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An Overview of Non-Invasive Flow Measurements Methods

Dick Whitson TUV NEL

Gordon Stobie Conoco Phillips

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Richard J. Whitson, TUV NEL Ltd
Gordon J. Stobie, ConocoPhillips Inc.

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1 INTRODUCTION

Many companies in a wide range of industry sectors have a major investment in process plant and a need to meter flowrate of the process fluid. Various forms of new non-invasive flow metering technologies are available, i.e. ones that can be applied from outside of a pipe without the need to break into the pipe. Whether there is a need to replace or update existing flow meters, replace obsolete metering technologies or a simple desire to avoid contamination or loss of expensive or hazardous fluid, metering techniques based on non-invasive methods are of wide interest.

Although flow measurement is the primary subject of this paper, the content also covers non-invasive techniques that do not actually measure flow but provide supplementary information related to the flow or condition of the process fluid.

Flow and flow-related non-invasive techniques generally fall into one of five categories:

- *Ultrasonic*
- Sonar
- Nucleonic
- Acoustic
- ECT Tomography

These non-invasive techniques can be used either individually or in combination. This opens up the possibility of retrofit to existing plant, which may have seen a "change of use" or a change in process conditions, to extend its useful life without the costs associated with invasive removal and replacement of old or outdated meters or other sensors. Non-invasive flow metering technologies also offer the potential as a tool for field checking or verification of the performance of embedded meters.

The paper reviews these technologies and how they are, or could be, applied in practice. The paper is in essence a summary of background work [1] and thinking that lead to the formulation of the TUV NEL "NIFM" Joint Industry Project [2].

In addition to the above technologies, non-invasive measurement of temperature is also covered.

2 GENERAL PRINCIPLES OF OPERATION

2.1 Ultrasonic Devices

These fall into two areas: Ultrasonic flow meters and Pulse-echo units.

2.1.1 Ultrasonic Flow Meters

Clamp-on ultrasonic flowmeters (USFM) are now common in many industrial fields and are by far the most common form in the ultrasonic category. Consequently, only a basic overview of the general principles will be provided here since there are many readily available texts on the subject.

In the simplest terms, ultrasonic flowmeters work on the basic approach of inputting a beam of ultrasonic energy (i.e. where the frequency is greater than 20 kHz) into the fluid from one transducer (the transmitter or emitter) and detecting that signal at a second transducer (the receiver) once the signal has travelled through the fluid inside the pipe. Most commonly the emitter and receiver are built into the same sensor and hence the ultrasonic transducer is often referred to as a transceiver since it can emit and detect signals.

The basis of the clamp-on ultrasonic approach, Fig.1, is that the transducers are attached to the outside of the pipe wall and the beam must pass through the wall before it enters the fluid and then back through the wall before it can be detected. A sonic coupling compound, gel or material is often used between the transducer and the pipe wall to improve the transmission and reception of the pulse and also to make the installation more repeatable. Due to systematic errors introduced in the positioning and mounting of the transducers, clamp-on arrangements are often supplied with a mounting gauge or clamping bar to ensure that transducers are located in the correct position.

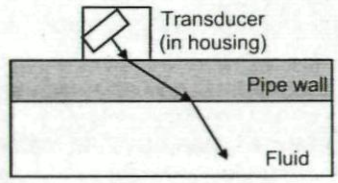


Fig.1 – Clamp-on arrangement

For permanent locations, transducer mounting blocks can be welded to the pipe wall rather than simply clamped to provide a more secure installation.

The acoustic-impedance (i.e. density times speed of sound) of the transducer, coupler, pipe wall and fluid all affect how much signal gets into the fluid and the angle at which it propagates. As a result of the impedance mismatch between steel pipe walls and gaseous fluids, up to a few years ago clamp-on transducers were more commonly used for liquid flow measurement since less powerful transceivers are required. Clamp-on transducers for gaseous systems are now also available but can be subject to a lower limiting pressure due to these impedance matching effects.

Measuring under extreme temperatures (+400°C to -200°C), can be achieved by using transducers that are mounted at a distance back from the pipe using either thin-plate wave-guides (or "hockey-sticks") or BWT (bundled wave technology) buffers. This results in only a slight loss in signal amplitude. Flexim's WaveInjector® is based on the wave-guide principle, Fig.2, and comes in two variants that use different forms of coupling methods (either gel or metal tape) depending on the operating temperature region. A conventional coupling gel is used to couple the sensors to the special waveguide plates.

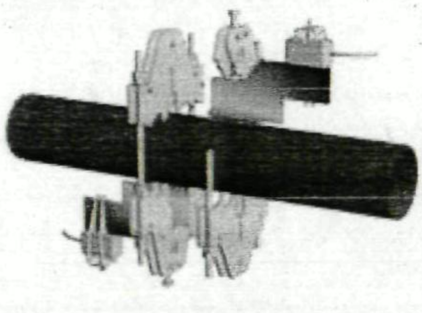


Fig.2 - Flexim's WaveInjector

Meters and sensors provided by different manufacturers have different capabilities and different types of diagnostic routines but are generally of a single-path design although some have 2-paths.

Clamp-on ultrasonic devices are most commonly used in single-path arrangements to give a basic measurement of flow but could be used in multi-path groups to improve the accuracy. This is a topic that is the subject of ongoing research at TUV NEL and other organisations.

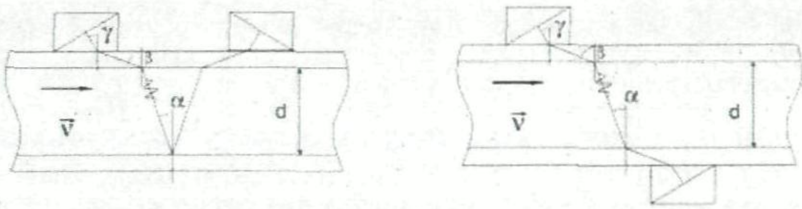
Many meters will only achieve optimum accuracy (<1%) if used in conjunction with a flow conditioner to force a flat, turbulent flow profile. However, that is not always possible in practice so general accuracy of single-path units is of the order of ± 3%.

Development work is still ongoing on clamp-on technology not only in the areas of sensor design, signal type and signal processing methods but also to extend its range of applications.

Generally one of two basic methods are used to derive the flowrate of the fluid: the **Time–of-Flight** (TOF) approach and the **Doppler** approach. A few meters use a combination of TOF and Doppler or other methods and are consequently classed as hybrid meters.

Time-of-Flight (TOF) or Transit-Time (TT) method

This is the most common method used by clamp-on ultrasonic meters. The beam of ultrasonic noise is projected at an angle across the pipe, Fig.3, and the flight time of the signal between the two transducers is related to the velocity of the fluid and the speed of sound of the fluid. Rather than use only the transit time from the upstream to the downstream transducer, the roles of the transducers is then reversed (i.e. the emitter becomes the receiver and visa-versa) and the transit time from downstream to upstream is also obtained. This allows the fluid velocity to be calculated independently of the fluid speed of sound (assuming constant conditions).



a) Reflection path b) Direct path
Fig.3 - Basic TOF clamp-on arrangement

Transducers can be arranged in a "reflection" (bounce) configuration, Fig.3a), where sensors are mounted on the same side of the pipe and the signal is reflected off the opposite wall, or in a "direct" configuration, Fig.3b), where sensors are mounted on opposite pipe walls. Bounce configurations are more common in small pipes and direct configurations in large diameter pipe.

Once the flow velocity has been calculated the transit-time equations can be applied to calculate a value for the fluid speed of sound which may then be used as a form of check, or diagnostic, on the meter's function since the value should be in agreement with an expected value derived from assumed or known fluid properties. Although many meters use the speed of sound in internal diagnostic routines, the value is not always available to the meter user.

The flow velocity is an average value across the path taken by the beam. A Reynolds Number based "profile correction factor" is applied to this on the assumption that the flow profile is either reasonably flat for turbulent flow or parabolic for laminar flow. Most flow manufacturers derive their own flow profile correction factors and this is one factor that can give rise to differences in the measurement accuracy of different makes of meter and their susceptibility to non-ideal flow conditions. As with many other forms of flowmeter, operation in a transitional flow region is particularly problematic since there will be doubt as to the actual profile correction required.

Since particles (either solids or bubbles) in the flow can attenuate and disperse the beam, the method works best in clean, single phase fluid where the beam path lengths are well known (from pipe and transducer geometry). Some modern TOF meters are now capable of measuring dirty liquids due to improvements or enhancements in the software methods used.

Under ideal flow profile conditions, accuracy of single path clamp-on USFM can be better than 1% but generally under realistic conditions, taking account of repeatability on sensor locations, imprecise pipe size (or pipe condition) and proximity of bends, they are typically no better than 5%.

Doppler Shift Method

In a Doppler based system, Fig.4, the projected ultrasonic beam is bounced off "particles" in the flow and the receiver detects the reflected beam with a frequency shift that can be related by a linear function to the flow velocity.

The linearity constant is itself a function of the speed of sound in the fluid, the emitted frequency and the beam angle.

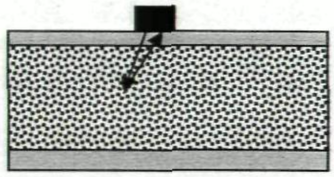


Fig.4 – Doppler method

To operate effectively the fluid has to contain sufficient concentration of "particles" to reflect the beam in order that a frequency shift can be detected. In liquids the liquid has to have at least 25 ppm of 30 micron or larger particles (for a 1 MHz beam) to operate but this concentration size ratio is dependent on the beam frequency: lower frequencies require greater concentrations and larger particle size. Some modern high frequency medical Doppler units (running at 8 MHz) have such a short wavelength to be able to reflect off flow eddies.

Doppler meters are used primarily for liquids and are common in paper making and industries handling slurries. Industrial units typically operate in the 1 to 2 MHz range and have a fixed beam so it is not possible to be certain which part of the flow is being measured. This limits their accuracy to typically 2% at best even under ideal conditions.

2.1.2 Pulse Echo Method

These use ultrasonic transceivers similar to those used for clamp-on USFM but in a simpler configuration, Fig.5. They project a beam of ultrasonic energy at right-angles into the pipe and measure the time delay of the reflected beam, i.e. the echo, received back at the transceiver. They are most commonly used to measure wall thickness based on a known, or assumed, speed of sound in the pipe wall material.

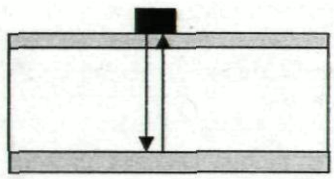


Fig.5 – Pulse-echo arrangement

With suitable transducers and signal detection software the method can be used to measure interface level if the speed of sound in the fluid is also known. Conversely, if the diameter or reflection positions are known with some confidence, the speed of sound in the fluid or pipe wall can be measured. Discrimination of level in nearly-full or nearly-empty conditions are however difficult to achieve since the reflection from the interface is too close to a wall reflection.

2.2 Sonar Based Methods

These use an array of passive sensors distributed axially along a pipe to listen to, characterise and interpret naturally occurring pressure fields (e.g. vortices or pressure-ripple), that propagate in process piping. The array signal processing methods at the heart of these devices use techniques similar to beam-forming applications developed over several decades for underwater sonar-based navigation hence the term "Sonar". The methods generally use the 100-1500 Hz frequency region. The techniques were originally introduced into the oil and gas industry in 1998 for use in downhole multiphase flow metering but are also applicable to single phase flows.

Two different forms of signal manipulation can be used.

Sonar-based **"convective"** flow measurement involves characterising the speed at which coherent vortical structures flow past the axial array of sensors on the pipe wall. The sensors can be any pressure or strain-based sensor. These coherent structures are inherent features of the turbulent boundary layer. The signal processing algorithms are used to generate a "k-ω" plot, Fig.6, to obtain the slope of a "convective ridge" since this can be related to the flow velocity via a Reynolds Number based calibration process. The convective approach is claimed to suit liquid and liquid-continuous single and multiphase applications.

K-ω plot showing Convective Ridge

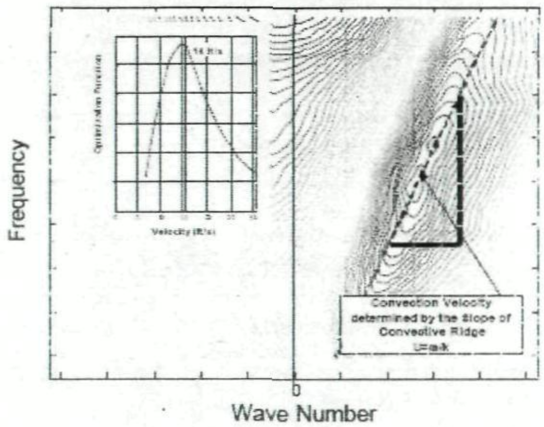


Fig.6 - Convective flow ridge

Sonar-based **"acoustic"** flow measurement is based on comparing the speed at which ambient sound waves propagate with the flow to those propagating against the flow. This method is well suited to applications where the average flow velocity is an appreciable fraction of the speed of sound of the fluid at rest: otherwise the velocity difference (with and against the flow) is too small to resolve. The signal processing algorithms are used again to generate a k-ω plot but this time to identify "acoustic" ridges, Fig.7, for sound travelling with and against the flow. The gradient of these ridges is related to the velocity; hence the speed of sound and the volume flow velocity can be derived. The approach is claimed to be suited to gas and steam applications with Mach numbers in the 0.1 region. Even if the flow is stationary, or very low, the "acoustic" method can be used to measure the velocity of sound in the fluid but only if there is a source of noise, e.g. pressure-ripple, in the system.

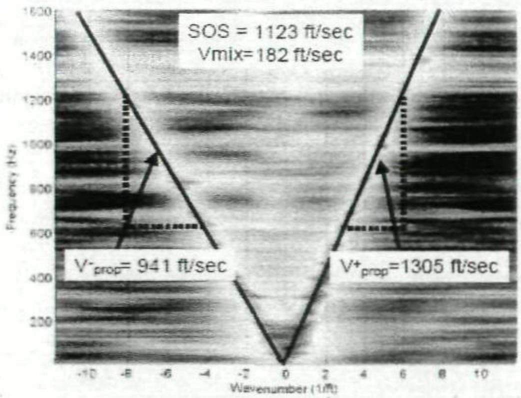


Fig.7 - Acoustic ridges

2.3 Nucleonic Methods

This is a general heading that more correctly describes the type of source/sensor used rather than the actual way in which the signals are processed. Nucleonic is the general term now more commonly used to refer to use of radioactive or gamma-ray sources.

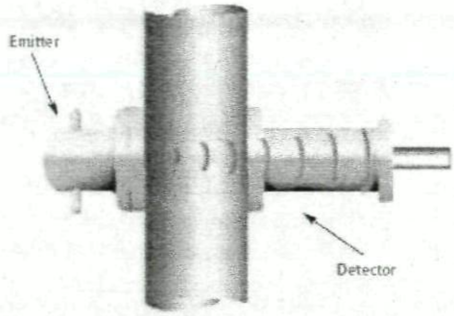


Fig.8 - Gamma-ray setup

The fundamental principle these rely on is the fact that, above a certain energy, gamma-ray absorption depends mainly on the density of the intervening material between an emitter and a detector sited at opposite sides of a pipe, Fig.8. Since the Gamma-ray source, e.g. Caesium-137, ^{137}Cs, or Americium-241, ^{241}Am, has a very long half-life (30 years in the case of ^{137}Cs, 430 years for ^{241}Am) it can be considered as a stable, constant strength source so any deviation in the strength of the detected signal will be due to density changes in the medium itself. Use of a dual energy gamma source, for example ^{137}Cs at 662 keV and ^{241}Am at 60 keV, provides finer discrimination of the density variations.

A density to intensity relationship is established during calibration of the particular device using reference fluids and known pipe wall thicknesses. If the fluid properties change, the meter generally has to be re-calibrated [3].

How that density variation is subsequently used depends on the actual commercial meter and examples are discussed in Section 3.4.

2.4 Acoustic Methods

These involve passive listening to the noise generated in a system and to then relate patterns or features in the frequency spectrum to the flow rate.

Certain devices are based on listening to noise created by pressure reduction devices (e.g. a valve) and to then use pattern recognition techniques (see Section 2.6.2) to relate features in the noise frequency spectrum to the flow rate.

Acoustic emission (AE) is a technique originally applied in the field of Non-Destructive-Testing of materials. It relies on passively listening for the high frequencies (10 kHz – 2 MHz) generated when materials crack or break or when particles strike or rub against walls, i.e. where there is some friction. Apart from structural assessment, AE methods are applied in the process industry to measure sand content, for leak detection and for flow measurement. The method is commonly used for slurry mixes or fluid with hard particulates, e.g. sand, where if the flowrate is known the slurry mixture can be derived from the particle impact signals. Sensors are commonly mounted on bends or at points in the system where particle impact is most likely but can be mounted on straight pipe lengths. Flowrate could possibly be obtained by cross-correlating signals from two detectors [4].

2.5 Tomography

Tomography is defined as "imaging by sections". It is a technique that relies on the measurement of some parameter between sensors arranged around the perimeter of a pipe, Fig.9, to provide information or an image, a tomogram, of the spatial distribution of the pipe contents [5]. The process involves applying a signal to each sensor in turn and monitoring the received signal at all of the other sensors. Tomographs can consist of a series of slices at different positions, or "planes", along a pipe but to do this requires separate banks of sensors at each plane.

Once a complete scan of the entire set of sensors has been carried out at a given plane, the data is processed to provide a tomogram of the contents. The rate at which a scan of the section can be performed depends on the number of sensors, 8 or 16 are typical, the speed of the data capture system and the complexity of the processing algorithms used to generate the image. The image resolution on the tomogram is dictated by the number of sensors used and by the processing algorithms used.

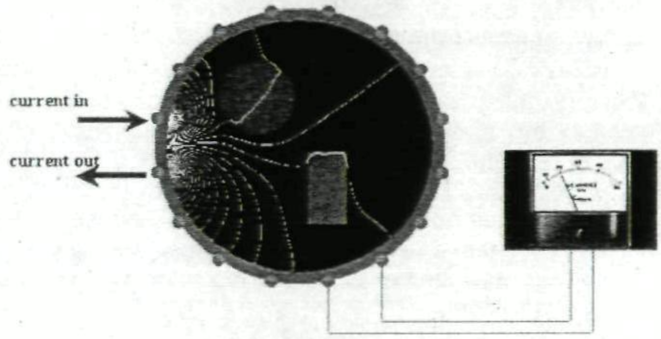


Fig.9 - Tomograph Layout

In the context of this study, tomography is generally applied in multi-phase flows and the general name given to the field is "Industrial Process Tomography".

Individual tomographic techniques usually take their names from the parameter being measured, which in turn is related to some physical property of the material being measured. For example, in Electrical Capacitance Tomography (ECT), [6] the property is capacitance and relies on the difference in electrical permittivity of the fluids. In Electrical Resistance Tomography (ERT) it is electrical resistance, in Electrical Impedance Tomography (EIT) it is impedance, in Electromagnetic Tomography (EMT) it is the magnetic field, in Magnetic Resonance Tomography (MRT), or Magnetic Resonance Imaging (MRI), it is magnetic resonance.

ECT, ERT and EMT are more commonly encountered in industry whereas MRT and MRI are more commonly applied in the medical field for scanning of soft tissue. There are many other forms of tomography used in a wide range of industrial sectors.

One important feature of ECT, EIT and EMT is that the fluid must be a dielectric. If the pipe walls are electrically conducting then sensors need to be wetted and electrically isolated from the pipe wall. However if the pipe walls are non-conducting the technique can be non-invasive hence its relevance to this study.

2.6 Processing Methods

Quite separate from the underlying technologies described above, one of a number of common methods are frequently employed to process the measured data.

2.6.1 Cross-Correlation Methods

These use the mathematical cross-correlation of two or more signals from sensors separated a distance apart, typically 0.5 D to 1 D, to identify a time delay, Fig.10, which can then be related to the average flowrate. Devices can either be Active or Passive.

Active devices work by detecting modulation changes caused by particulate material, gas bubbles or turbulence in the flow between two beams.

Passive devices work by listening to the flow generated noise in a system and mathematically cross-correlating the signals at a number of sensor locations along the length of a system.

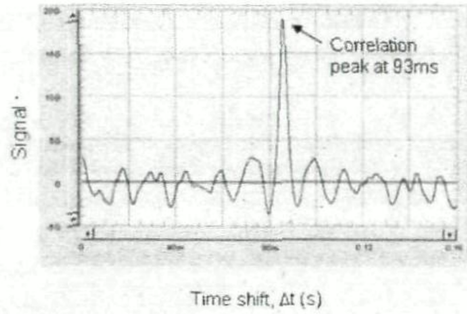


Fig.10 - Cross-correlation example

2.6.2 Pattern Recognition Methods

One form of this technique is based on identifying common flow patterns between signals from different sensors arranged along a system that relate to time delays between sensors caused by the flow velocity. In this form the technique is applied to the timing difference between sensors being based on an entire flow-pattern across a pipe section rather than simply the signal from a single sensor path as described in Section 2.6.1.

In another variation of pattern recognition, a single sensor detects the noise at a location in the system and uses a knowledge based approach to compare a measured "finger-print" against one in its database and thereby infer the flowrate. Here the pattern that is being sought is in the frequency spectrum of the in-pipe noise. Some training of the meter is required to establish the useful flow-to-pattern relationships.

2.6.3 Digital Signal Processing (DSP) Methods

This is a general term applied in many manufacturer's product information to live or post-processing of the signals to improve the signal to noise ratio. The transducer signals are captured and digitised, allowing computers to then perform advanced filtering or signal processing of the data. DSP techniques have become more widely available due to the rapid increase in computing power seen over recent years. In some contexts, DSP appears to be based on signal averaging but in others it is not clear exactly what manipulation of the data is taking place. This lack of clarity in product literature is thought to be intentional since the exact methods are generally subject to intellectual property right, patent or copyright.

3 EXAMPLES OF COMMERCIALLY AVAILABLE DEVICES

This section is not intended to be an exhaustive list of all commercially available devices but simply a series of examples of the more common commercial meters.

3.1 Ultrasonic Meters for Liquids

Siemens, Endress+Hauser, Krohne, GE Sensing, Ultraflux, Flexim/Katronic/Yokagawa, Polysonic, and many others offer clamp-on meters for liquid service use. The key features of the more common models will be discussed but only in sufficient detail to give the reader an appreciation of the similarities and differences between models. Manufacturers claim different levels of accuracy but generally this is in the ± 1% to ± 3% range: this is typical for a single-path USFM.

3.1.1 Siemens FUS1010 Meter

Siemens offer clamp-on ultrasonic meters that employ their trade marked "WideBeam" technology. The transducers supplied generate compression waves which generate a resonating wave in the pipe wall. This has the claimed advantage of generating a wider ultrasonic beam which is less susceptible to changes in fluid sonic velocity. It is also claimed that WideBeam technology is more tolerant of entrained solids and gases in the flowing medium.

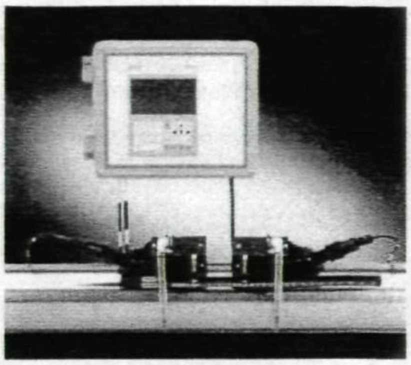


Fig.11 – Siemens FUS1010

The FUS1010, Fig.11, is a standard clamp-on system and can be supplied with up to 4 paths. Also available is a modified version, the 1010S, which uses clamp-on transducers installed on a spool piece in the factory. Other variants are available.

3.1.2 Endress+Hauser's Prosonic Flow Meters

Endress+Hauser offer a range of clamp-on ultrasonic liquid-flow measurement systems for pipe sizes up to 3000 mm in diameter. The principle transmitter model is the Prosonic Flow 93 which can operate with two measurement paths although other versions such as the 91W and the portable battery operated 92U/W are also available as portable measurement units on water-based flows. A range of transducers is available including standard, extended temperature range and a miniature version for small pipe diameters. Accessories include a pipe wall thickness sensor and a velocity of sound measurement system for unknown liquids.

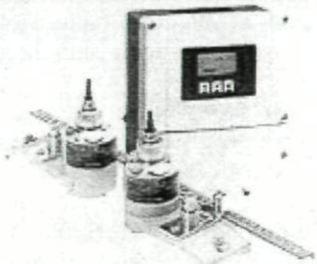


Fig.12 – Prosonic Flow 93P

3.1.3 Krohne's UFM 610P and Optisonic 6300 Meters

Krohne offer two types of clamp-on meter for liquid service, each built around a single transducer pair and working on the Transit-Time principle. The UFM 610P, Fig.13, is a portable device which can operate in either single traverse or in reflected path mode and has a claimed measuring error of better than ±2% of reading. A relatively recent addition to the range is the Optisonic 6300 series and UFC300 controller which comes in a range of detector sizes to suit pipe sizes in the 2"-160" range. The 6300 series offer continuous measurement of the velocity of sound in addition to flowrate and other diagnostic parameters.

Similar units for welding on to metal pipelines (UFM 800W) or building onto open channels (UFM 800C) are also marketed.

Fig.13 - Krone UFM 610P

3.1.4 GE Sensing's P878 Meter

Many of GE Sensing's ultrasonic meters are available in a clamp-on version, often for fixed installation. The PT878 however, Fig.14, is a portable battery-powered version, operating on the transit time principle + DSP correlation. It is supplied with a wall thickness gauge in the form of a hand held transducer which uses the pulse–echo method to locate the inner surface of the pipe.

Fig.14 – P878

3.1.5 Ultraflux UF and Minisonic Meters

The Ultraflux UF family of ultrasonic flowmeters accommodates a range of clamp-on and wetted transducers. In the clamp-on versions, two cross-path diametric planes may be used.

A miniaturised range, Fig.15, with updated electronics and portable versions with similar specification (the Minisonic P and DigisonicE+) are also available.

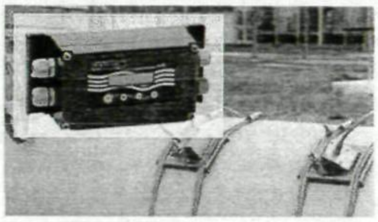


Fig.15 – Minisonic 600/2000

3.1.6 Other Meters for Liquids

A number of other manufacturers provide clamp-on meters for liquids. Brief details of the more interesting features of certain of these are:

- EESIFLO's "sonalok" range covers a number of types of portable meter, some working on the Transit-Time method, some on Doppler and some offering a dual mode (Doppler and transit-time) capability. Their hand-held "EASZ" model in addition to providing flowrate has a separate probe for measurement of pipe wall thickness and the velocity of sound in the fluid that looks to be based on the pulse-echo method.

- Thermo Fisher Scientific Group's Polysonics DCT7088 is a portable flowmeter that is based on the Transit-Time method but enhanced by a Digital Signal Processing (DSP) method in combination with correlation detection methods. The meter claims to have the highest flow range of any portable ultrasonic flowmeter (0-15 m/s) and an accuracy of ± 0.5%.

- Katronics/FLEXIM produce a number of flowmeters (FLEXIM being the original equipment manufacturer). Their FLUXUS ADM 6725 model is a portable dual mode flowmeter based on the Transit-Time method and a trademark "NoiseTrek" method that is based on evaluation of frequency and phase shift information in the ultrasonic signals but also appears to be a variant of the Doppler method. Their FLUXUS KAT220 model includes options for various added features such as wall thickness measurement and multiple channels.

- Preso® produce a number of sizes of "ThermoTrack" meter targeted at energy flow monitoring in water pipes in commercial and industrial buildings. Here a clamp-on Time-of-flight ultrasonic meter is used in combination with clamp-on temperature measurement to compute the heat-flow. Meters can operate singly but can also be integrated into a large network of up to 128 meters to monitor energy flow throughout a system. In 2005 Preso® introduced a new compact clamp-on USFM primarily aimed at the domestic water industry for pipes in the 12 mm to 50 mm size (but can measure on pipes up to 3m diameter). These come with the flow computer integral with the sensors to make a very compact clamp-on arrangement.

3.2 *Ultrasonic Meters for Gas*

Four main companies currently provide gas clamp-on meters; Siemens, GE Sensing, Flexim and Ultraflux.

3.2.1 Siemens FUG1010 Meter

The FUG1010 meter, formerly the Controlotron 1010GC (before acquisition), works on the same "WideBeam" principle as Siemens FUS1010 liquid meters. It is suitable for natural and process gas and has an operating temperature range from -40° to + 120°C. This is in essence a TOF approach but rather than transmit an ultrasonic signal through the pipe as in a conventional clamp-on meter, the wide-beam approach excites the pipe wall at its resonant frequency.

The primary measurement path, Fig.16, is through the pipe wall then diagonally through the gas, reflecting off the far pipe wall to the receiving transducer. The ultrasound also follows a second sonic path between the two transducers through the pipe wall only. The transit time of this signal is independent of the gas flow, offering a "zero-flow" reference that is claimed to eliminate zero drifts and allow zero-setting without halting the flow. The broad beam also extends beyond the vicinity of the transducers, which it is claimed provides operation over a wider range of flow velocities and suffers less impairment in the presence of wet gas.

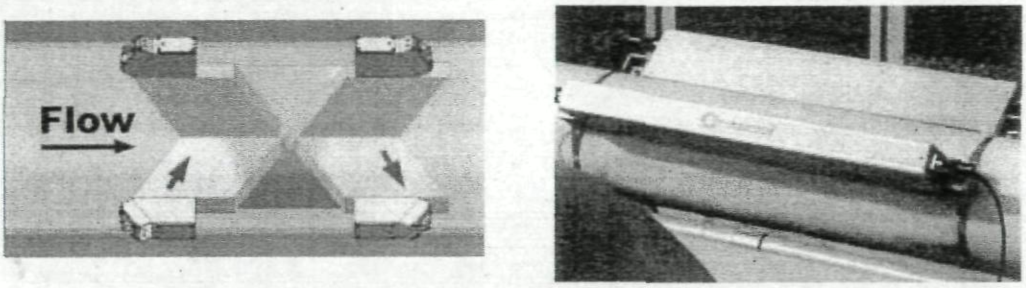


Fig.16 - Siemens' wide-beam transducer technology.

The wide-beam transmission system operates at a higher frequency than conventional insertion-type meters, which it is claimed gives greater immunity to valve and ambient pipeline noise.

In all of its variants the meter operation is limited by a minimum gas pressure; generally 4 bar.

3.2.2 GE Sensing Digital Flow GC868 and CTF878 Meters

The DigitalFlow GC868, Fig.17, was one of the earliest clamp-on ultrasonic meter for gas service on the market. The device uses the TOF principle, sending a coded ultrasonic burst across the flow. The path configuration used is a single traverse i.e. transducers are located at opposite sides of the pipe. Also a minimum gas pressure is required to ensure transmission of the signal into and out of the flowing gas. This is typically at least 5 bar for air and 12 bar for natural gas, however the minimum pressure is also dependent on pipe size and required flow velocity range.

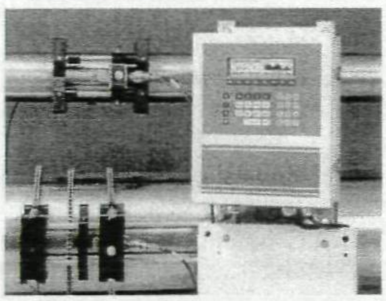


Fig.17 – GC868 meter

In 2005, GE Sensing (then Panametrics) introduced the CTF 878 model, Fig.18, which is described as a "Correlation Tag" Clamp-on ultrasonic meter. This meter employs the cross-correlation technique. The main advantage claimed is its ability to operate at pressures down to atmospheric (gas density limit of 1.2 kg/m^3). The meter is applicable to all types of

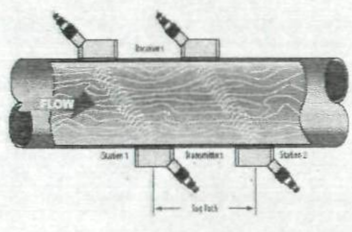


Fig.18 - CTF878 meter

acoustically conducting gases but should not be wet or saturated with moisture.

GE Sensing also offer a flare gas meter (the GF878), but it is based on wetted transducers. The CTF878 meter may be a candidate for flare gas measurement although its maximum gas velocity of 46 m/s and maximum pipe size of 750 mm diameter may limit its use for that application.

3.3 Expro Meters SONARtrac Meters

SONARtrac meters use both of the sonar-based methods described in Section 2.2. Liquid flow rate is determined using the "convective" approach on flow turbulence whilst the velocity of sound of the fluid is derived using the "acoustic" approach. The entrained gas percentage is calculated directly from the measured speed of sound using standard mixture relationships. The sensor heads (typically 800mm long) are clamped to pipe sections of 2 to 36 inches nominal bore, Fig.19.

The SONARtrac comes in different versions but there are essentially three relevant to this study.

The VF-100 measures Volume Flow (using the convective method), the GVF-100 measures only the Gas Volume Fraction (using the acoustic approach) whilst the VF/GVF-100 measures both.

Measurement range in liquid is given as 1 to 10 m/s with a ± 1% accuracy and an entrained gas range of 0-20% with an accuracy of ± 5% by volume. Accuracy of ± 0.5% has been demonstrated against a calibration laboratory's reference flowmeter in an 8" NB water line.

Fig.19 - SONARtrac VF/GVF-100

Measurement results for the SONARtrac in combination with a Differential-Pressure meter show gas flow rate to approximately ± 2% and liquid rates to within ± 10% over a wide range of wet gas flows with gas oil ratios ranging from less than 4000 scf/bbl to greater than 100,000 scf/bbl.

Since the meter is based on the use of PVDF piezo-electric sensors it has a temperature limit of less than 100°C.

The company are soon (early 2009) to introduce a meter based on "Active" sonar technology to improve the low-flow capability and will re-badge the SONARtrac as their "Passive" model.

3.4 Nucleonic Devices

3.4.1 Neftemer Multiphase Meter

This clamp on meter [7], Fig. 20, is based on a ^{137}Cs gamma-densitometer combined with advanced signal processing and pattern recognition techniques to provide velocity measurement of gas, water and oil phase fractions in vertically upwards multiphase flows.

From research work carried out on the meter in Russia, "patterns" in the gamma absorption spectrum have been found for both liquid and gas that are strongly related to velocity. Gas bubbles below a critical size are entrained in the liquid and

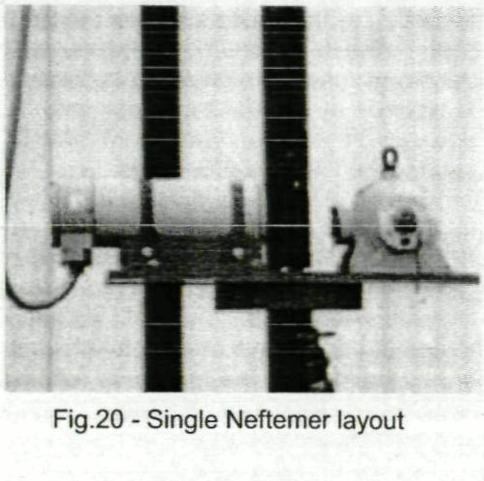


Fig.20 - Single Neftemer layout

are used to give liquid velocity. Average velocity of all bubbles is used to give gas velocity.

Once a set of single-phase γ-absorption coefficients have been input to the system during calibration, phase fraction is determined from:

- The overall γ-density at the detector
- Absorption at two pre-defined γ-energy levels
- The overall shape of the detected spectrum (which it is claimed is related to oil, water and gas fractions)

The phase fractions and liquid and gas velocities when combined with area gives phase flowrates.

Sampling takes place at a scan rate of 250 Hz with the main calculation cycle running every 2 seconds. Separate passes of the data are used for liquid mass flowrate, gas volume flowrate and (mass) watercut of liquid. These are integrated to get totals for liquid, oil, water and gas.

The target market [7] is in thermally stimulated, high watercut, heavy oil wells although other markets are being addressed.

The meter has been in field-operation in the Komi Republic since 2001 and by end of 2005, 50 wells were operating with multiple assemblies with a further 150 wells planned in 2006.

Test work is still ongoing with field and laboratory testing having been carried out in 2006.

- The field tests [7] compared PD meter results for Oil and turbine meter results for water at crude oil gathering stations against Neftemers installed directly on three 3-phase carbon-steel pipelines. Results show mass errors (2 * standard deviation) of 2.4% for liquid, 6.8% for water, 10.9% for oil and 3.5% for water-cut.
- The laboratory results were on stainless-steel pipe using light lubricating oil, tap-water, air mixes and results are generally within a ± 5% relative error.

The testing highlighted issues associated with possible differences when the application is different to the Russian oil fields (i.e. the type of oil) and could highlight the need for the Neftemer to be "trained" on new flow patterns for specific installations before it can correctly apply its algorithms. This is consistent with the general fact [3] that densitometers need to be re-calibrated if the properties of the fluid change compared to those the meter was calibrated in. Development is ongoing.

3.4.2 Tracerco PRI 160/116c Smart Density Gauge

Tracerco provide a straightforward density gauge, Fig.21, that normally uses a ^{137}Cs radioactive source to provide an indication of:

- Density in three, two or single phase flows
- Measurement of oil-in-water or water-in-oil
- Carry over or under of one phase into another such as liquid in gas lines
- Solids build-up

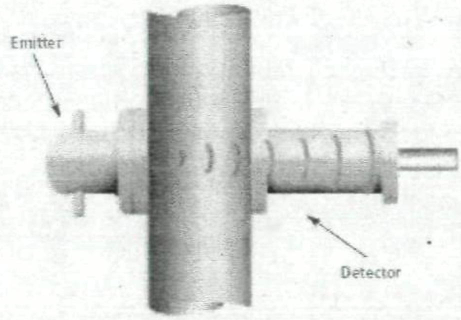


Fig.21 - Density Gauge

The response time of the meter can be selectable, fixed or dynamic 0.1 to 999 seconds. The accuracy depends on the selected response time and the intensity of the radiation flux at the detector. As with all γ-densitometers [3], the gauge has to be calibrated against known fluids in given pipe sizes to be able to measure absolute density levels rather than simple density-changes.

3.4.3 Tracerco PRI 116c-ATX Slug Monitor

Tracerco also provide a slug monitor that is in essence based on two of its PRI 116c density gauges spaced a known distance apart, Fig.22. The product information is vague (intentionally?) on the exact analysis method used but states the analysis method is based on gamma densitometry combined with "unique diagnostic software" and is able to offer an instrument capable of characterising process slugs.

The monitor can determine:

- Slug velocity
- Slug size
- Slug duration
- Estimated time of arrival of the slug at specific vessels

The response time of the meter can either be fixed or dynamic, 0.05 to 650 seconds.

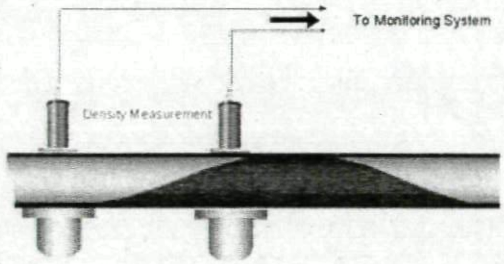


Fig.22 – Slug Monitor

The monitors are provided as unique, bespoke systems designed to meet individual customer requirements.

3.4.4 Tracerco PRI 150-H Smart Level Gauge

This is another Tracerco product based on use of radioactive sources but this time used to measure liquid level in fluid reservoirs, Fig.23.

Each monitor is tailor designed for the particular application in order to measure liquid or solid levels such as crude oil, produced water or sand in a wide range of surface or sub-sea vessels.

Claimed accuracy is usually 2% but this depends on the particular installation. The radioisotope source is normally Caesium or Cobalt.

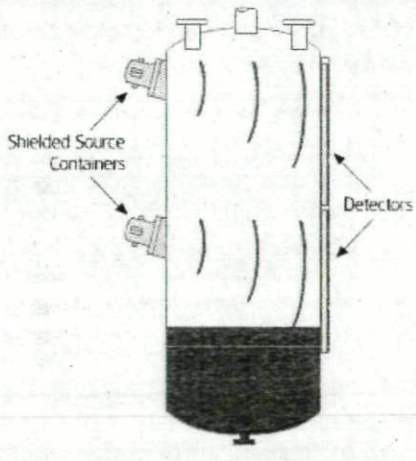


Fig.23 - Level Monitor

3.4.5 Kvaerner's Duet Multiphase Meter

The Duet meter is based on the principles of gamma-ray absorption and cross-correlation and was originally developed by the Australian CSIRO Mineral Group but was licensed to Kvaerner in 1998. The meters employs two gamma-ray densitometers separated axially a fixed distance apart; one a ^{137}Cs source and the other a dual-energy ^{137}Cs and ^{241}Am source (to provide gamma-rays at 662 and 60 keV respectively). Fig.24 shows the "slip-on" version of the duet although the meter comes in topside, subsea and mobile versions but these are in a standard spool-piece configuration. Flow is vertically up.

Velocity measurement is made by cross-correlating the two ^{137}Cs densitometer sources which contain the signature of disturbances such as bubbles or slugs within the flowline.

The oil, water and gas fractions are obtained from the dual-energy ^{137}Cs and ^{241}Am gamma-ray absorption measurement.

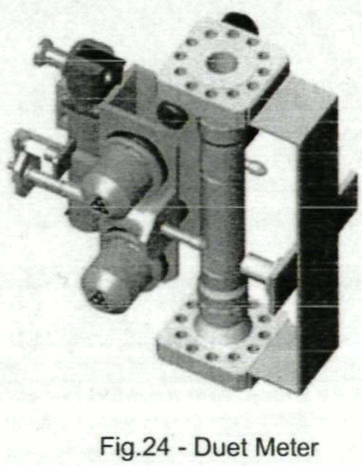


Fig.24 - Duet Meter

The energy of the "soft" gamma-ray (60 keV in this case) is relatively high for a dual-energy system allowing the technique to be applied in large diameter pipes.

Claimed accuracies are: Gas flowrate, < ± 10%, Liquid flowrate, < ± 10%, Water cut, < ± 4%.

3.5 ClampOn™ DSP Particle Monitor & other ClampOn™ monitors

The ClampOn™ sensor, Fig.25, provides real time measurement of sand production in oil or gas flow lines. It works on the principle of acoustic emission (although ClampOn™ refer to their sensors as "Passive Ultrasonic Intelligent Sensors") combined with advanced DSP techniques.

The sensors are "intelligent" in that the signal processing is performed in the sensor itself. New software releases to provide increased functionality can be downloaded into the sensor as they become available. The sensors can be fitted with optional pipe wall temperature and internal circuit temperature measurement and the systems can be retrofitted.

Systems for subsea operation are available based on the same technology (although larger than the sensor shown in Fig.25), and can be installed or retrieved by ROV and come in "deep-water", "compact" and "shallow-water" versions for operation to 4500m, 2500m and 50m depths respectively.

Fig.25 - DSP sensor Topside

ClampOn™ offer three other products based on the same sensors as in their Particle Monitor System:

- The "Corrosion/Erosion Monitor" employs a master sensor to communicate with up to eight slave sensors positioned along a chosen pipe section to watch for pipe-wall thickness changes (of 1% of the wall thickness at 0.02mm resolution) to build up a pattern of changes.
- The "Leak Monitor" provides detection of leaks in flowlines, valves, flanges and other pipeline components.
- The "DSP Ultrasonic Spectrum Analyser" digitises the ultrasound signal received by the sensor from 20 – 1000 kHz, performs frequency analysis in real-time and sends the spectrum digitally to a PC where application specific algorithms can be applied and the results stored and presented.

3.6 Abbon Flow Master – Acoustic Multiphase Meter

This is based on advanced software processing of passive acoustic energy patterns measured at a single clamp-on sensor. The meter works on acoustic emission principles combined with pattern recognition and other signal processing techniques. The sensor can be attached to a choke valve or some other component that will inherently generate flow noise. Alternatively it can be supplied attached to a flow-conditioner and this is the configuration shown in Fig.26. The method relies on the acoustic energy signals generated from the choke valve or flow conditioner being characteristic of the rate and composition of the flow. The meter can either be used on its own, in groups (i.e. a number reading on different pipelines) or in combination with some other form of multi-phase flow meter to provide backup or improve accuracy.

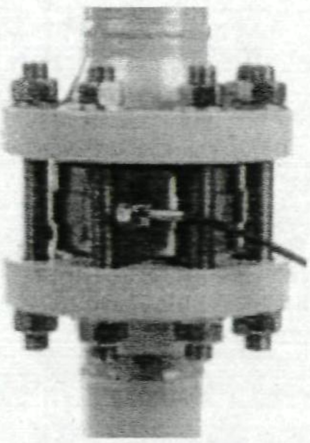


Fig.26 - Flow Master

Abbon claim that this technology has applications in:

- Multiphase flow measurement
- Wet-gas measurement
- Sand detection and measurement
- Slug flow analysis and characterisation
- Foam detection

The operating range is based on the system calibration carried out in the field or on the manufacturer's test facility and has a claimed accuracy of < 1% dependent on the calibration method. The calibration process trains the meter to recognise particular features of the noise spectrum that can be related to flowrate or fluid composition effects.

3.7 Tomography

In order for ECT, ERT or EMT systems to detect differences between fluids, there needs to be a reasonably large difference between the properties of the fluids and consequently tomography techniques are generally applied to multiphase flows. The following sections only cover descriptions of a few devices as a means of identifying general features relevant to this present study. A significant amount of research is being undertaken into development of Tomography systems including those based on Ultrasonics and on multi-plane arrays to provide 3-D tomography but only current models are discussed here. Systems that combine different types of tomography, e.g. ERT in combination with ECT, are referred to as dual-modality systems.

3.7.1 TomoFlow R100

TomoFlow provide a dual-plane 8-electrode ECT tomography system, Fig.27, that combines tomography with cross-correlation and pattern recognition techniques to provide both a view of the contents in a pipe and also the flow rate in "zones" across the pipe section.

Although the R100 is provided as a spool piece it consists of a non-invasive sensor mounted on a Perspex pipe but the general principle could (possibly) be modified for true non-invasive measurement on any non-conducting pipe.

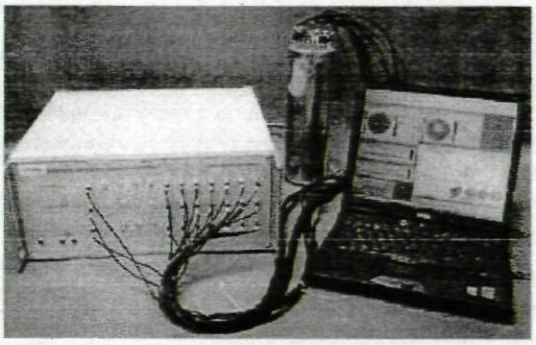


Fig.27 - R100 system

Tests at TUV NEL [5] on three phase mixes of crude oil, water and nitrogen have been carried out with GVF varying in controlled amounts from 0 to 95% and water-cut from 5 to 95%. These tests showed the ECT device was useful to visualise flow patterns but for accurate measurement of GVF should be used in conjunction with other techniques. Since those tests (2002) development in the signal processing algorithms may have improved the situation.

TomoFlow can provide the sensor or the processing software separately.

TomoFlow's "Flowan" software provides off-line calculation of more detailed statistics and flow patterns and can provide velocity detail on 13 zones, Fig 28, across the pipe section.

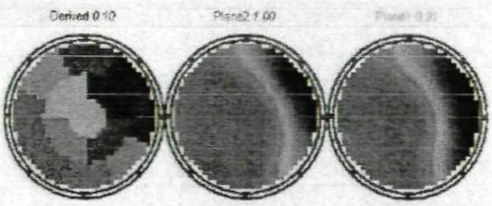


Fig.28 – Image reconstruction

3.7.2 ITS p2000 and m3000 Systems

Industrial Tomography Systems provide a number o tomography systems. Two of the main ones are th p2000 based on a 16 electrode ERT for measuremen

Fig.29 - m3000 Dual-mode system

in two-phase situations and the m3000dual, Fig.29, which is a dual-mode system employing 16-electrodes but with ERT and ECT capability for measurement of multi-phase flows.

Each of the models comes in two sizes; a "compact" for 1 or 2 plane measurement or "full" for up to 8 planes. Claimed display rate (as at 2002) is 30 frames per second for a typical 16–electrode configuration using standard analysis methods (i.e. on-line rather than off-line) and that 100 frames per second are possible with reduced spatial resolution. With more recent increases in computing power it can be expected that current frame rates may be higher than this.

ITS offer sensors (either as individual sensors or arrays built into spool pieces), entire systems or processing software separately so can be used with other sensor heads.

3.8 Summary of Non-Invasive Metering Features

The key attributes of the various categories of meter reviewed are:

- **Ultrasonic** – Active use of ultrasonic signals. Meters in liquids run in the MHz region whereas meters for gases typically run in the 50 kHz - 500 kHz range. Generally single diametral path, but multi-paths possible, flow profile corrections based on assumed Reynolds numbers, need 20D upstream to achieve claimed accuracy of typically ± 3%, velocity of sound information, sensitive to wall-thickness accuracy; some come with thickness pulse-echo sensor. Gas meters can be adversely affected by ultrasonic noise from control valves.

- ***Sonar*** – *Passive listening to system noise in the 100-1500 Hz range, speed of sound and* flow velocity are both measured as average quantities across the section. Monitoring gas lines for liquid content and liquid lines for gas content

- **Nucleonic** – Based on γ-densitometry to get mean variation across pipe section and used to measure volume fractions in multiphase flows. Calibrated against density of known fluids. Can be used in dual-paths separated a known distance apart with correlation methods to get flowrates. Some use pattern recognition techniques on single-path to identify features in the γ-absorption spectrum that relate to flowrate and composition.

- **Acoustic Emission** – Passive listening to system noise or friction noise in the 10 kHz-1000 kHz range. Has to be trained to recognise patterns in the frequency spectra that relate to flow for the specific system in which it is fitted unless this is a standard fit for which the relationships are already known, e.g. with a provided flow profiler.

- **Tomography** - Active measurement mostly of electrical properties of contained fluid to get flow patterns across a slice section of pipe. Most common methods in process systems are ERT and ECT both of which are used for 2-phase flow. Some meters provide both and hence have better success in multiphase flow. When used in dual or multi-plane configurations can use correlation techniques to derive velocity and flowrate information in "zones" across pipe section. ECT is the only (?) candidate for non-invasive use but the pipe has to be electrically non-conducting. Research is ongoing and new techniques may provide non-invasive use.

Table 1 summarises the key features of each technology.

Table 1 – Summary of the Key Features of Non-Invasive Flow Metering Technologies

Technology	Measured Parameter							Applicable Fluids					
	Averaged flow	Speed of sound	Density	Solids content	Wall thickness	Flow pattern	Zoned flow	Liquid	Sand/oil	Gas	Wet gas	Two phase	Multi phase
USFM	*	*						****		**			
Pulse-echo					*			*		*	*	*	*
Sonar	*	*						*		*	*		
Nucleonic	* **vertical**		*					*				*	****
Acoustic	*			*				*	*		*		*
ECT Tomography	*					*	*					*	*

4 COMBINATIONS OF TECHNIQUES AND SUPPLEMENTARY USES

The devices reviewed can obviously be used in a stand alone mode to provide the measured parameter they were designed for (e.g. flowrate, density etc.). Consequently, they could be used to replace faulty or outmoded devices without the need necessarily of having to remove these from a system, assuming the original could be left in the system without any adverse effects.

The non-invasive technologies discussed can also be used to provide a check on imbedded devices, for example spool piece meters. If used for this purpose the accuracy of the non-invasive meter needs to be considered against the accuracy of the imbedded device. Imbedded meters will generally be more precise than non-invasive meters.

Certain of the non-invasive techniques naturally complement each other and if used together could provide additional functionality or simply added confidence in the measured parameter. Even used on their own, some of the meters and methods may provide additional information than available from traditional flowmeters.

The following sections briefly discuss three supplementary uses involving the speed of sound.

4.1 Speed of Sound to Measure Dispersed Gas or Liquid Volume Fraction

LVF and GVF in dispersed 2-phase flows can be derived from the speed of sound of the fluid using well established mixture relationships [8] if the liquid and gas fluids are known: e.g. water/air, air/oil etc... Any of the non-invasive devices that provide the user with access to the speed of sound can effectively be used to provide either LVF or GVF subject of course to the constraints imposed if the impedance change (of the mixture) is so great as to cause path failure on the meter due to signal loss.

For a given speed of sound there are normally two mathematical solutions; one for a liquid/gas mix and one for a gas/liquid mix. Keeping the application to situations where there is a small amount of free gas bubbles in a liquid or where there is a small amount of dispersed liquid droplets in a gas (i.e. wet-gas) points more readily to a unique solution.

Some of the liquid USFMs include an indicator for GVF. The SONARtrac meter has been applied in Prudoe Bay to measure GVF as a means of correcting for discrepancies in allocation factors obtained from a Coriolis meter measuring density and bulk flowrate. Flow testing has shown that the SONARtrac unit when used in combination with a DP meter, can assist in correcting the DP meter over-reading in wet-gas flows and also (again in combination) provide gas and liquid rates.

With closely known pipe geometry a pulse-echo system should also be able to measure the velocity of sound so could potentially be used as a check on 2-phase dispersed flow mixture. Some portable clamp-on meters currently on the market offer an independent measure of the wall thickness and velocity of sound by using a separate pulse-echo clamp-on transducer for that purpose.

4.2 Speed of Sound to Derive Viscosity and Density in Dispersed Liquid/Gas Mixes

In a similar way to the approach described in Section 4.1, once the LVF or GVF are known then an Algebraic Slip Model can be used [9] to calculate the viscosity of the mix. This is the approach used in commercial CFD packages such as Fluent and Phoenics. Mixture density can also be calculated using simple mixture relationships.

These would be useful to confirm fluid density or flow Reynolds Numbers which might then have a bearing on the calibration of any meter (e.g. venturi, turbine meters etc..), not just USFMs, that use Reynolds Number based or other flow profile related correction factors.

4.3 Density and Calorific Value of Hydrocarbon Gas Mixtures

AGA8 and AGA10 provide the basic calculations by which the density, compressibility and speed of sound of hydrocarbon gases can be obtained but only for a known gas mixture.

The meter diagnostic functions of a multi-path, wetted ultrasonic flowmeter have been used to accurately measure the speed of sound of a complex petroleum gas mixture [10]. The meter was used in combination with a Gas Chromatographer and field results showed the speed of sound to be within 0.2% of the values given by calculation from the known gas fractions. It is not possible to calculate the gas mix constituents explicitly from the speed of sound without making assumptions about the mixture since there is no unique backwards relationship to the gas proportions. However, in combination with pressure, temperature and measured levels of CO_2 and N_2 constituent [11] velocity of sound can be used as an "inferential property" to derive density and other parameters of the gas mix. Several people have done this and patented their particular technique or processing algorithms.

Although this work used a wetted multi-path meter, any of the devices that provide a speed of sound could be used as a check on the function of other metering devices such as Gas Chromatographers or as a means of identifying real-time changes in gas mix.

5 TEMPERATURE MEASUREMENT

Temperature is one of the most commonly measured parameters in process systems since many physical properties of the fluid are a function of temperature.

Surface mount temperature sensors have been commercially available for a large number of years. It is widely accepted that any sensor at the pipe or system surface will be limited by the fact that the local surface temperature, may not be the same as the fluid temperature at that point and will, due to thermal inertia, not respond as quickly to changes in operating conditions as will the actual temperature of the fluid.

Apart from conventional surface mounted temperature sensors, two additional forms of non-invasive temperature measurement are "Thermal Imaging" and "Optical-Fibre" sensors.

5.1 Non-contact Thermal Imaging

These work by using a thermal imaging camera aimed toward the portion of the system being studied.

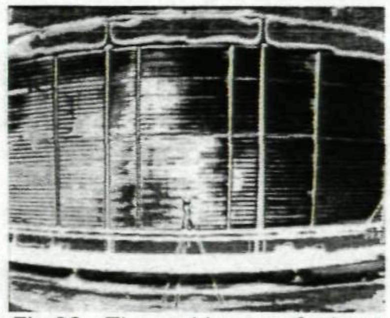


Fig.30 - Thermal image of a heat exchanger

It is widely used in many military and industrial fields to gather an overall view of the heat signature of an item or plant, Fig.30, either to study energy loss or identify local hot or cold spots without having to physically instrument a system with temperature sensors. Although still images can be captured, the devices generally work at the frame-rate of the video device, typically 30 frames a second. The temperature resolution depends on the number of colour shades the camera can discriminate; on low-end systems this is typically 256 shades. Temperature range is typically in the -20 to 200°C range (giving 1°C resolution on a 256 shade system) although more expensive systems can measure at higher temperatures.

In a thermally lagged system, if the lagging characteristics are known (material type, thickness, insulation properties) an estimate of the underlying surface temperature can be made from the lagging's external temperature.

A number of manufacturers provide devices, for example, those made by Fluor and Sierra Pacific Innovations.
Since this is a non-contacting device its installation generally involves simply mounting the camera on a support and pointing it at the region of interest. Thermal imaging camera systems are generally one-man portable and often used for mobile trouble-shooting or information gathering exercises but can also be used for long-term continual monitoring.

Thermal imaging can be a useful tool for plant management to give some global indication of where heat-loss occurs in a system or item of plant, such as a heat exchanger, or as an indicator of liquid level in reservoirs and heat exchangers.

5.2 Optical fibre as a Temperature Sensor

A pulsed laser connected to the end of a length of optical fibre can be used for Distributed Temperature (DTS) sensing based on the principles of Distributed anti-Stokes Raman Theory (DART). The laser light is backscattered through the fibre due to changes in density and composition of the fibre as well as due to molecular and bulk vibration. The Raman component of backscattered light is related to the absolute temperature of the fibre irrespective of laser power, launch conditions or fibre geometry and hence can be used to measure absolute temperature.

Optical fibre as a temperature sensor offers benefits of remote measurement in hazardous environments or where there is a large amount of electromagnetic noise and hence possibility of data corruption. Fibres can be 2 km in length with a best spacial resolution down to 1m but with special processing and improvements in the laser source, this can be improved to sub-metre resolution. Data acquisition time however is in the form of minutes rather than seconds.

DTS is used for monitoring of transformers, steam pipes in power plant and as general fire-warning system to detect hot-zones. In addition it is used in the medical field.

6 NON-INVASIVE FLOW MEASUREMENT JOINT INDUSTRY PROJECT

A formal launch meeting of this 18-month project was held in Houston in November 2008 and sufficient project sponsors are already signed-up to allow work to commence in early 2009. The detailed project content is being finalised with these sponsors but is likely that testing will focus on commercial devices from four of the non-invasive techniques: Ultrasonic, Sonar, Nucleonic and Acoustic.

Testing is planned in single, two-phase and multiphase fluids to look at comparative performance of the techniques. The intent is to test a number of devices simultaneously to establish their limitations in proximity to bends, Fig.31, and in dealing with "unknown" pipe conditions, Fig.32, such as pipe ovality and internal surface roughness.

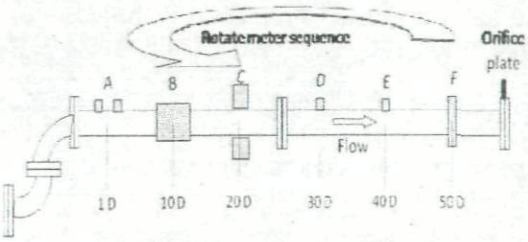


Fig.31 - Pipe Bend Test Configuration

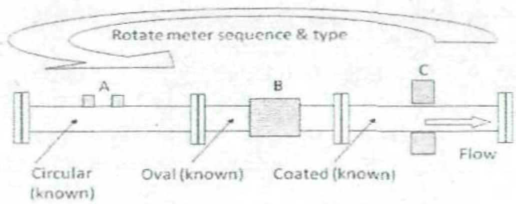


Fig.32 – Pipe Installation Effects Configuration

7 CONCLUSIONS

A range of different non-invasive technologies and commercial devices have been reviewed. In broad terms, indications are that there are a number of viable non-invasive technologies available that could be used either in stand-alone metering mode, to supplement existing meters, to provide property correction factors (density and viscosity) for existing meters or to provide additional information and metering of multiphase flow.

Generally the accuracy of these methods is collectively ± 5% of value although tighter accuracy can be achieved but only for ideal flow profiles, i.e. where the meter is installed 20D downstream, 10D upstream of disturbances. Devices that use a true average flow over a section rather than an average from a single path can also be expected to have tighter accuracy. USFM clamp-ons (and many of the other methods) are used mainly in single-path configurations and accuracy could be improved if used in multi-path configurations.

Use of speed of sound to derive LVF and GVF in dispersed 2-phase flows show promise. This may also provide a means whereby correction factors for density can be applied to other forms of meter.

Tomography is a subject undergoing change due to the rapid pace of development in the power of computer processors and has potential for detailed multiphase flow measurement and "zoned" flow information if used in multi-plane configurations in combination with cross-correlation analysis techniques. Current meters however tend to be based on spool-pieces.

Some Acoustic Emission sensor systems have already been ruggedized for subsea use and come with "intelligent" on-board processing. These could potentially be put to wider use as smart sensors in combination with some of the other signal processing systems reviewed to provide an increased capability for subsea deployment.

A number of the methods involve some form of "trained" pattern recognition that relates some feature in either a noise or γ-absorption spectrum to flowrate. There appears to be evidence to suggest that the flow-to-spectrum relationships are not universal, i.e. when derived on one test rig they do not apply to another configuration, where the pipe material has perhaps changed or where the fluid is different. This would place some limitations on the usefulness of these techniques and points to the possible need for them to be re-trained on each installation.

Certain techniques although not directly flow-measurement can be applied to flow systems to provide additional information that might be helpful for plant operation or management.

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