SONAR-BASED VOLUMETRIC FLOW AND ENTRAINED AIR MEASURMENT FOR PULP AND PAPER APPLICATIONS

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Abstract

A sonar-based flow measurement technology for simultaneously measuring volumetric flow rate and volumetric percent of entrained air in paper and pulp slurries is described. The technology utilizes sonar array processing techniques to perform two independent measurements to characterize the process fluid. Firstly, the meter provides mixture volumetric flow by tracking the speed at which naturally occurring turbulent structures convect with the flow past an axial array sensors. The flow meter can be implemented either pressure transducers ported directly to the process fluid or with non-intrusive sensors clamped-on to existing process piping. Secondly, the meter utilizes the same sensors to determine the speed at which naturally occurring sound propagates through the process fluid. The speed of sound measurement provides an accurate and robust measurement of entrained air. Utilizing these two first principles based measurements, the sonar flow meter provides total mixture flow rate, while measuring and correcting for entrained air.

Data is presented that demonstrates the ability of the sonar meter to measure flow rates in single phase flows to within 0.5% accuracy for flows ranging from 3 to 20 ft/sec in a wide range of diameters. Calculations are presented demonstrating the link between entrained air and mixture sound speed indicating that the sonar meter can measure entrained air on a real time basis to an accuracy of better than 0.1% by volume.

Introduction

Multiphase process flow rate is a critical process control parameter for the paper and pulp industry. Knowing the amounts of liquid, solids and entrained gases flowing in process lines is key to optimizing the overall the papermaking process (Matula, 2000). Unfortunately, significant challenges remain in the achieving accurate, reliable, and economical monitoring of multiphase flow rates of paper and pulp slurries. Reliability challenges arise due the corrosive and erosive properties of the slurry. Accuracy challenges stem from the multiphase nature of the slurries. Economical challenges arise from the need to reduce total lifetime cost of flow measurement, considering installation and maintenance costs in addition to the initial cost of the equipment.

Currently, there is an unmet need for multiphase flow measurement in the paper and pulp industry. Real time flow measurement is typical restricted to monitoring the total volumetric flow rate in a process line without providing information on the composition of the process mixture. For example, electromagnetic flow meters are the most widely used flow meters in the paper and pulp industry, however they provide no indication of presence of entrained air, with its presence resulting in an over prediction of the volumetric flow of process fluid by the amount of air entrained. Consistency meter provide a measurement of the percentage of solids within the process, however this technology remains more of an art than a science. Furthermore, although entrained air is known to have a large, often deleterious, impact on the paper making process, instrumentation is currently not available to provide this measurement on a real time basis.

This paper describes how sonar based technology addresses the need for accurate, reliable multiphase flow measurement in the paper and pulp industry. Sonar flow meters utilize a sound speed measurement in conjunction with a volumetric flow measurement to simultaneously monitoring flow rate and entrained air. A flowchart for measuring flow with entrained air is shown in Figure 1. By providing real time measurements of total volumetric flow rate, liquid flow rate, and gas volume fraction of entrained air, the sonar flow meter provides a unique measurement capability for optimizing the paper making process.

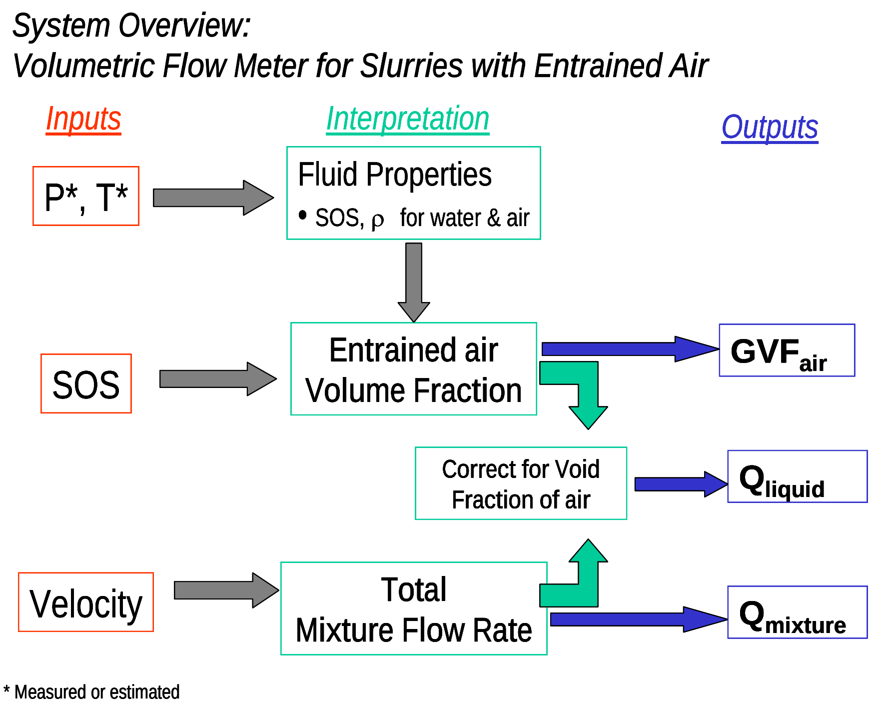


Figure 1: Flowchart for measuring flow rates in Slurries with entrained air

Measurement Methodology

The sonar flow meter utilizes sonar processing techniques to provide two fundamental measurements on the process fluid. Firstly, by tracking the speed at which coherent structures within the process fluid convect past the sensors, the meter provides a measurement of the total volumetric flow. Secondly, by determining the speed at which acoustic disturbance propagate within the process fluid lines, the meter determine the percentage of entrained air presence in the process fluid. Both measurement are derive by interpreting the unsteady pressure field within the process piping using multiple transducers displaced axially over ~ 2 diameters in length. The flow measurements can be performed using ported pressure transducers or clamp-on, strain-based sensors.

Volumetric Flow Rate

To measure volumetric flow, the sonar meter characterizes speed at which coherent vortical structures convect past an axial array of sensors using beam-forming techniques developed over several decades for underwater acoustic applications. Coherent structures are an inherent feature of turbulent boundary layers present in all turbulent pipe flows. Unlike conventional vortex shedding meters, no internal geometry is required to generate these structures.

Figure 2 illustrates the relevant flow features of turbulent pipe flow along with an axial array of sensors. As shown, the time-averaged axial velocity is a function of radial position, from zero 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. Vortical structures, often termed turbulent eddies, are superimposed over time averaged velocity profile. These coherent structures contain temporally and spatially random fluctuations with magnitudes typically less than 10% percent of the mean flow velocity and are carried along with the mean flow. Experimental investigations have established that eddies generated within turbulent boundary layers remain coherent for several pipe diameters and convect at roughly 80% of maximum flow velocity (Schlichting, 1979).

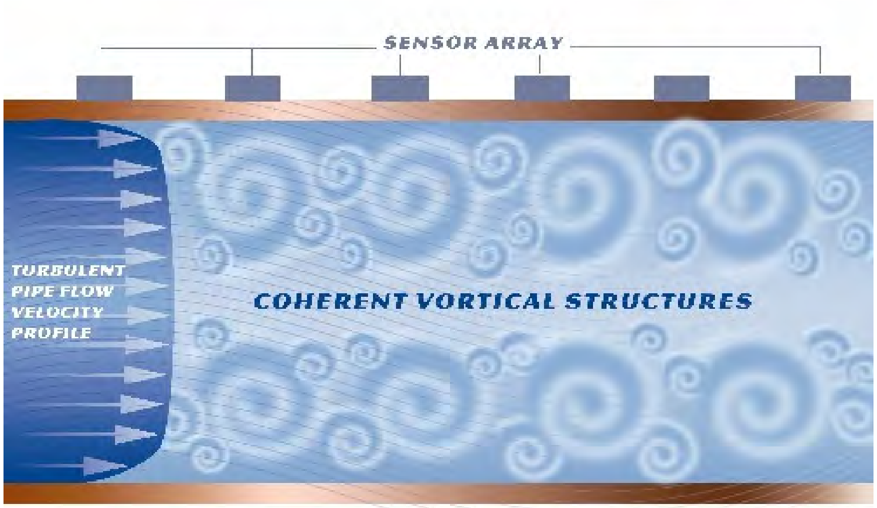


Figure 2: Coherent Structures within Turbulent Pipe Flows

From a volumetric flow measurement perspective, the volumetrically averaged flow velocity is of interest. The volumetrically averaged flow velocity, defined as the total volumetric flow rate, Q, divided by the cross sectional area of the conduit, A, is a useful, but arbitrarily defined property of the flow. In fact, given the velocity profile within the pipe, little flow is actually moving at this speed. The precise relationship between the convection speed of turbulent eddies and the flow rate is determined experimentally through calibration for each.

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:

$$\mathrm{Re} = \frac{inertial}{viscous}\,forces = \frac{\rho u \frac{\partial u}{\partial x}}{\mu \frac{\partial^2 u}{\partial y^2}} = \frac{UD}{\nu}$$

Where ρ is the fluid density, μ is the dynamic viscosity, U is the volumetrically averaged flow velocity and ν (= μ /ρ) is the kinematic viscosity.

The critical Reynolds number for pipe flows, above which flows are considered turbulent, is ~2300. Most flows in the paper and pulp industry have Reynolds number ranging from one hundred thousand to several million, well within the turbulent regime. In addition to demarcating a boundary between laminar and turbulent flow regimes, the Reynolds number is a similarity parameter for pipe flows, i.e. flows in geometrically similar pipes with the same Reynolds number are dynamically similar (Schlichting p.12).

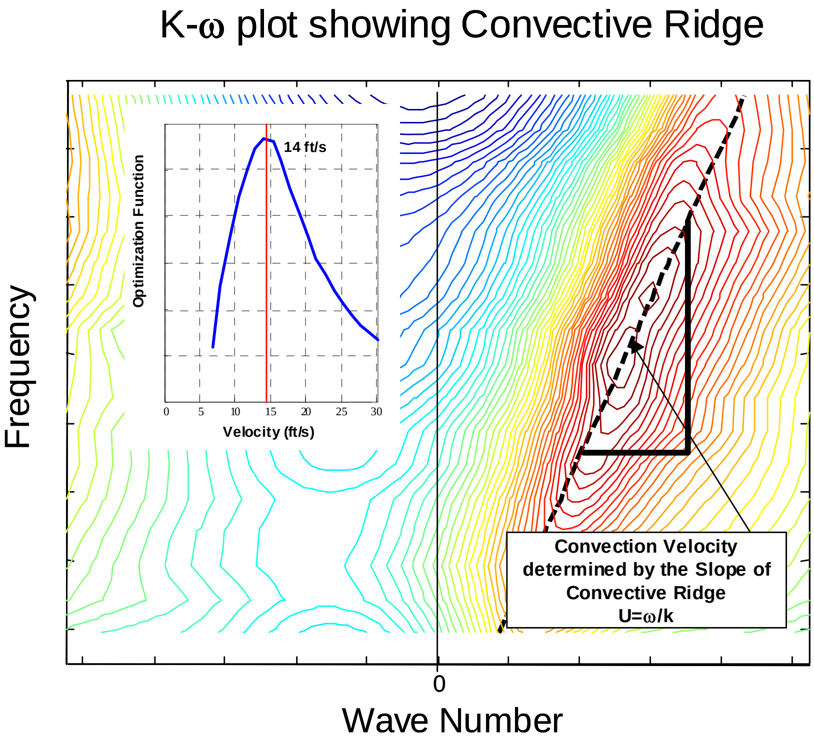
The Convective Ridge

The sonar flow meter uses the convection velocity of coherent structures (eddies) inherent within turbulent pipe flows to determine the volumetric flow rate. The sonar-based algorithms determine the speed of the turbulent eddies by characterizing both the temporal and spatially frequency characteristics of the flow field. For a series of coherent eddies convecting past a fixed array of sensors, the temporal and spatial frequency content of pressure fluctuations are related through a dispersion relationship which can be expressed as follows:

$$\omega = kU_{convect}$$

Here k is the wave number, defined as $k=2\pi/\lambda$in units of 1/length.,ω is the temporal frequency in rad/sec, and $U_{convect}$ is the convection velocity or phase speed of the disturbance. The dispersion relationship basically states that temporal variations observed at a fixed location are proportional to the convection speed and inversely proportional to the spatial wavelength of the disturbance.

In sonar array processing, the spatial / temporal frequency content of time stationary sound fields are often displayed using “k-ω plots”. K-ω plots are essentially three-dimensional power spectra in which the power of a sound field is decomposed into bins corresponding to specific spatial wave numbers and temporal frequencies. On a k-ω plot, the power associated with a pressure field convecting with the flow is distributed in regions which satisfies the dispersion relationship developed above. For turbulent boundary flows, this region is termed “the convective ridge” (Beranek, 1992) 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 sensor and identifying the slope of the convective ridge.



Convection Velocity determined by the Slope of Convective Ridge U=ω/k

Figure 3: K-w plot generated from an array of sensors listening to water flowing in a 6 inch pipe at ~1000gpm.

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 14.2 ft/sec was determined. The intermediate result of the optimization procedure is displayed in the insert, showing that optimized value is a unique and well-defined optima.

The k-w plot shown in Figure 3 illustrates the fundamental principle behind sonar based flow measure, namely that axial arrays of pressure transducers can be used in conjunction with sonar processing techniques to determine the speed at which naturally occurring turbulent eddies convect within a pipe. However, to provide an accurate flow measurement, the relationship between speeds of these turbulent eddies and the volumetrically averaged flow rate within the pipe must be quantified through calibration. To this end, three geometrically similar sonar flow meters with diameters of 3 inch, 6 inch, and 16 inch were tested at a flow meter calibration facility for flows ranging from 20 to 20,000 gpm. Figure 4 shows the convection velocity determined using the sonar-based techniques, normalized by the volumetrically averaged flow rate supplied by the calibration facility as a function of Reynolds number. As shown, the measured convection velocity, i.e. the slope of the convective ridge, ranged between 99% and 102% of the volumetrically averaged flow rate over the entire range test. A low-order Reynolds number calibration, shown on Figure 4, was developed from this data for this class of meters.

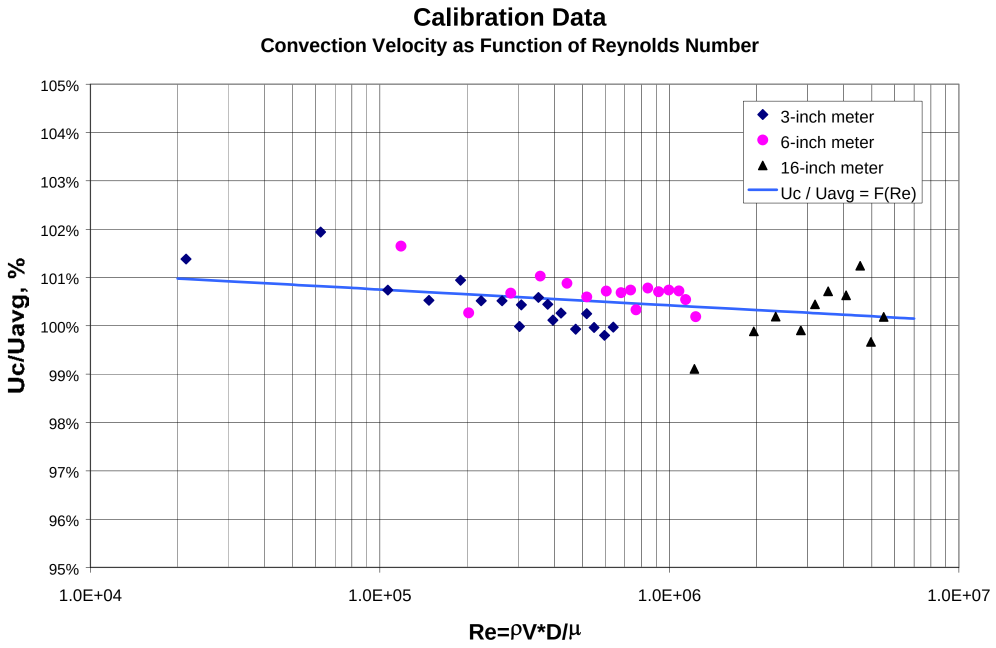


Figure 4: Measured Convection Velocity (normalized by the volumetrically-averaged velocity) as a function of Reynolds Number

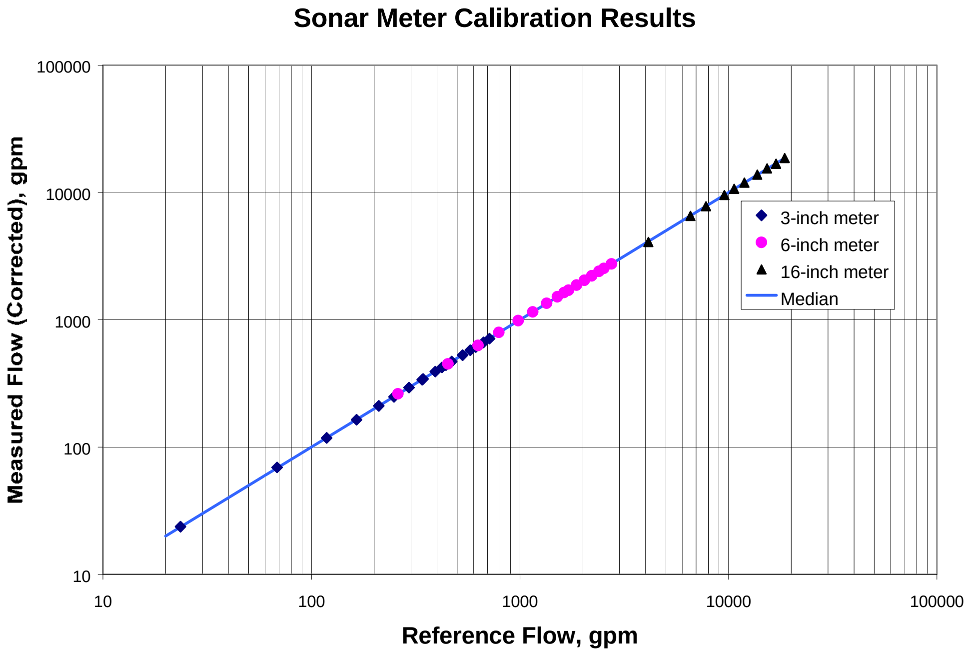


Figure 5: Volumetric Flow Rate measured using the Sonar based flow meter versus Reference Flow Rate

Figure 5 shows the volumetric flow rate measured by the calibrated sonar meters plotted versus reference flow. Calibration data was recorded for the three flow meters with volumetrically averaged flow velocities ranging from 3-30 ft/sec. Using the Reynolds number calibration shown on Figure 4 for the three geometrically scaled meters, the sonar meter measured the volumetric flow rate to within 0.5% accuracy over a combined operating range from 20 gpm to 20000 gpm,. It is important to note that this flow metering approach has no fundamental size limitations and is applicable to turbulent flows in pipes of all diameters and Reynolds numbers. Furthermore, similarity laws suggest, and data from Figure 5 support, that the relationship between convection velocity and flow rate from geometrically similar meters of any size is be governed by similar Reynolds number based calibrations.

Entrained Air Measurement

As outlined in Figure 1, the sonar meter measures the speed at which acoustic waves propagating in the process piping to determine the amount of entrained air in the process line. The connection between speed of sound of a two-phase mixture and phase fraction is well established for mixtures in which the wave length of the sound is significantly larger than flow inhomogenieities, i.e. bubbles, in the flow. Thus, for long wavelength sound propagation, the sound speed of a mixture can be related to volumetric phase fraction (ϕ_i) of the components and the sound speed (a_i) and densities (ρ_i) of the components through the following relation.

$$\frac{1}{\rho_{mix} a_{mix_\infty}^2} = \sum_{i=1}^{N} \frac{\phi_i}{\rho_i a_i^2} \qquad \text{where } \rho_{mix} = \sum_{i=1}^{N} \rho_i \phi_i$$

The mixing rule essentially states that the compressibility of a mixture ($1/(\rho\ a^2)$) is the volumetrically-weighted average of the compressibility's of the components. For gas / liquid mixtures at pressure and temperatures typical of paper and pulp industry, the compressibility of gas phase is orders of magnitudes greater than that of the liquid. Thus, the compressibility of the gas phase and the density of the liquid phase primarily determine mixture sound speed., and as such, it is necessary to have a good estimate of process pressure to interpret mixture sound speed in terms of volumetric fraction of entrained air. The effect of process pressure on the relationship between sound speed and entrained air volume fraction is shown in Figure 6.

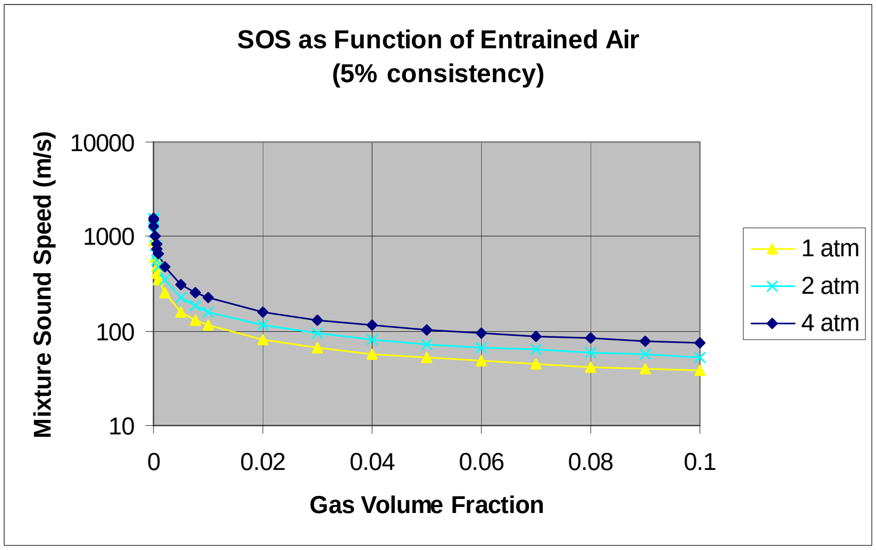


Figure 6: Mixture Sound Speed as a function of entrained air volume fraction for a 5% consistency slurry over a range of process pressures

Conversely, however, detailed knowledge of the liquid / slurry is not required for entrained air measurement. Variations in liquid density and compressibility with changes in consistency have a negligible effect on mixture sound speed compared to the presence of entrained air. Figure 7 shows the mixture sound speed as a function of entrained air volume fraction for two slurries, one with 0% wood fiber and the other with 5% wood fiber by volume. As shown, the relationship between mixture sound speed and gas volume fraction is essentially indistinguishable for the two slurries. Furthermore, mixture sound speed is shown to an excellent indicator of gas volume fraction, especially for the trace to moderate amounts of entrained air, from 0 to 5% by volume, typically encountered in the paper and pulp industry.

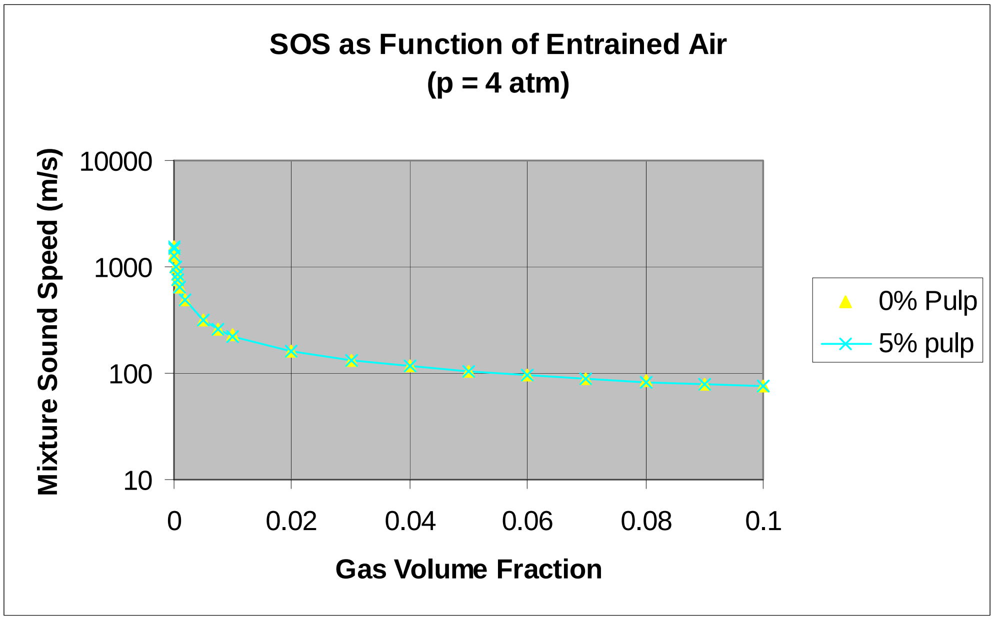


Figure 7: Mixture Sound Speed a function of entrained air volume fraction for pure water and a 5% consistency slurry at 4 atm process pressure

Speed of Sound Measurement

As described above, the relationship between mixture sound speed and entrained air 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 present significant challenges to ultrasonic sound speed measurement devices.

Ultrasonic meters typically operate in 100 KHz to several MHz frequency range. For these meters, entrained air 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 inhogenieties, such as stratification of entrained air 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 velocity of operationally generated sound in the ~100 to 1000 Hz frequency range. 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 any 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.

$$k = \frac{\omega}{a_{mix}}$$

As before, k is the wave number, defined as $k=2\pi/\lambda$, ω is the temporal frequency in rad/sec, and a_{mix} is the speed at which sound propagates within the process piping. 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 $a_{mix} + V_{mix}$ and one for the sound traveling against the flow at a speed of $a_{mix} - V_{mix}$.

Figure 8 shows a k-ω plot generated for acoustic sound field recorded from water flowing at a rate of 240 gpm containing ~2% entrained air by volume in a 3 in, schedule 10, stainless steel pipe. The k-ω plot was constructed using data from an array 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 sound speed for this for this mixture was 330 ft/sec (100m/s), consistent with that predicted by the Wood equation. Note that adding 2% air by volume reduces the sound speed of the bubbly mixture to less than 10% of the sound speed of liquid-only water.

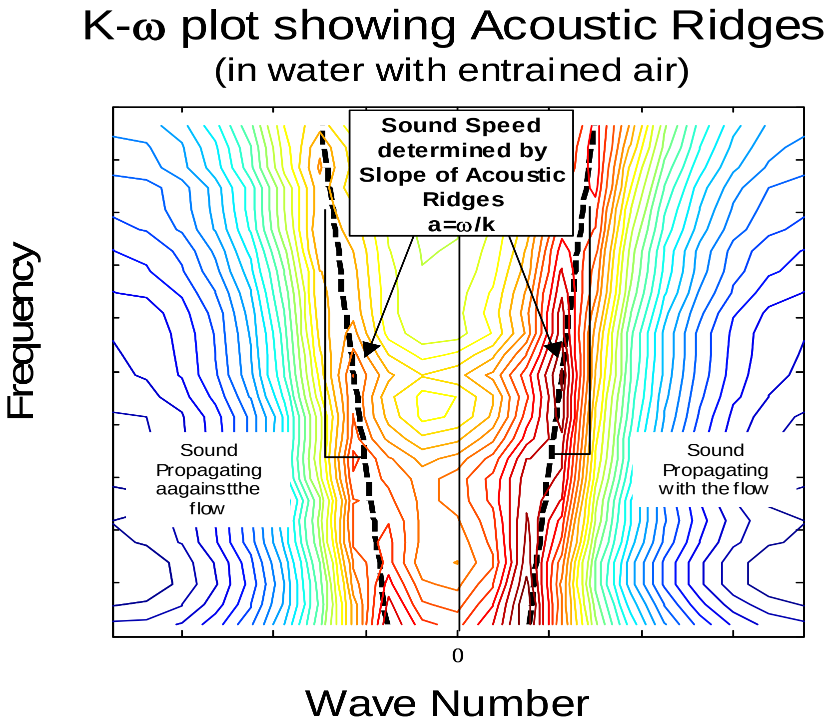


Figure 8: K-w plot for Acoustic field within 3 inch pipe containing ~2% air by volume entrained in water flowing 240 gpm

Summary

A Sonar-based flow measurement methodology was presented with properties well-suited to meet the multiphase flow measurement challenges in the pulp and paper industries. The sonar meter provides volumetric flow and gas volume fraction by applying sonar processing techniques to extract two fundamental measurements from the unsteady pressure field with process piping networks, namely convection velocity and sound speed. Both are measurements are performed with the same physical hardware. The methodology can be applied using array of either ported pressure transducers or clamp-on strain based sensors.

Data was presented showing the ability of track the speed of turbulent eddies and that this speed closely tracks the volumetric flow rate in a pipe. Using a Reynolds number based calibration, the Sonar flow meter demonstrated 0.5% accuracy over a wide range flow rates.

The principle of operation for sonar-based entrained air measurment was presented. Through well-established analytical models, the link between mixture sound speed and entrained air content of in pulp and paper slurries was presented. The relationship provides an accurate means to measure gas volume fraction (within ~0.1% by volume) without requiring detailed knowledge of slurry consistency. Data was presented showing the ability of the sonar meter to characterize the acoustic pressure field and extract sound speed from a bubbly liquid containing ~2% entrained air.

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