SONAR-BASED VOLUMETRIC FLOW METER FOR CHEMICAL AND PETROCHEMICAL APPLICATIONS

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Abstract
A sonar-based flow measurement technology, capable of clamp-on flow measurement of single and multiphase flow applications within the chemical and petrochemical industries, is described. Developed and field proven in oil and gas production industry over the last five years, sonar-based flow measurement technology provides robust accurate volumetric flow rate measurement for a broad range of process fluids, slurries, pipes sizes and flow conditions.

The sonar-based flow metering technology utilizes an array of sensors to listen to, and interpret, unsteady pressure fields within standard process flow lines. The methodology can be implemented using pressure transducers, directly ported in to the process fluid, or using strain-based sensors clamped-on to existing process piping. Flow rate is determined using sonar array processing techniques which track the speed at which turbulent eddies, inherent to turbulent pipe flow, convect past the sensor array. This convection speed is directly related to volumetric flow rate through a Reynolds number calibration.

Results from a calibration facility for both ported-pressure and strain-based, clamp-on configurations of the sonar flow meters are presented. Calibration testing of the sonar-based flow metering technology demonstrated 0.5% accuracy in volumetric flow using a single Reynolds number based calibrations applicable to a family of geometrically similar sonar meters ranging in diameters from 3 to 16 inches. Data is also presented from a field trial in which the sonar-based flow measurement is demonstrated on water-conveyed, solid polymer slurry. This data demonstrates the applicability of sonar-based flow measurements to multiphase slurries, a class of flows that represent a long-standing flow measurement challenge within the chemical and petrochemical processing industries.

Introduction
Volumetric flow rate of process fluids is a critical parameter in process control and optimization within the chemical and petrochemical industries. Reflecting this, the chemical and petrochemical industry is the single largest user of industrial flow meters, spending upwards of $1 billion dollars annually on process flow meters. This paper describes a new class of flow meters that offers advantages over conventional flow measurement technologies for applications important to the chemical and petrochemical industry.

Industrial flow meters are often classified into two technology-based categories: old technology and new technology flow meters. The old technology category refers to flow measurement technologies that have been in use for greater than 70 years, and includes turbine meters, orifice plates and variable area flow meters. The new technology category includes technologies which have emerged over the last 30~50 years. The major types of new technology flow meters include coriolis, electromagnetic, ultrasonic and vortex flow meters. Typically, new technology flow meters offer advantages over the old technology flow meters in performance, functionality, and reliability. Each type has evolved to serve various aspects of the diverse range of applications within the industrial flow meter landscape. Despite the diverse array of measurement technologies currently available, the chemical and petrochemical processing industries continue to have unmet needs for accurate, reliable, and economical monitoring of many single and multiphase flow applications, including, for example, large diameter pipes and liquid-conveyed solid particle slurries.

Sonar flow measurement technology was first introduced into the oil and gas industry in 1998 for use in downhole multiphase flow metering applications (Kragas, 2002), and is currently being adapted for use in other industries including the chemical and petrochemical industries. The measurement principle involves characterizing the speed at which coherent vortical structures flow past an array of sensors, pressure or strain-based sensors, mounted axially along the pipe. Since the coherent structures within the process fluid are inherent features of turbulent boundary layer, no internal geometry is required to generate these structures. This measurement principle is distinct from other existing flow measurement technologies, and has attributes that differentiate it from existing flow measurement technologies. From an array signal processing perspective, sonar-based flow measurement is analogous to beam-forming applications developed over several decades for underwater sonar-based navigation (Nielsen, 1991). Sonar-based measurements can be implemented using pressure transducers directly ported into the process fluid or using strain-based sensors clamped-on to the outside of the process piping. With its ability to clamp-on to existing process lines eliminating any process-wetted hardware, the clamp-on configuration is particularly well-suited for many corrosive and abrasive process flows commonly encountered in the chemical and petrochemical industries.

Volumetric Flow Rate

A schematic of the relevant structures within a turbulent process flow is shown in Figure 1. As shown, the time-averaged axial velocity is a function of 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. The turbulent eddies are superimposed over a time averaged velocity profiles. These coherent structures contain 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).

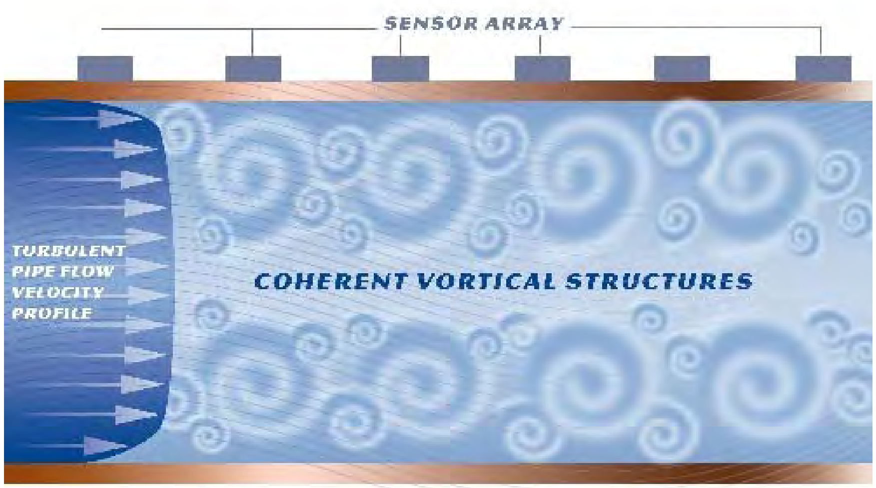

Figure 1: Coherent Structures within Turbulent Pipe Flows

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 chemical and petrochemical 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).

Sonar Processing

The sonar-based 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, 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 three-dimensional power spectra in which the power of a sound field is decomposed into bins corresponding to specific spatial wavenumbers and temporal frequencies. On a k-ω plot, the power associated with a pressure field convecting with the flow is distributed in regions that satisfy 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-ω plot indicates the speed of the turbulent eddies. Thus, identifying the slope of the convective ridge provides a means to determine the convection speed of the turbulent eddies; and with calibration, the precise volumetric flow rate within a pipe.

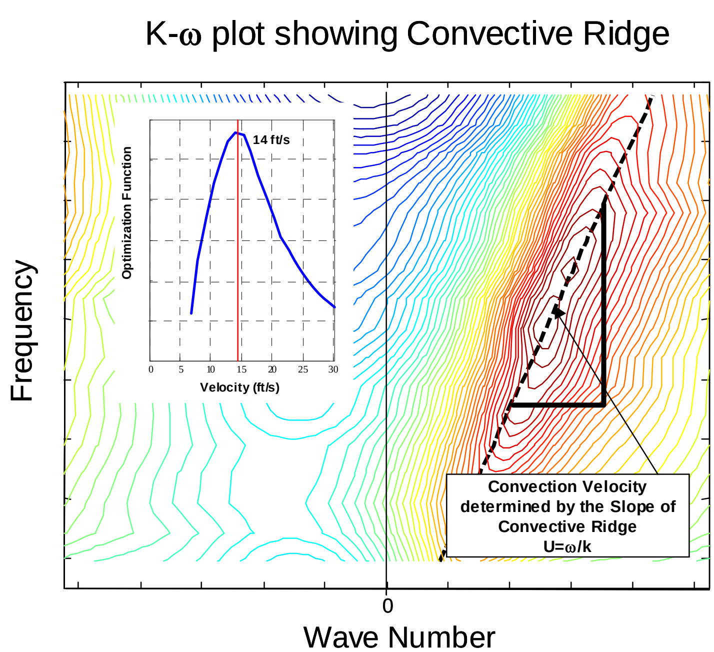

Figure 2: K-ω plot generated from an array of sensors listening to water flowing in a 6 inch pipe at ~1000gpm.

Figure 2 shows a k-ω plot generated from the using the 6-inch diameter sonar-based flow meter, shown in Figure 3, operating at a calibration facility. As shown, 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 optimization function is displayed in the insert as a function of convection velocity, showing that optimized value is a well-defined optimum.

Figure 3: Photograph of a 6-inch diameter Sonar-based flow meter using 5 ported pressure transducers

Calibration

The k-ω plot shown in Figure 2 illustrates the fundamental principle behind sonar-based flow measurements, 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 the speed 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-based 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 5 shows the volumetric flow rate measured by the calibrated sonar-based flow 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 in Figure 4 for the three geometrically scaled meters, the sonar-based meter measured the volumetric flow rate to within 0.5% accuracy over a combined operating range from 20 gpm to 20,000 gpm.   It is important to note that the sonar flow metering methodology has no fundamental size or flow rate limitations, being applicable to turbulent flows in pipes of all diameters and Reynolds numbers. Furthermore, similarity laws suggest, and data from Figure 4 support, that the relationship between convection velocity and flow rate from geometrically similar meters of any size can be calibrated with a single Reynolds number based calibration.

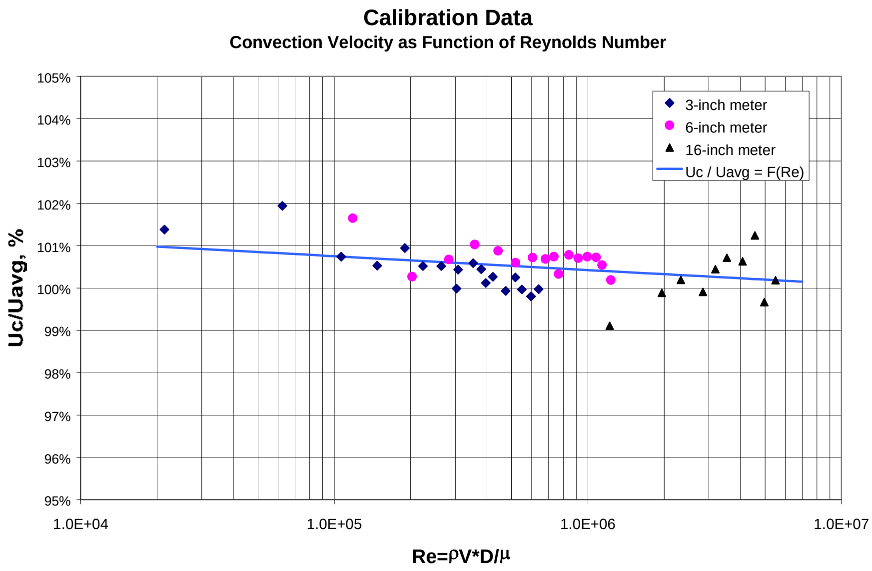

Figure 4: Ratio of convection velocity to volumetrically-averaged flow rate as function of Reynolds Number for 3", 6", and 16 " Sonar-based flow meters

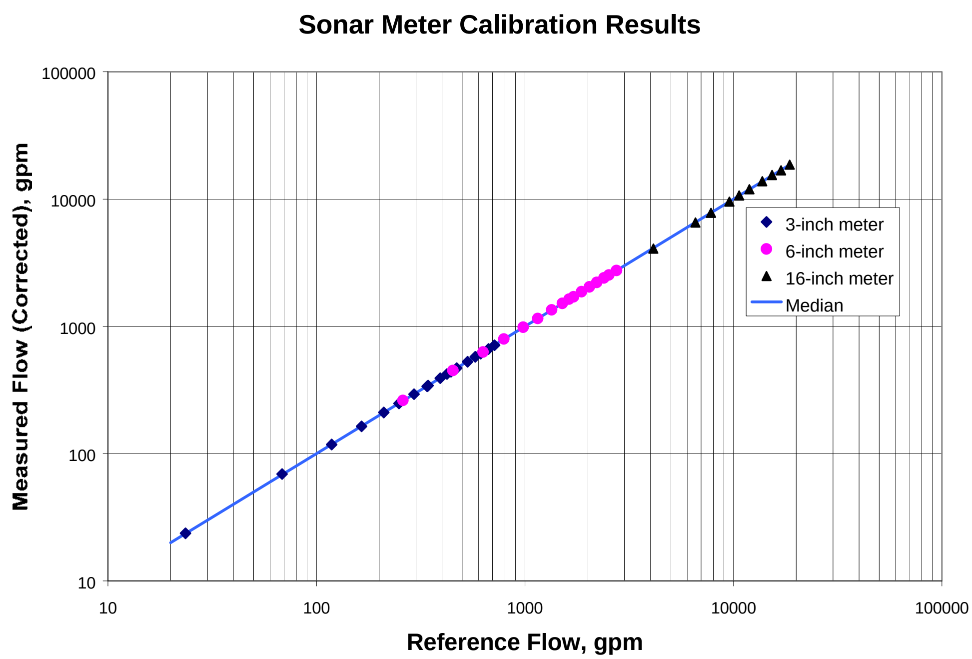

Figure 5: Volumetric Flow Rate measured using the Sonar based flow meter versus Reference Flow Rate

Strain-based Clamp-on Configuration

As developed above, sonar-based flow measurements have been performed with 1) arrays of ported pressure transducers or 2) with strain-based sensors clamped-on the existing process lines. The ability to clamp-on and measure single and multiphase industrial flows is an important feature of sonar-based flow metering technology.

Figure 6 shows an 8-inch sonar-based flow meter using six strain-based sensors clamped onto a schedule 40 stainless steel pipe. Calibration data from this configuration is presented in Figure 7. In this investigation, the clamp-on flow meter measured the flow rate of water to within 1.0% accuracy over of range of 500 gpm to 5,000 gpm in an 8-inch pipe.

Figure 6: Photograph of an 8-inch diameter Sonar-based flow meter using six Clamp-on strain-based sensors

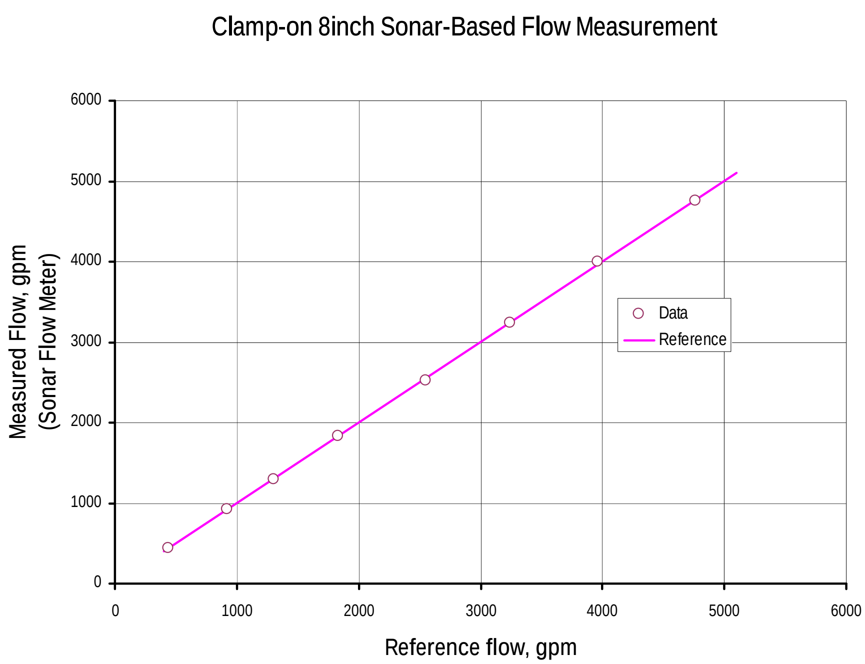

Figure 7: Volumetric Flow Rate measured using the Sonar based flow meter versus Reference Flow Rate

Field Test Results: Polymer Slurry Application
The calibration data presented above demonstrates that sonar-based flow meters can provide an accurate, first principles-based, flow measurement over a range of pipes using either ported pressure or clamp-on based strain sensors in clean, single phase (water) applications. However, unlike many conventional flow metering technologies, sonar-based flow measurement is equally well-suited for both single and multiphase flows.

To evaluate the applicability of sonar-based flow measurement technology to multiphase flows important to the chemical processing industry, a field trial was conducted on 3 inch flow line carrying a near-boiling, water-conveyed slurry of 1/8" to 1" sized polymer crumbs ranging from 0 to 8% mass fraction. Liquid-conveyed, solid-particle slurries are widely used in chemical manufacturing. Due to the erosive nature of the flow, varying chemical composition, potential for clogging, and other reasons, an accurate and reliable flow measurement of these slurries has proved difficult for conventional flow meter technologies.

For the field trial a ported-pressure spool-piece was designed and fabricated to meet the specifications of the plant operator. The spool-piece housed five, flush-mounted pressure transducers, and was fabricated using standard, 3 inch, 150 lb flanges. Prior to installation, the spool-piece was hydrostatically tested to 250 psi. As a benchmark, the sonar-based flow meter was compared with the output of an 3-inch electromagnetic (mag) flow meter installed in-line on the same process piping. A comparison of the sonar-based flow meter and the existing mag meter is shown in Figure 8 during, and just prior to, process start-up. During this part of the process, the operator had high confidence in the electromagnetic flow meters ability to measure the flow rate, As shown, the mag meter and sonar-based flow meter show good correlation, demonstrating the applicability of sonar-based flow measurement technology to this important class of multiphase slurries.

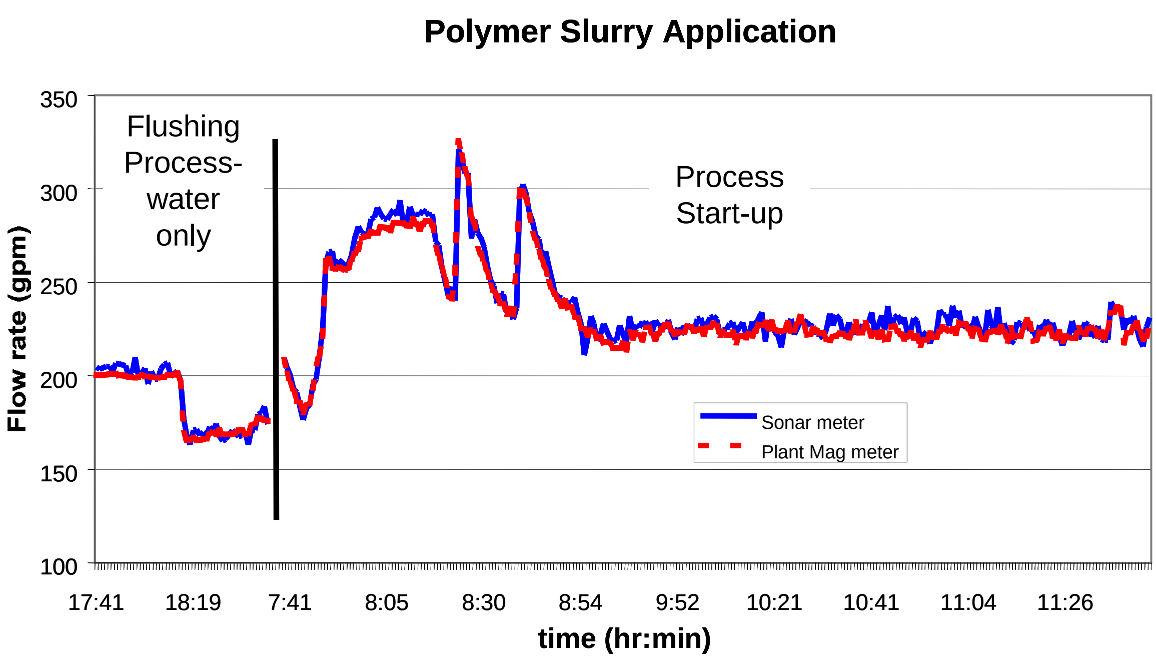

Figure 8: Comparison of Sonar-Based Flow meter with Electromagnetic flow meter on a liquid-conveyed, solid-particle slurry

Summary

Sonar-based flow measurement technology for volumetric flow was introduced. Sonar-based flow measurement is a new class of flow metering technology that is well suited for chemical and petrochemical applications. Sonar flow meters use sonar array processing technology to determine the speed at which naturally occurring turbulent eddies flow through a process flow. Sonar flow meters can be implemented with either port-pressure configurations or with strain-based clamp-on sensors.

Data was presented showing the ability of sonar-based flow metering technology to track the speed of turbulent eddies within process lines. Calibration data confirmed that the speed of the turbulent eddies closely tracks the volumetrically-averaged flow velocity in the pipe. Exploiting similarity laws, a Reynolds-number-based calibration was developed for a set of three geometrically similar, sonar-based flow meters to demonstrate 0.5% accuracy over of range of flow rates spanning 20 gpm to 20,000 gpm. Calibration data from an 8-inch clamp-on version of the meter was presented as well.

Results from a field trial of a sonar-based flow meter on a water-conveyed, polymer slurry were presented. Data shows that the sonar based flow meter performed comparably with an existing electromagnetic flow meter monitoring the same process line.

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