Solution Mining Research Institute, 2007 Spring Technical Conference
Basel, Switzerland, 29 April – 2 May 2007

CLAMP-ON, SONAR-BASED VOLUMETRIC FLOW RATE AND ENTRAINED GAS MEASUREMENT FOR INDUSTRIAL APPLICATIONS

Daniel L. Gysling, CiDRA Corporation
Douglas H. Loose, CiDRA Corporation
Alex M. van der Spek, ZDoor BV

---

1 ABSTRACT

A clamp-on, sonar-based flow measurement technology for simultaneously measuring volumetric flow rate and process fluid sound speed is described. The technology utilizes sonar array processing techniques to perform two independent measurements to characterize the process fluid, each well-suited for single and multiphase flows. First, the meter provides volumetric flow by tracking the speed at which naturally occurring, flow-generated pressure fields convect past an array of strain-based sensors clamped-on to existing process pipe. Second, the meter provides compositional information by measuring the speed at which naturally occurring sound waves propagate through the process fluid using the same clamp-on sensors. Measuring the speed of sound of a process fluid utilizing this sonar technique is analogous to measuring process fluid density and has many compositional based applications. A primary example of this is using process sound speed to accurately measure the amount of entrained gas in liquid–continuous mixtures.

The ability to measure volumetric flow and process sound speed reliably and accurately in single and multiphase applications with a non-intrusive, clamp-on device significantly enhances the observability of the many industrial processes.

Data are presented from sonar-based volumetric flow and sound speed compositional measurements for brine and refined hydrocarbon product applications at a natural gas liquid (NGL) storage facility.

2 INTRODUCTION

Volumetric flow is a critical measurement in process control and optimization for most industrial processes. The current industrial flow meter market is often classified into two technology-based categories: old technology and new technology. Old technology flow meters include flow measurement technologies that have been in use for more than 70 years, and include turbine, orifice plate and variable area flow meters. The new technology flow meters include technologies which have emerged over the last 30~50 years. These new technologies typically offer advantages over the old technologies in performance, functionality, and reliability. The major types of new technology flow meters include ultrasonic, electromagnetic, vortex, and Coriolis flow meters. Each type has evolved to serve various aspects of the diverse range of applications within the industrial flow meter landscape.

This paper describes sonar-based flow meter technology which utilizes sonar techniques[1] to listen to and interpret pressure fields generated by turbulent pipe flows. Sonar flow measurement technology represents a new class of industrial flow meters utilizing measurement principles distinct from existing technologies. Sonar flow meters were first introduced into the oil and gas industry in 1998 for use in downhole multiphase flow metering applications[2] [3]. Sonar flow measurement technology is currently being used in other industries such as oil and gas, mining and minerals, hydro transport, pulp and paper, chemicals and power generation.

Entrained gas in liquid-continuous flows is often an unwanted but unavoidable phenomenon that negatively impacts safety, environmental emissions, product quality or the ability to accurately determine the flow rate. For instance, entrained gas in the brine flow at an underground natural gas or natural gas liquid (NGL) storage facility can indicate an upset condition in the process or in the facility infrastructure and has serious safety and environmental concerns. Likewise in production of crude oil, gas carry under in the liquid outlet of a two-phase separator impairs the net oil flow rate measurement as the watercut meter is affected by the presence of free gas. It is well known that the resulting errors in the net oil rate can easily be 100% or more solely because of a small error in the watercut.

The sonar techniques that enable the interpretation of the naturally occurring pressure fields inside a pipe are also well suited to determine the speed of propagation of acoustic pressure fields. The speed of sound thus determined is a very sensitive indicator of entrained gas and it offers a superior alternative to today's mechanical sample taking analyzers.

The sound speed is also used to determine the compositional properties of a fluid in a pipe. As shown in Figure 1, in the case of refined hydrocarbon NGL products, at any given temperature and within a typical liquid-state pressure range the sound speed is unique and distinct for each different NGL shown. The ability to measure the sound speed is used to identify the type of product flowing through the pipeline or to control the blending ratio when mixing two different types of NGL's.

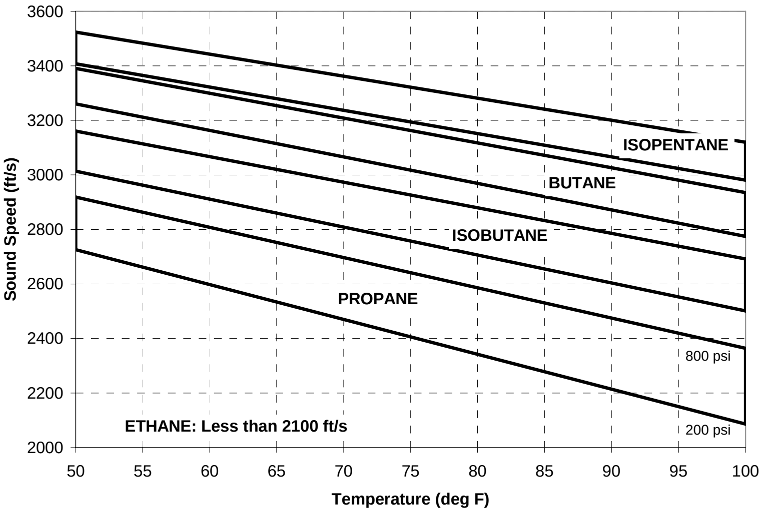

Figure 1: Sound Speed of Various NGL Products

The sonar methodology involves characterizing the speed at which coherent pressure waves, either vortical structures or acoustic pressure fields, convect past an axial array of sensors using beam-forming techniques developed over several decades for underwater acoustic applications. Since coherent vortical structures are an inherent feature of turbulent flow, no internal geometry is required to generate these structures. Likewise, in the majority of industrial processes the proximity of pumps, compressors, valves or sharp bends ensures that no source of sound is required. The sonar-based measurement is therefore entirely passive and it can be performed using an array of strain-based sensors mounted on the outside of the pipe. With no process-wetted hardware, the sonar flow measurement technology is well suited for the volatile fluids or aggressive slurries commonly encountered in many industrial applications.

3 FLOW RATE MEASUREMENT

The overwhelming majority of industrial process flows involve turbulent flow. Turbulent fluctuations within the process flow govern many of the flow properties of practical interest including the pressure drop, heat transfer and mixing. For these reasons, turbulent pipe flows have been extensively studied over the years with roots back to Osbourne Reynolds and Lord Rayleigh in the late nineteenth century[4].

3.1 Turbulent pipe flow

For engineering applications, considering only the time-averaged properties of turbulent flows is often sufficient for design purposes. For sonar flow metering technology, understanding the time-averaged velocity profile in turbulent flow provides a means to interpret the relationship between speed at which coherent structures convect and the volumetrically averaged flow rate within a pipe. For turbulent flows, the time-averaged axial velocity varies with radial position, from zero at the wall to a maximum at the centerline of the pipe. The flow near the wall is characterized by steep velocity gradients and transitions to relatively uniform core flow near the center of the pipe. Figure 2 shows a representative schematic of a velocity profile and coherent vortical flow structures present in fully developed turbulent pipe flow.

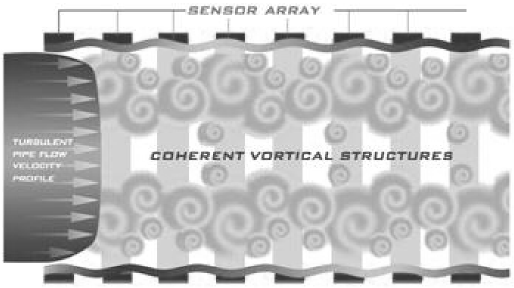

Figure 2: Coherent Structures in Turbulent Pipe Flows.

The vortical structures are superimposed over time averaged velocity profile within the pipe and contain temporally and spatially random fluctuations with magnitudes typically less than 10% percent of the mean flow velocity. The Reynolds number (Re), based on pipe diameter (D), characterizes many of the engineering properties of the flow. The Reynolds number is a non-dimensional ratio representing the relative importance of inertial forces to viscous forces within a flow. Pipe flows with Reynolds numbers exceeding a critical value, typically 2300, are turbulent. Those with Reynolds numbers below this value are laminar. The vast majority of flows in industrial processes are turbulent with Reynolds numbers far in excess of the critical value.

3.2 Coherent turbulent structures

Turbulent pipes flows are highly complex flows. Predicting the details of any turbulent flow is one of nature’s great-unsolved problems. However, much is known regarding the statistical properties of the flow. For instance, turbulent pipe flows contain self-generating, coherent vortical structures often termed “turbulent eddies”. The maximum length scale of these eddies scales with the diameter of the pipe. These structures remain coherent for several pipe diameters downstream, eventually breaking down into progressively smaller eddies until the energy is dissipated by viscous effects. Experimental investigations have established that eddies generated within turbulent boundary layers convect at roughly 80% of maximum flow velocity. For pipe flows, this implies that turbulent eddies will convect at approximately the volumetrically averaged flow velocity within the pipe. The precise relationship between the convective velocity of turbulent eddies and the flow rate for each class of meter can be calibrated empirically as described below.

3.3 Characterizing the unsteady pressure field

The sonar flow metering methodology uses the convection velocity of coherent structures within turbulent pipe flows to determine the volumetric flow rate. The convection velocity of these eddies is determined by applying sonar array processing techniques to determine the speed at which eddies convect past an axial array of dynamic strain measurements distributed along the pipe outer circumference. The sonar-based algorithms determine the speed of eddies by characterizing both the temporal and spatial frequency characteristics of the flow field. For a train of coherent eddies convecting past a fixed array of sensors, the temporal and spatial frequency content of pressure fluctuations are related through the following relationship:

$$u = \frac{\omega}{k} \tag{1}$$

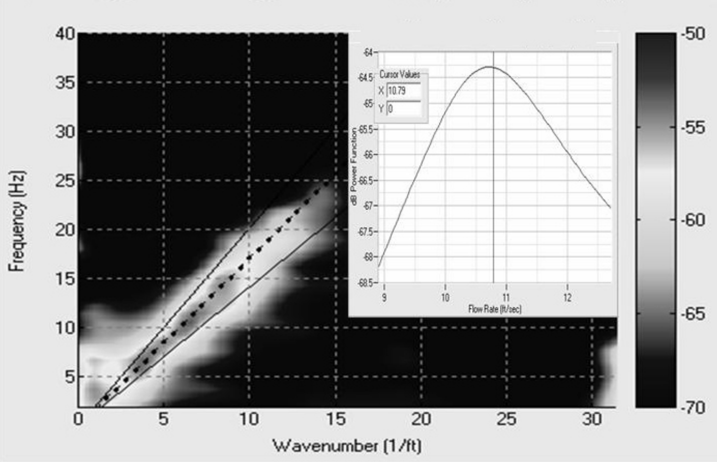

Figure 3: k-w Plot Showing Convective Ridge

Where *u* is the convective velocity of the unsteady pressure fluctuations (m/s), ω is the temporal frequency (rad/s) and *k* is the wave number (rad/m), defined as $k=2\pi/\lambda$ where λ is the wavelength (m). In sonar array processing, the spatial/temporal frequency content of time stationary sound fields are often displayed using “k-w plots”. k-w plots are essentially two dimensional power spectra in which the power of a pressure field is decomposed into bins corresponding to specific spatial wave numbers and temporal frequencies. On a k-w plot, the power associated with a pressure field convecting with the flow is distributed in regions which satisfy the dispersion relationship developed above. This region is termed the “convective” ridge[5] and the slope of this ridge on a k-w plot indicates the convective velocity of the pressure field. This suggests that the convective velocity of turbulent eddies, and hence flow rate within a pipe, can be determined by constructing a k-w plot from the output of a phased array of sensors and identifying the slope of the convective ridge. Figure 3 shows an example of a k-w plot generated from a phased array of transducers listening to a 16 inch pipe flowing water at approximately 350 l/s. The power contours show a well-defined convective ridge. A parametric optimization method was used to determine the “best” line representing the slope of the ridge. For this case, a slope of 3.2 m/s was determined. The intermediate result of the optimization procedure is displayed in the insert, showing that the optimized value is unique and constitutes a well-defined maximum.

3.4 Sonar flow meter calibration

The k-w plot shown in Figure 3 illustrates the fundamental principle behind sonar based flow measurements, namely that an axial array of transducers can be used in conjunction with sonar processing techniques to determine the speed at which naturally occurring turbulent eddies convect within a pipe. The next issue is to quantify the relationship between the measured speed of the turbulent eddies and the volumetrically averaged flow rate within the pipe.

To quantitatively evaluate this relationship, a number of geometrically similar sonar flow meters with diameters between 2 and 30 inches were tested with water at a flow meter calibration facility for a wide range of flow rates. Using a low-order Reynolds number based calibration, spanning the operating range of flow meters of different physical sizes, the sonar meter measured the volumetric flow rate to within 0.5% accuracy. It is important to note that this flow metering approach has no fundamental size limitations and should be applicable to turbulent pipe flows of all diameters and Reynolds numbers. Furthermore, similarity laws suggest, and calibration data support, that the relationship between convection velocity and flow rate from geometrically similar meters of any size is be governed by same Reynolds number based calibration.

3.5 Industrial applications

Numerous industrial applications for the sonar based flow measurement have been developed in close co-operation with end users over a period of several years. The industrial applications are to be found where the clamp on, non intrusive, large bore capability of the sonar based principle results in undisputed advantages in terms of life cycle cost, reliability or the sheer impossibility to make any other measurement device work. Examples of such are:

- Brine and refined hydrocarbon pipelines.
- Hydro transport of oil sand[6].
- Thick stock flow in paper and pulp[7].
- Air conveyed transport of particulate material.
- Two phase flow of water and oil[8] [9].
- Sewer water processing.
- Flow of coating pastes.
- Magnetite flow in minerals processing.

Several of the above examples of industrial flows are characterized by their abrasive and/or corrosive nature. In many cases this necessitates the use of special pipe materials or the use of lined (Teflon, rubber, concrete) pipe. The phenomenon of pressure fluctuation induced circumferential pipe strain is universal and independent of the precise nature of the pipe material or lining. As a result a sonar based measurement can, in most cases, be applied without a process shut-down, without cutting the pipe and without elaborate operational procedures or safety measures.

4 MEASUREMENT OF GAS CONTENT

Using a similar hardware platform it is also possible to measure the speed of sound of acoustic waves propagating in the process fluid. The propagation of acoustic waves occurs at frequencies much above the frequency domain of vortical pressure fluctuations, therefore the same sonar processing can be applied to determine both the acoustical velocity and the voritical velocity at the same time. The relation between speed of sound in a two-phase mixture and the volumetric phase fraction is well known in the case when the wavelength of sound is larger than the pipe diameter and hence also significantly larger than any process inhomogeneities such as bubbles.

4.1 Speed of sound in liquid/gas mixtures

The mixing rule[10], known as Wood's equation[11], expresses the fact that in a mixture the compressibility of the mixture equals the volumetrically averaged compressibility of the pure components. For the mixture density a similar rule holds: the mixture density equals the volumetric average of the pure component densities. Because the speed of sound in a fluid equals the square root of the compressibility over the density, the two mixing rules can be written as:

$$\begin{aligned} \frac{1}{\rho c^2} &= \frac{\varphi}{\rho_g c_g^2} + \frac{1-\varphi}{\rho_l c_l^2} \\ \rho &= \varphi \rho_g + (1-\varphi)\rho_l \end{aligned} \qquad (2).$$

Here, φ is the in-situ volume fraction of gas at line conditions, c is the speed of sound, ρ the density and the subscripts g and l refer to the gas and liquid phase respectively. Figure 4 illustrates the relation between mixture sound speed and gas content for a gas/water mixture. In most industrial processes, at moderate temperature and pressure line conditions, the compressibility of the gas phase is orders of

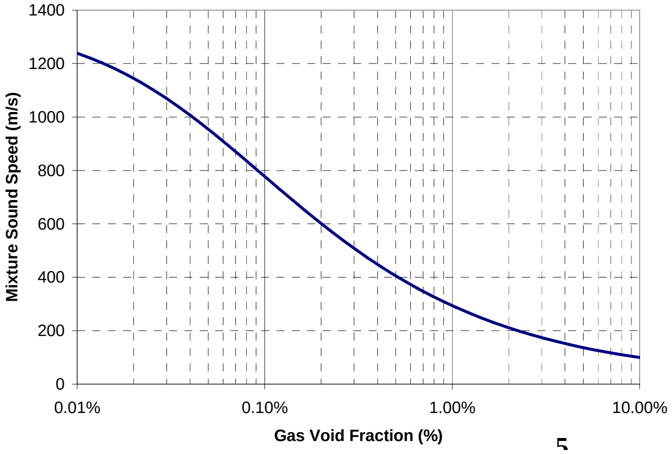

Figure 4: Mixture Sound Speed vs. Gas Void Fraction

magnitude larger than the compressibility of the liquid phase. Inversely, the density is dominated by the liquid density. As such, it will be necessary to measure the process pressure (when varying) as both the gas density and the liquid density are significant when determining the gas void fraction from the mixture sound speed.

Conversely, neither the speed of sound in the liquid nor the speed of sound of the gas is a significant factor for mixtures where one phase is gaseous. In fact, the denominator of the first term in the Wood's equation equals the product of process pressure and polytropic exponent of the gas demonstrating that the gas content at line conditions can be determined using the speed of sound independent of the gas molecular weight or the gas temperature. Hence, the determination of the gas content using mixture speed of sound is independent of the gas type and will be accurate irrespective of the type of gas, which can be air, hydrocarbon, carbon-dioxide, hydrogen or any mixture thereof.

4.2 Measurement of the speed of sound

As described above, the relationship between mixture sound speed and entrained gas in bubbly liquids is well established. However, as will be developed below, in bubbly flows, these relations are only applicable for the propagation of relatively low frequency, long wavelength sound. While this restriction does not present any significant obstacles for the sonar meter, it does prevent ultrasonic sound speed measurement devices from making this measurement.

Ultrasonic meters typically operate in 100 kHz to several MHz frequency range. For these meters, entrained gas bubbles have length scales on the same order as the acoustic waves generated by the ultrasonic meters. This poses several problems for ultrasonic measuring devices. Firstly, the bubbles scatter the ultrasonic waves, impairing the ability of the ultrasonic meter to perform a sound speed measurement. Secondly, ultrasonic meters rely on information derived from only a small fraction of the cross sectional area of the pipe to be representative of the entire cross section, an assumption that breaks down for flows with non-uniform distributions of in homogeneities, such as stratification of entrained gas towards the top of process lines.

Sonar flow meters use an approach developed and commercialized specifically for multiphase flow measurement in the oil and gas industry in which multiphase challenges described above are routinely encountered. Sonar meters measure the propagation speed of operationally generated sound in the ~100 to 1000 Hz frequency range which is sound audible to the human ear. In this frequency range, sound propagates as a one-dimensional wave, using the process pipe as a wave-guide. The wavelength of sound in this frequency range (>1 m) is typically several orders of magnitude larger than the length scale of the bubbles or flow non-uniformities. The long wavelength acoustics propagate through multiphase mixtures unimpeded, providing a robust and representative measure of the volumetrically averaged properties of the flow.

For the sound speed measurement, the sonar flow meter utilizes similar processing algorithms as those employed for the volumetric flow measurement. As with convective disturbances, the temporal and spatial frequency content of sound propagating within the process piping is related through a dispersion relationship.

$$c = \frac{\omega}{k} \qquad (3).$$

As before, k is the wave number (rad/m), ω is the temporal frequency (rad/s), and c is the speed at which sound propagates within the process piping (m/s). Unlike disturbances which convect with the flow, however, sound generally propagates in both directions, with and against the mean flow. For these cases, the acoustic power is located along two acoustic ridges, one for the sound traveling with the flow at a speed of $c + u$ and one for the sound traveling against the flow at a speed of $c - u$.

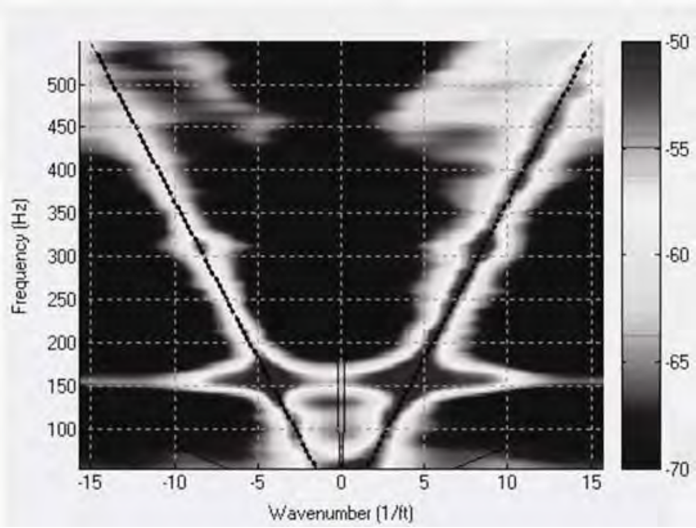

Figure 5: k-w Plot for 3% Entrained Air in Water.

Figure 5 shows a k-w plot generated for acoustic sound field recorded from still water containing ~3% entrained gas by volume in an 8 in, schedule 80, vertically oriented Plexiglas pipe. The k-w plot was constructed using data from an array of strain based sensors clamped to the outside of the pipe. Two acoustic ridges are clearly evident. Based on the slopes of the acoustic ridges, the measured sound speed for this for this mixture was 70 m/s, consistent with that predicted by the Wood equation. Note that adding 3% air by volume reduces the sound speed of the bubbly mixture to less than 10% of the sound speed of liquid only water.

4.3 Industrial applications

The sonar based measurement of process aeration using the speed of sound covers almost 5 orders of magnitude, from 0.01% to above 20%, and is therefore universally applicable to a wide variation of process conditions. There are two applications for the measurement of entrained gas of distinctly different character. First there are those where gas in the process liquid must be controlled or avoided altogether. Examples of such are:

- Brine pipelines in natural gas or NGL storage facilities.
- Natural froth lubricity flows.
- Gas sparging in flotation cells.
- Dissolving carbon dioxide in beverages.
- Entrained air in the thin stock flow to a paper machine's headbox[12].
- Entrained air in filling stations for domestic household products.

Second there are applications where entrained gases negatively affect the process indirectly by affecting other types of meters. Examples of this second kind are:

- Errors in custody transfer metering resulting from product flashing or aeration.
- Errors in consistency measurement of paper stock.[13]
- Errors in the determination of net oil using watercut meters[14].
- Errors in Coriolis determined volume flow as a result of product aeration[15].

4.4 Speed of sound in two-component liquid mixtures

The same mixing rules given by equation 2 above also apply to mixtures of two differing liquid components by simply replacing the subscripts *g* and *l* with *l1* and *l2* representing liquid component 1 and liquid component 2. In this case since the compressibility of the two liquid components are of the same order, the density and sound speed of each of the two components must be known. Measurement of the mixture sound speed can then be used to determine the volume fraction of each component as it is flowing through a pipe. For example, measuring the mixture sound speed through sonar techniques has been used to determine the volumetric ratio of oil and water in oil and gas production applications. Additionally this methodology can be used to measure the volumetric ratio of two NGL products when blending to a specific mix.

5 UNDERGROUND STORAGE FACILITY FIELD TRIAL

Two *SONARtrac*® meters manufactured by CiDRA Corp. were installed at an underground salt dome NGL storage facility as a field trial to better understand the performance and value of the sonar flow meter in typical applications at this type facility. The operator was interested in a meter that would provide accurate flow rate measurements with cost-effective installation and little or no maintenance. The accuracy requirement was not necessarily at a level that would be expected for custody transfer requiring an expensive measurement skid, but rather at a level sufficient for check-type metering. Because the *SONARtrac* flow meter is installed by clamping on to outside pipe surface it does install quickly and easily without the need to shut down the process. Also, since the *SONARtrac* is not intrusive, has no moving parts and does not require precise alignment and acoustic coupling gels there is no requirement for periodic maintenance or calibration and has proven to be robust over long-term operation even when exposed to severe outdoor environmental conditions and seasonal extremes. Additionally, the ability of the same sonar meter hardware platform to measure the process fluid sound speed and entrained gas fraction was also of interest.

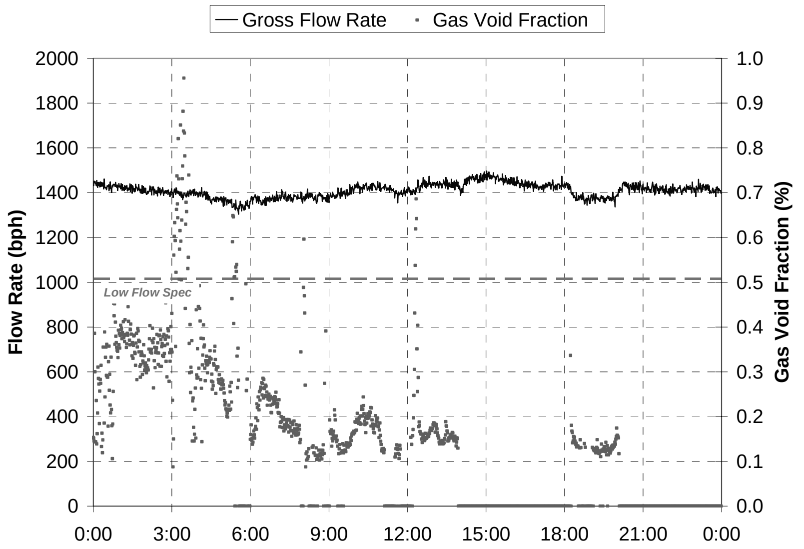

Figure 6: *SONARtrac*® Flow Rate and GVF Measurement of 10" Brine Application

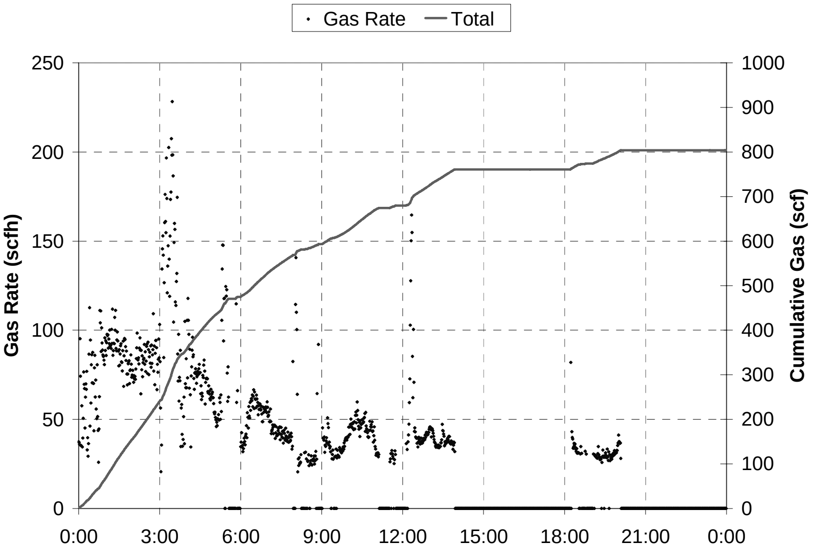

Figure 7: *SONARtrac*® Gas Flow Rate and Cumulative Gas Volume of 10" Brine Application

The first application is a sonar meter installed on a 10-inch line to measure the flow rate of brine into and out of the storage well, and additionally to measure the level of air or hydrocarbon gas present in the liquid brine. The sonar meter proved to be a more accurate, stable and reliable measurement of the flow rate than the orifice plate meter run that was previously used. Additionally the entrained gas fraction or gas void fraction (GVF) measurement indicated that air or hydrocarbon gas was present in the brine intermittently and at varying level. Figure 6 shows sample flow rate and GVF data during a 24-hour period of operation. Note that the GVF is variable and is as high as 1% (by volume). Combining the flow rate measurement and the GVF measurement gives the ability to determine the gas phase flow rate in real time and total cumulative gas volume as shown in Figure 7.

The second application is a sonar meter installed on a 10-inch NGL pipeline that is used to transport various NGL's including ethane, propane, n-butane, i-butane and natural gasoline. In this case the sonar meter was used as a check meter to measure the flow rate which could be compared to the custody transfer quality turbine meter skid (0.25% reported accuracy) and to use the sound speed measurement to confirm what type NGL was flowing in the pipeline. As shown in Figure 8, the flow rate measurement matched very closely to the turbine meter. Overall the sonar meter was within 1% of the turbine meter in nearly all cases. The measured sound speed is also shown on the upper curve in Figure 8. A distinct drop in the measured sound speed from approximately 3250 ft/sec to 2900 ft/sec (990 to 885 m/s) is seen just after midnight. The line temperature was around 85 °F. Using data from Figure 1 the sound speed change clearly indicates a product change from iso-pentane to n-butane.

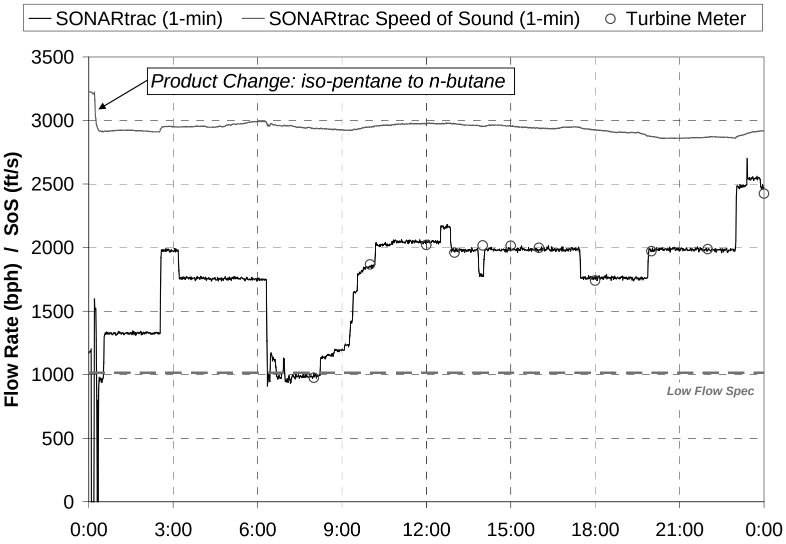

Figure 8: SONARtrac® Flow Rate and Sound Speed Measurement on 10" NGL Application

6 CONCLUSIONS

Sonar based flow monitoring enables the direct measurement of the convective transport velocity of turbulent eddies in pipe flow and it enables the direct measurement of the speed of sound propagating through the pipe. Both measurements can be made using an array of strain based sensors clamped to the outside of the process piping.

Evidence is presented to prove that the convective transport velocity of turbulent eddies is proportional the volumetrically averaged mean velocity. A Reynolds number based, empirical calibration is introduced which yields 0.5% accuracy for Newtonian fluids. Thus, a novel technique based upon naturally occurring phenomena in pipe flow allows the realization of a calibrated flow meter.

It is shown how the speed of sound in a two-phase medium can be used to derive compositional information such as volumetric fraction of entrained gas in two-phase gas/liquid flows and product identification in two-component liquid flows. When determining gas content, the effect of liquid and gas properties is discussed. Neither the temperature nor the gas molecular weight has any influence, only the liquid density and the process pressure must be known. When identifying product type in two-component liquid flows, the pure-phase density and sound speed of both components is required.

Industrial applications of the sonar based flow meter are discussed. An example field trial of brine and NGL flow applications at an NGL storage facility is given where the passive nature of the sonar based instrument and the additional ability to measure mixture sound speed and entrained gas content proved to be a distinct advantage.

7 ACKNOWLEDGEMENTS

The results presented in this work have benefits from several years of collaborative efforts to develop sonar-based flow measurement. The authors gratefully appreciate the efforts of the many colleagues and co-workers that have contributed to results presented herein.

8 REFERENCES

---

1 NIELSEN, R.O., Sonar signal processing, Artech House Inc, Norwood, MA, 2001, ISBN 0-89006-453-9

2 KRAGAS, T. K., et al., “ Downhole, Fiber Optic Multiphase Flow Meter: Field Installation” Presented at the Society of Petroleum Engineers Annual Conference, SPE Paper #77654, September, 2002.

3 KRAGAS, T. K., et al., “Downhole Fiber-Optic Multiphase Flowmeter: Design, Operating Principle, and Testing,” Presented at Society of Petroleum Engineers Annual Conference, SPE Paper #77655, September, 2002.

4 LANDAU M.T., MOLLO-CHRISTENSEN, E., Turbulence and Random Processes in Fluid Mechanics, 2nd Edition, Cambridge University Press, Cambridge, UK, ISBN 0-521-42213-2, 1992.

5 BERANEK, L.L., VER, I.S.,” Noise and Vibration Control Engineering,” Section 14.6, John Wiley and Sons, New York, ISBN 0-471-61751-2, 1992

6 GYSLING, D.L., MUELLER, E., Application of sonar based, clamp on flow meter in oil sand processing, ISA 2004 Exhibit and Conference, Edmonton section, April 2004.

7 GYSLING, D.L., LOOSE, D.H., Sonar based volumetric flow meter for pulp and paper applications, CiDRA Corporation, Wallingford, CT, 2003, unpublished work.

8 GYSLING, D.L., VAN DER SPEK, A.M., Fiber optic downhole multiphase flow meter: flow loop evaluation for oil/water mixtures, Downhole Instrumentation seminar, North Sea Flow Metering Workshop, Glasgow, Scotland, 23 October 2000.

9 GYSLING, D.L., VANDEWEIJER, T., VAN DER SPEK, A.M., Development of a permanent downhole twophase flow meter, SRI multiphase metering and pumping conference, Houston TX, February 2000

10 MC WILLIAM, D. DUGGINS, R.K., Speed of sound in bubbly liquids, Proc Instn Mech Engrs, Vol 184, Part 3C, 1969-1970.

11 WOOD, A., A textbook of sound, New York, NY, 1st edition, 1930

12 GYSLING, D.L., LOOSE, D.H., Sonar based volumetric flow and entrained air measurement for pulp and paper applications, TAPPI Spring Technical Conference, paper 58-1, Chicago, IL, May 2003.

13 STOOR, T., ÄMMÄLÄ, A. NIINIMÄKI, J., Measurement of air content of pulp suspension – sonar method, APPITA 2005 pulp and paper conference, Auckland 16 – 19 May 2005.

14 GYSLING, D.L, LOOSE, D.H., Using sonar bsed gas volume fraction meter for improved net oil rate measurement, Canadian School of Hydrocarbon Management, Toronto, 2005.

15 GYSLING, D.L., BANACH, T. Accurate liquid phase density measurement of aerated liquids using speed of sound augmented Coriolis meters, ISA, Houston, October 2004.