SONAR-BASED VOLUMETRIC FLOW METER FOR PULP AND PAPER APPLICATIONS

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Abstract
A sonar-based flow measurement technology well-suited for the pulp and paper industry is described. Developed and field proven in numerous applications within the oil and gas industry over the last four years, the methodology provides robust, high-accuracy, volumetric flow rate measurement for a broad range of single and multiphase flow applications. The methodology can be implemented with pressure transducers ported to process fluid or with non-intrusive sensors clamped-on to existing process piping. Sonar-based flow metering technology utilizes an array of sensors to listen to the unsteady pressure field within standard process flow lines. Flow rate is determined using sonar array processing techniques to track the speed at which coherent structures, inherent within the turbulent pipe flow of the process fluid, convect past the sensor array. This convection speed is directly related to volumetric flow rate through a Reynolds number calibration. Results from a single-phase calibration facility are presented demonstrating 0.5% accuracy for pipes ranging from 3 to 16 inches in diameter.

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 used for greater than 70 years and includes turbine meters, orifice plates 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 meters, electromagnetic flow meters, vortex flow meters, and coriolis flow meters. Each type has evolved to serve various aspects of the diverse range of applications within the industrial flow meter landscape. For the pulp and paper industry, the electromagnetic flow meter has emerged as the dominant type of flow meter.

This paper describes sonar-based flow meter technology which utilizes sonar techniques 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 (Kragas, 2002). Sonar flow measurement technology is currently being adapted for use in other industries such as pulp and paper, chemicals and power generation.

The methodology involves characterizing speed at which coherent vortical structures convect past an axial array of sensors using beam-forming techniques developed over several decades for underwater acoustic application. Since these coherent structures are an inherent feature of turbulent boundary layers, no internal geometry is required to generate these structures. The sonar-based measurement can be performed using pressure sensors directly using ported into the process fluid or sensed through the wall of the pipe with clamp-on, strain-based sensors. With no process-wetted hardware, the sonar flow measurement technology is well suited for the corrosive and abrasive slurries commonly encountered in the pulp and paper industry

Turbulent Pipe Flow

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 reason, turbulent pipe flows have been extensively studied over the years with roots back to Osbourne Reynolds and Lord Rayleigh in the late nineteenth century (Landau, 1992).

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 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 1 shows a representative schematic of a velocity profile and coherent vortical flow structures present in fully developed turbulent pipe flow.

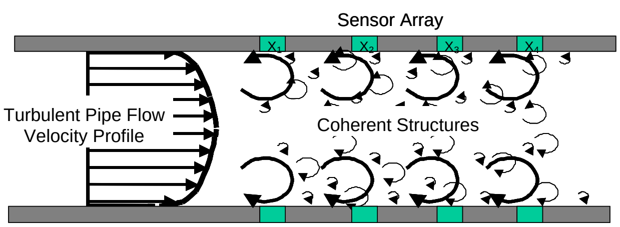

Figure 1: Coherent Structures within Turbulent Pipe Flows

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:

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

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.

Pipe flows with Reynolds numbers exceeding a critical value, typically Re_{crit} ~2300, are turbulent. Those with Reynolds numbers below this value are laminar. Figure 2 shows the Reynolds for a range of flows representative of those employed in the pulp and paper industry, indicating that all of the flows considered are turbulent with Reynolds number far in excess of the critical number

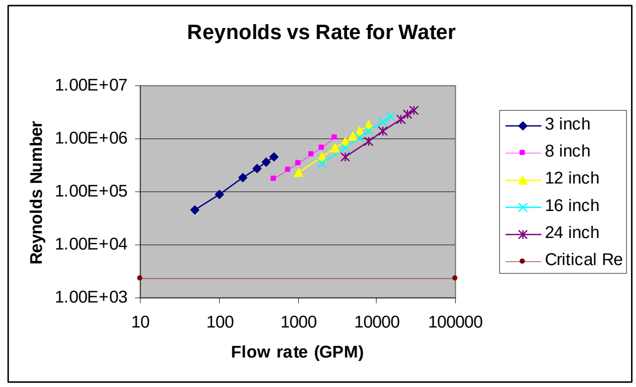

Figure 2: Reynolds Numbers for Water Flows in Common Industrial Processes

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, scaled with radius, with the same Reynolds number are dynamically similar (Schlichting p.12). Empirical studies have shown that velocity profiles in turbulent pipe flows are well represented by the 1/nth power law.

$$\frac{u}{U_{\max}} = \left(\frac{1-y}{R} \right)^{\frac{1}{n}}$$

with "n" ranging from 6 to 10 as weak function of Reynolds number. Figure 3 shows the velocity profiles predicted by empirical equation developed over for flows over a range of Reynolds numbers of 3 orders of magnitude.

From a volumetric flow measurement perspective, the volumetrically averaged flow velocity is of interest. The volumetrically averaged flow velocity, defined as V=Q/A, is a useful, but arbitrarily defined property of the flow. Here, A is the cross sectional area of the pipe and Q is the volumetric flow rate. In fact, given the velocity profile within the pipe, little flow is actually moving at this speed. The relation between this quantity and maximum flow velocity at the centerline of the pipe is shown in Figure 4 as a function of Reynolds calculated based on the 1/nth power law.

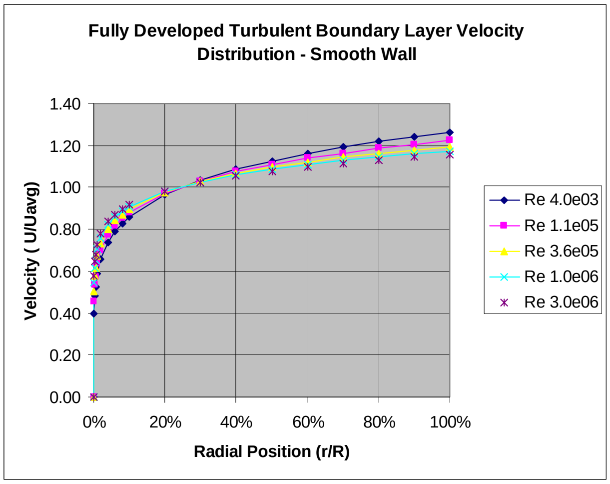

Figure 3: Velocity profiles for Fully Developed Turbulent Flows for a range of Reynolds Numbers

As shown, the ratio between the volumetric average flow velocity and the maximum velocity is a weak function of Reynolds number ranging from slightly below 80% near the critical Reynolds numbers to slightly greater than 85% of the centerline velocity at Reynolds above 1e06.

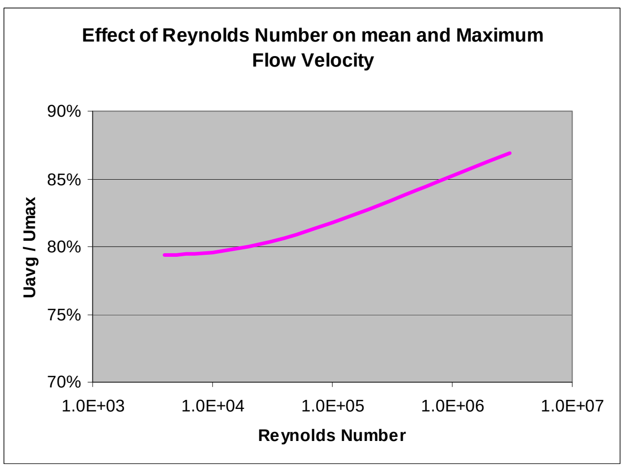

Figure 4: Volumetrically Averaged Flow Velocity normalized by Centerline Flow Velocity as Function of Reynolds Number

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 is set by the diameter of the pipe (TL p. 13, 14). These structures remain coherent for several pipe diameters downstream (Schlichting, 1979), 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 (Schlichting, 1979). 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 convection speed of turbulent eddies and the flow rate for each class of meters can be calibrated empirically as described below.

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Characterizing the Unsteady Pressure Field

The sonar flow metering methodology uses the convection velocity of coherent structure with turbulent pipe flows to determine the volumetric flow rate. The convection velocity of these eddies is determined by applying sonar arraying processing techniques to determine the speed at which the eddies convect past an axial array of unsteady pressure measurements distributed along the pipe.

The sonar-based algorithms determine the speed of the eddies by characterizing both the temporal and spatially 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:

$$\omega = kU_{convect}$$

Here k is the wave number, defined as $k=2\pi/\lambda$ and has units of 1/length, ω is the temporal frequency in rad/sec, and $U_{convect}$ is the convection velocity. Thus, the shorter the wavelength (larger k) is, the higher the temporal frequency.

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. 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-ω plot from the output of a phased array of sensor and identifying the slope of the convective ridge.

Figure 5 shows an example of a k-ω plot generated from a phased array of pressure transducers listening to a 6 inch pipe flowing water at approximately 1000 gpm. 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.

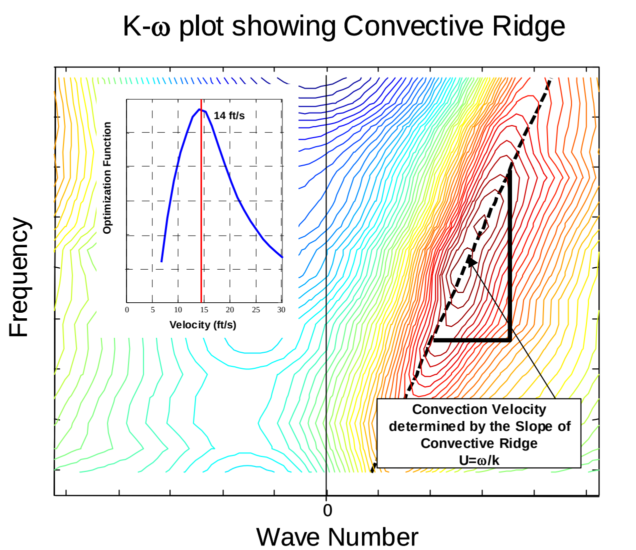

Figure 5: K-w plot generated from an array of sensors listening to water flowing in a 6 inch pipe at ~1000gpm

The k-w plot shown in Figure 5 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. The next issue quantify the relationship between speed of the turbulent eddies and the volumetrically averaged flow rate within the pipe.

To quantitatively evaluate this relationship, 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 6 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 6, was developed from this data for this class of meters.

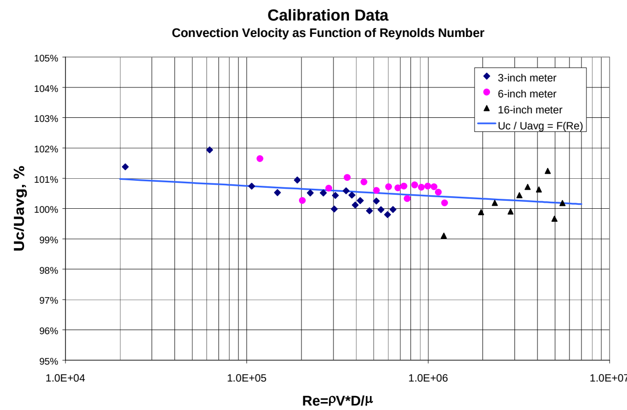

Figure 6: Measured Convection Velocity (normalized by the volumetrically-averaged velocity) as a function of Reynolds Number

Figure 7 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 a single Reynolds number calibration spanning the operating range of the three 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 data from Figure 6 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.

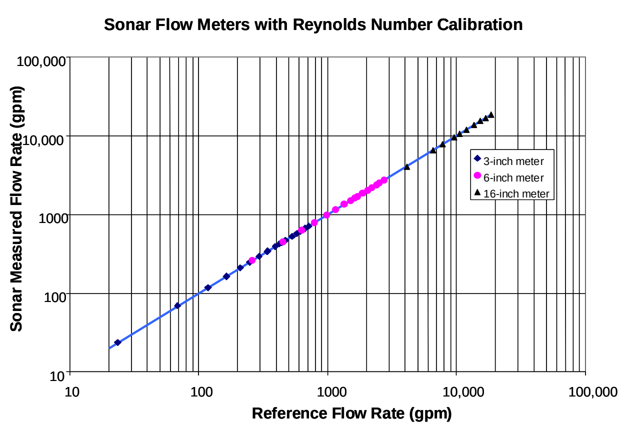

Figure 7: Volumetric Flow Rate measured using the Sonar based flow meter versus Reference Flow Rate

Summary

Sonar flow metering technology for volumetric flow measurement well suited for industrial processes was introduced. Sonar flow meters use an array of sensors axially distributed along the pipe to determine the speed at which naturally occurring turbulent eddies flow through a pipe.

Well known results from turbulent boundary layer theory are presented to establish the behavior of these naturally occurring coherent structures and to link their properties to the time averaged properties of turbulent pipe flows.

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. Exploiting similarity law, a Reynolds number based calibration was developed for a broad range, the Sonar flow meter demonstrates a 0.5% accuracy over a wide range of Reynolds number.

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