measurements. Sound speed estimated from Wood's equation (Dong and Gudmundsson 1993). Pipe diameter 5-1/8 inch.

Test No	WHP bar	WHT C	Total Flow Rate m3/d	Mixture Density kg/m3	Flow Velocity m/s	Sound Speed m/s	Water-hammer Theoretical bar	Measured bar
1	131	60	3820	595	3.32	268	5.30	5.22
2	131	60	3868	596	3.36	268	5.37	5.11
3	131	60	3800	602	3.30	268	5.32	5.15
4	138	51	2532	623	2.20	285	3.90	3.67
5	138	51	2571	620	2.23	285	3.94	3.66
6	138	51	2555	623	2.22	285	3.94	3.65

Table 2 - Sound speed values obtained on Gullfaks B from pressure transducer spacing of 83.35 m (from ball valve to wellhead). Pressure signal 50 Hz low-pass filtered before cross-correlation (Falk and Gudmundsson 1999b).

Test No.	Sound Speed m/s
1	166.7
2	166.7
3	172.1
4	166.2
5	171.1
6	177.9
7	170.6
8	170.1
Average	170.2

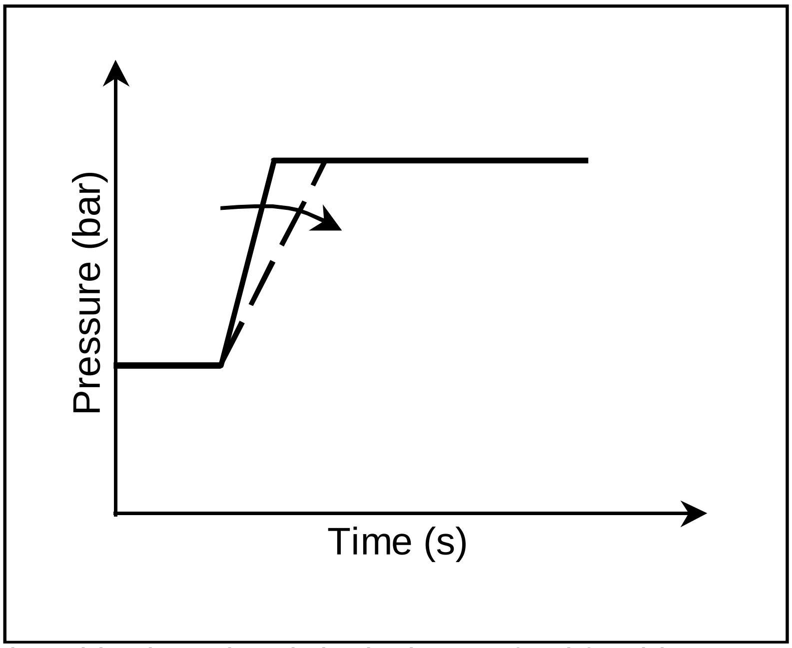

Fig. 1 – Water-hammer measured on quick-acting a valve. Closing time increases from left-to-right.

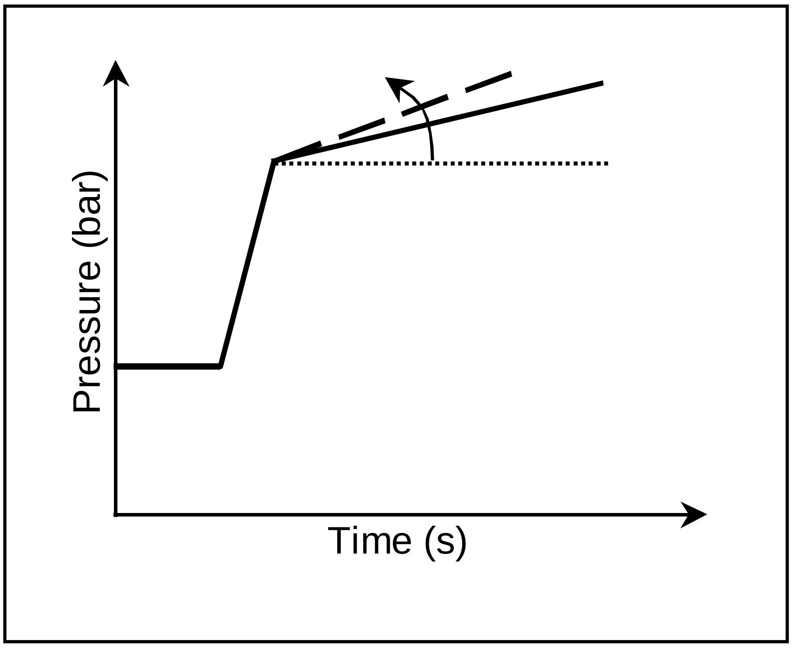

Fig. 2 – Line-packing measured after the closing of a quick-acting valve. Line-packing increases upwards.

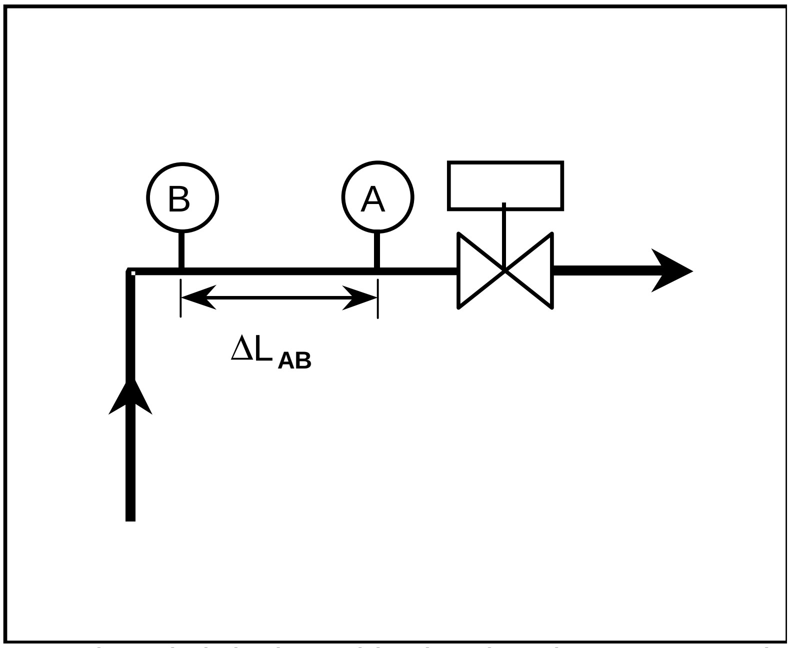

Fig. 3 – Simple set-up for the Pressure-Pulse method, showing a quick-acting valve and two pressure transducers up-stream.

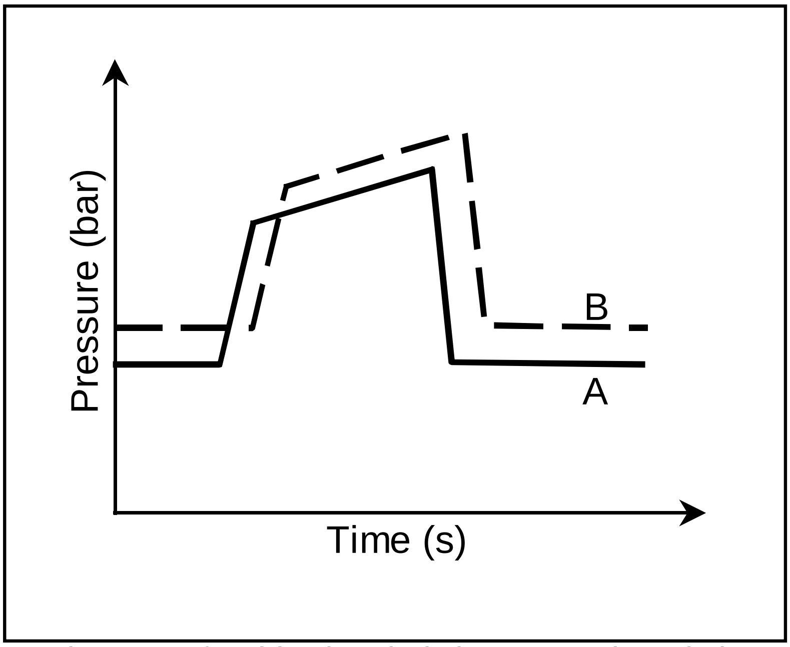

Fig. 4 – Two pulses, A and B, measured up-stream of a quick-acting valve in the Pressure-Pulse method.

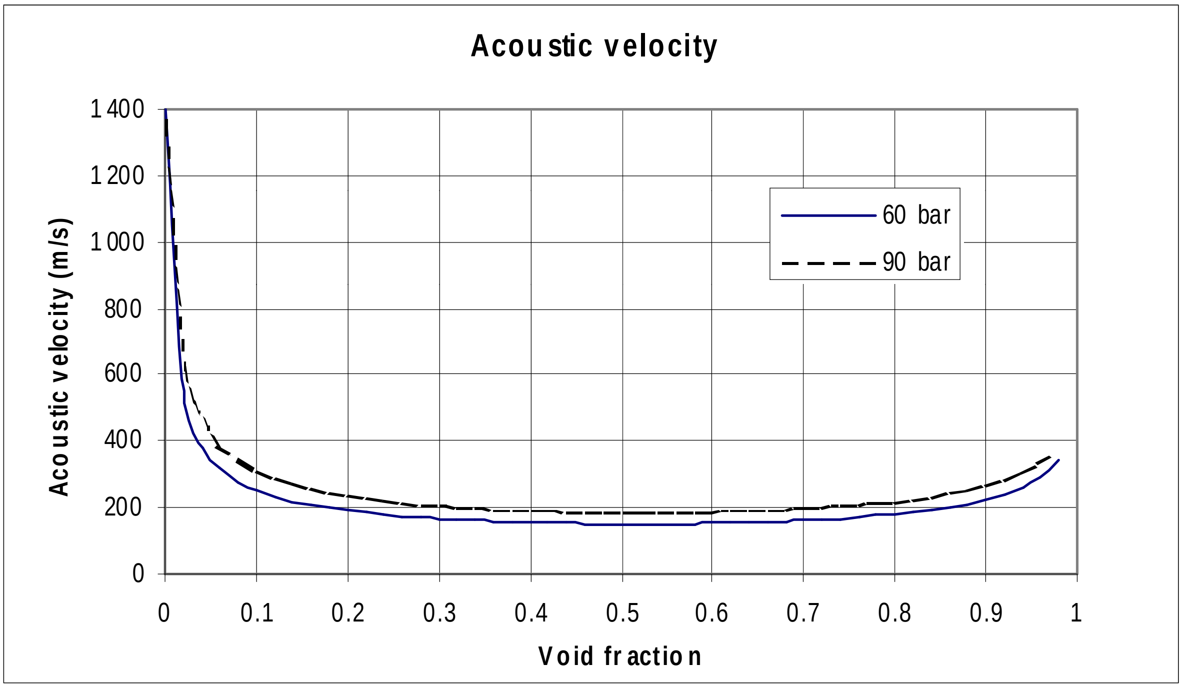

Fig. 5 – Speed of sound in gas-oil mixture at 60 and 90 bar. Calculated from Wood's model for homogeneous mixtures and assuming PVT-properties typical for North Sea wells.

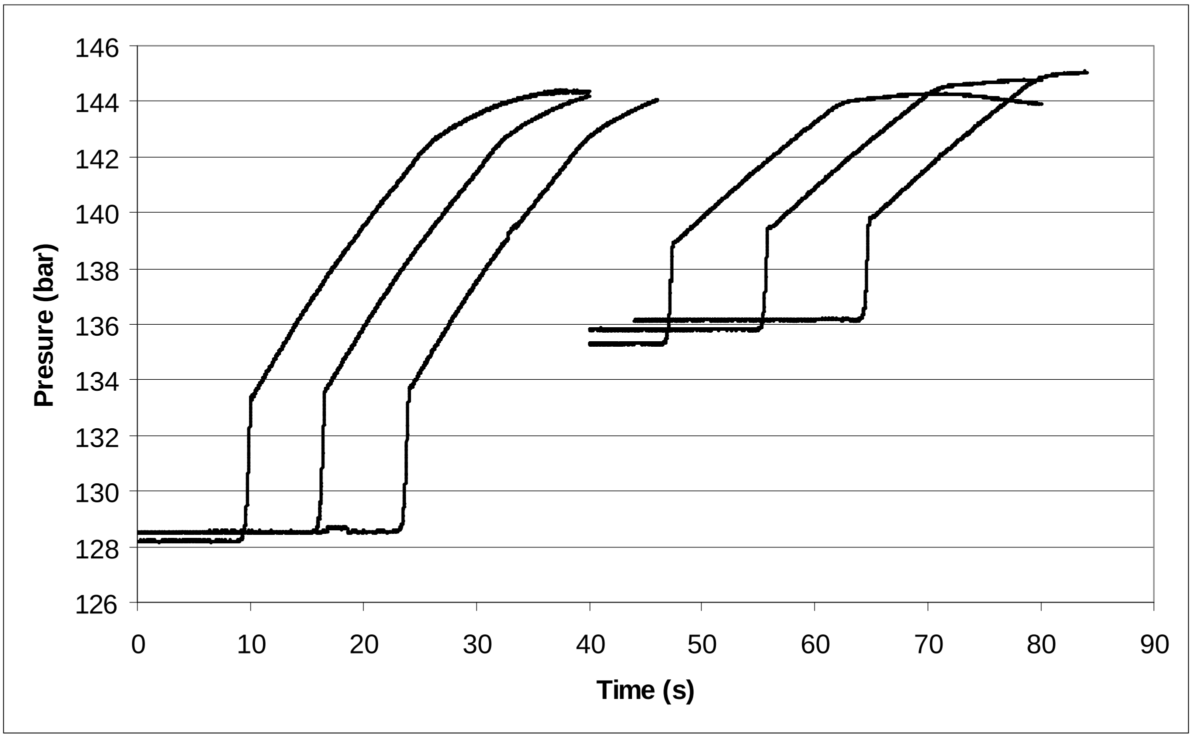

Fig. 6 – Pressure vs. time for Pressure-Pulse tests on Gullfaks A to test the water-hammer effect.

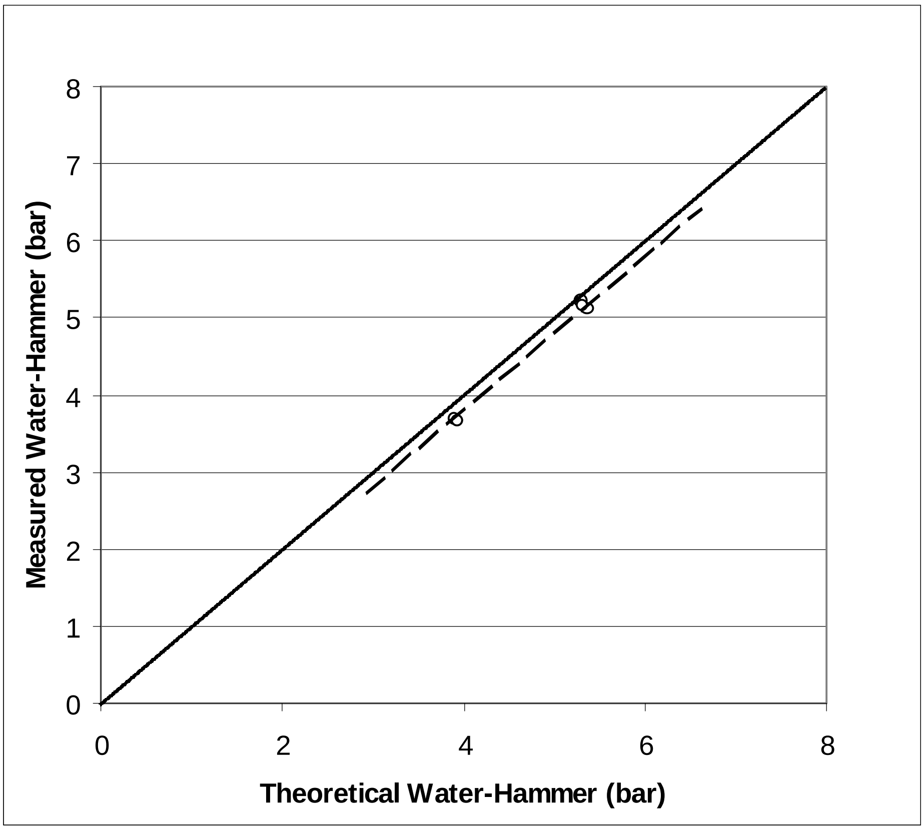

Fig. 7 – Theoretical and measured water-hammer for Pressure-Pulse tests on Gullfaks A.

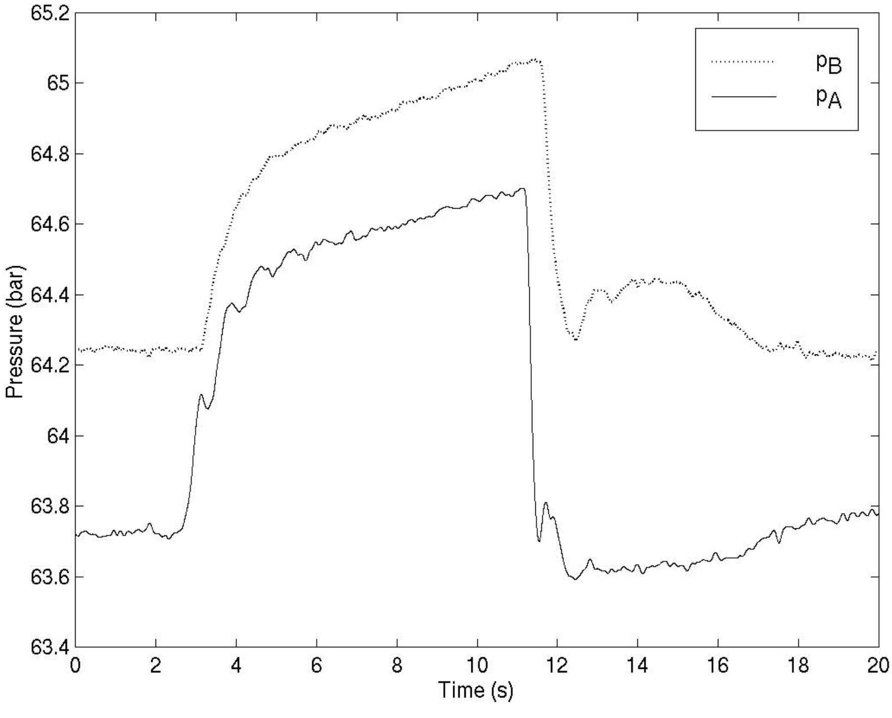

Fig. 8 – Pressure-Pulse measurements at locations A and B spaced 83.35 m up-stream a quick-acting valve. The speed of sound was estimated 170 m/s from cross-correlation.