CiDRA SONARtrac Flow Meters: An Alternative Flow Measurement Technology

Author:
Bob Markoja
CiDRA Technical Services
Wallingford, CT, USA
+1.203.265-0035 x3399
bmarkoja@cidra.com
www.cidra.com

For Presentation At:
Committee on Operation and Maintenance of Nuclear Power Plants / ISTOG Winter 2011 Meeting (December 5 – 9, 2011)
Clearwater, Florida, USA

CiDRA SONARtrac Flow Meters: An Alternative Flow Measurement Technology

ABSTRACT:

Flow instruments are vital tools used for verifying system and component performance. Traditionally, measuring flow is primarily accomplished using ultrasonic flow meters and magnetic flow meters (mag meters), which require significant installation labor and a considerable length of straight pipe to yield accurate results. Given the right conditions, ultrasonic and mag meters are effective; however, in other instances they can lead to decreased testing reliability. In applications where accurate flow measurements are needed and where system out-of-service time is a concern, *SONARtrac* flow meters are a viable solution to consider. This paper provides the theory of operation and technical justification behind the *SONARtrac* flow meter along with current industry applications.

INTRODUCTION:

The American Society of Mechanical Engineers Operations & Maintenance Code for Operation and Maintenance of Nuclear Power Plants (ASME O&M Code) specifies pump testing requirements. Tests conducted periodically must demonstrate flow rate performance within +/- 20% of pump design. Pump flow rate instrumentation (flow meters) must have a stated accuracy of +/- 2%.

The test location(s) could be a considerable distance downstream of the pump in order to have a test location that had adequate straight pipe runs to facilitate tests. The piping between the pump outlet and test location can contain branch pipe runs. The valves that isolate the branch runs can potentially leak, negatively affecting the test results. In some cases, multiple flow rate measurements at numerous branch locations are summed to provide a total flow rate measurement from a given pump.

In July 2010, CiDRA personnel were contacted regarding use of their SONARtrac VF-100 flow meter to perform these tests on six salt water pumps.

SONARtrac FLOWMETER PRINCIPLE OF OPERATION[1]

Introduction

Sonar array-based flow meters operate by using an array of sensors and passive sonar processing algorithms to detect, track, and measure the mean velocities of coherent disturbances traveling in the axial direction of a pipe. These disturbances are grouped into three major categories: 1) disturbances conveyed by the flow, 2) acoustic waves in the fluid, and 3) vibrations transmitted by the pipe walls. Each disturbance class travels at a given velocity. For example, the flow will convey turbulent eddies, density variations, or other fluid characteristics at the rate of the fluid flow. Liquid-based flows rarely exceed 30 ft/s (9 m/s). Acoustic waves in the fluid will typically have a minimum velocity of 260 ft/s (80 m/s) and a maximum velocity of 4950 ft/s (1500 m/s). The third group, pipe vibrations, travels at velocities that are several times greater than the acoustic waves. Thus each disturbance class may be clearly identified and accurately measured.

Flow Velocity Measurement

Flow velocity may be determined by focusing on the disturbances that are conveyed by the flow. These disturbances can be density variations, temperature variations, turbulent eddies, or others. Within most industrial processes, the most common flow disturbance is turbulence. Turbulent flow is composed of eddies, also known as vortices or turbulent eddies, which meander and swirl in a random fashion within the pipe. The overall mean velocity of the disturbances is equal to the flow velocity. An illustration of these turbulent eddies is shown below in Figure 1. These eddies are continuously created. Once created, they break down into smaller and smaller vortices, until they become small enough to be dissipated as heat through viscous effects of the fluid. For several pipe diameters downstream, these vortices remain coherent retaining their structure and size before breaking down into smaller vortices. The vortices in a pipe have a broad range of sizes. These vortices are distributed throughout the cross section of the pipe and therefore across the flow profile. Thus the average velocity of the fluid can be determined by tracking the average axial velocities of the entire collection of vortices.

Figure 1: Cutaway of Pipe Under Sonar Array Sensor Band to Illustrate Turbulent Eddies

Through the combination of an array of passive sensors and the sonar array processing algorithms, the average axial velocities of a collection of vortices or density variations is obtained. The sequence of events that occur to make this measurement possible is as follows:

- The passage of the turbulent eddies or density variations create a small pressure change on the inside of the pipe wall.
- This small pressure change results in a dynamic strain of the pipe wall itself Figure 2 (right hand side exaggerated).
- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe – no coupling gels or liquids are required.
- This electrical signal is detected by each element of the array of sensors. These sensors are spaced at precisely a set distance from each other (ΔL) along the axial direction of the pipe.
- The resulting electrical signal from each sensor element is interpreted as a characteristic signature of the frequency and phase components of the disturbance under the sensor.
- An array processing algorithm combines the phase and frequency information of the characteristic signature from the group of sensor array elements to calculate the velocity of the characteristic signature as it propagates under the array of sensors. In most applications, a minimum flow rate of 0.9 m/s (3 ft/s) is required to measure the flow velocity.

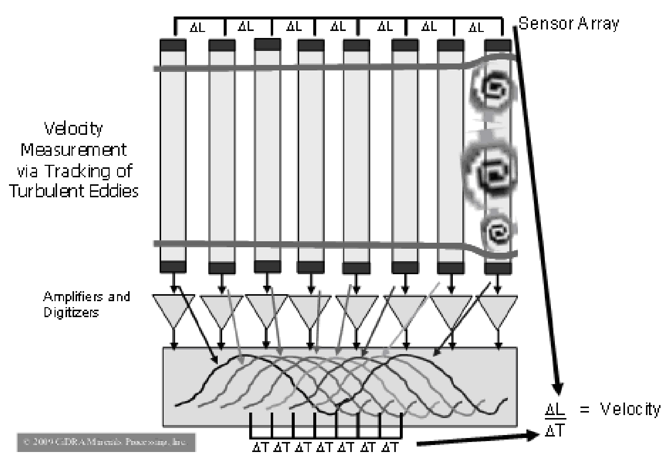

Figure 2: Illustration of Velocity Measurement from Strain Induced in Pipe Walls by Passing Turbulent Eddies

There are many challenges in performing this measurement in an industrial environment. The most difficult of which is resolving the relatively low level vortical disturbances from the relatively high noise levels. This noise includes acoustics and vibrations generated from large pumps and valves. The strength of the array processing algorithm is its ability to isolate and measure the velocities of the low level vortical components within the flow.

These velocity measurements have been demonstrated on many types of pipes with a wide variety of liners. The pipes include steel, PVC, HDPE, and fiberglass. Pipe linings include rubber, urethane, cement, and Teflon lined pipes, as well as pipes with scale buildup.

Speed of Sound and Gas Void Fraction (Entrained Air Bubbles) Measurement

The sonar array based technology may also be used to track acoustic waves traveling in the fluid. In most plants there is an abundance of acoustic waves propagating within the process pipes. These acoustic waves are generated naturally from a variety of sources. These sources include pumps, the flow through pipe geometry changes and bubbles within the fluid that generate acoustic waves through their natural oscillations. These acoustic waves are low frequency (in the audible range), and travel in the pipe axial direction, with wavelengths much longer than the entrained gas bubbles. An illustration of these acoustic waves in a pipe is shown in Figure 3 and, as can be seen in the figure, they can propagate in either direction down the pipe, or in both directions.

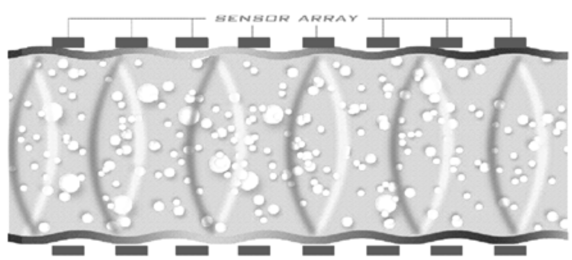

Figure 3: Illustration of Naturally Occurring Acoustic Waves Propagating in Pipe Under the Array of Sensors

Through the same array of passive sensors used to measure the flow velocity and similar sonar array processing algorithms, the average axial velocities of a collection of acoustic waves is obtained. Since acoustic waves are traveling pressure waves, they introduce localized pressure changes on the inside of the pipe walls during the course of cycling from compression to rarefaction and back. These pressure changes strain the pipe wall and are tracked in a similar manner as for the turbulent eddies or density variations. The process fluid can be multiphase, or multi-component single phase. In a multi-component single phase fluid, the acoustic velocity is a function of the ratio and acoustic properties of the two fluids, thus this measurement can be used to determine mixture ratios through application of the simple mixing rule (volume average of velocity).

In multiphase fluids that consist of a gas mixed with a liquid or slurry, the acoustic velocity can be used to determine the amount of entrained gas (gas void fraction) when the gas is in the form of bubbles that are well mixed within the liquid or slurry. Since the wavelengths of the acoustic waves are much larger than the bubble size, a complex interaction takes place that sets the acoustic velocity to be a strong function of the gas void fraction. The speed of sound is proportional to the square root of the ratio of the compressibility and the density, both of which are heavily influenced by air content. An example of the resulting relationship is shown in Figure 4. The particular values outlined by the curve in this figure are influenced by other factors, particularly pressure. Thus pressure at the location of the array based instrument must be measured or calculated. Once pressure is determined, the array based instrument is used to accurately measure the speed of sound, and the relationship between speed of sound and entrained air content is used to accurately quantify the amount of entrained air.

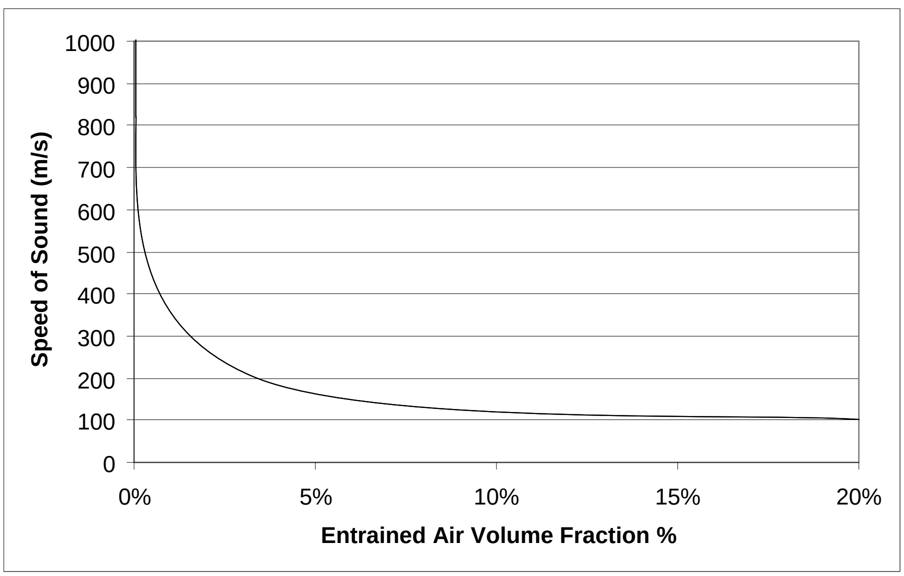

Figure 4: Example of Relationship Between Speed of Sound and Entrained Air Volume Fraction (Gas Void Fraction)

The gas void fraction measurement is used in a variety of different industries and applications. It is used for controlling the amount of air in a process fluid (use of anti-foaming or air entraining chemicals), nuclear density gauge correction, flow meter correction to provide true volumetric flow, diagnosis of pumping issues, detection of flashing, and air injection applications. It is being successfully used for entrained air applications ranging from 0.01% to 20% gas void fractions with an accuracy of 5% of the reading.

Physical Embodiment of Flow Monitoring Instrumentation Based on Sonar Array

In a commercial embodiment of this measurement principle, a flexible band of passive sensors is wrapped around and tightened onto the pipe. This is a dry fit that does not require gels or couplants since no ultrasonic signals are used. The sensor band is normally 19.5 inches (50 cm) long in the axial direction of the pipe and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 5. First the pipe is wiped down and any high points are sanded or filed away. Second, the flexible sensor band is wrapped around the pipe and a series of captive screws on the sensor band are used to tighten the band onto the pipe. Each screw uses a stack of spring washers to allow for pipe expansion and contraction, as well as ensure a set clamping force. Third, a protective cover with signal conditioning and diagnostics electronics is installed over the sensor band, and the sensor band is connected to the electronics in the cover. Fourth, the cable from the sensor head to the transmitter is installed and wired to the transmitter. Fifth, the front panel menu on the transmitter is used to configure the system.

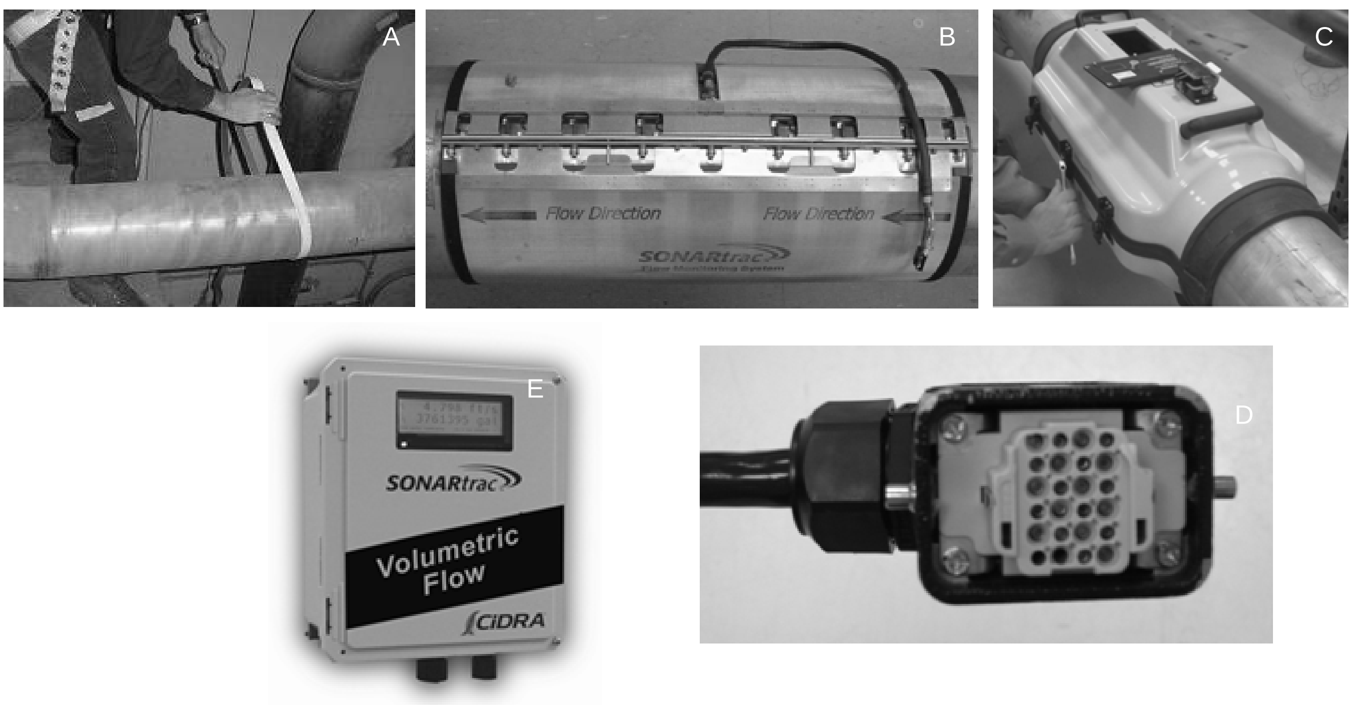

Figure 5: Installation Procedure from Top Left:
A: Pipe Preparation (Cleaning and Light Sanding)
B: Install Sensor Band
C: Install Sensor Cover
D: Install Sensor Cover to Transmitter ConnectorE: Configure Transmitter

Calibration and Long Term Stability

The flow measurement technique is not dependent on the absolute value of any analog signal. All the strain measurements are taken dynamically. Therefore, the calibration of the meter will not drift with time or temperature. The only two absolute measurements are the sensor spacing and the transmitter clock. The spacing between the sensors is set in the factory where they are bonded to a stainless steel sheet and cannot be adjusted by the customer.

The clock stability is better than 0.01% and thus is 50 times better than needed to maintain the flow meter's typical accuracy of +/- 1% in the field; and +/- 0.5% under reference conditions or after in-field supplemental calibration. As a result, the impact of clock stability can be neglected.

Installation Recommendations

The *SONARtrac* flow meter is recommended to be installed a minimum of 15 pipe diameters downstream and five pipe diameters upstream of an elbow fitting. If these pipe straight runs are not available, the meter will continue to operate; however, there may be a slight flow rate offset. For those applications where absolute accuracy is required, calibrations on process specific pipe configurations can be performed and custom calibration coefficients (K-factor) can be developed.

Technology Limitations

SONARtrac VF-100 Flow Meters are available in pipe sizes of 2-inch and larger. Out-of-box flow rate accuracy is +/- 1% and a repeatability of 0.3% for sizes up to 36-inch (assuming acceptable distance from upstream and downstream flow disturbances). Meter sizes up to 60-inch are available. The sensor head is pipe size specific.

The sensor relies on turbulent flow ~3 ft/sec (0.9 m/s) or greater flow velocity. Flow measurements below 3 ft/sec are often possible depending on process conditions.

Standard product upper temperature limit is 100°C (212°F). A 150°C (302°F) sensor head is also available.

The *SONARtrac* flow meter works on clean or dirty liquids, slurries, conductive and non-conductive liquids, magnetic and non-magnetic fluids, and aerated liquids. The system can quantify the amount of gas entrained in the liquid. These meters will measure wet and dry gas flows.

The flow meter measures the velocity of the process fluid and then calculates the volumetric flow based on pipe cross-section area. Therefore, the pipe must be full; the flow rate in partially full pipes will be over-reported.

Industry Applications

CiDRA *SONARtrac* Flow Meters are used extensively in the minerals processing, oil sands surface mining and pulp & paper industries. They are also being used in fossil fired power plants and refinery processes. They have recently expanded their application to include the nuclear industry with the installation of six flow meters for in-service tests on six salt water pumps.

SONARtrac meters work well on lined pipe (steel pipe lined with rubber, Teflon, PVC, etc.) so they are often used with corrosive and erosive slurries where other types of flow meters see extensive degradation and wear. *SONARtrac* meters are ideally suited for use on process safety management (PSM) lines containing corrosive or hazardous fluids since they are clamp-on and do not require flanges, fittings or other potential sources of leakage and are not process wetted.

The meter's ability to measure the amount of gas entrained in a liquid stream (gas volume / void fraction) enables process operators to accurately and cost effectively control anti-foam or air-entraining chemicals. The ability to measure air can be helpful for determining if there are process equipment leaks and the source of the leak.

PERFORMANCE VERIFICATION

An initial on-site demonstration and subsequent verification tests on six salt water pumps showed the *SONARtrac* meter would work on this application. However, a consistent flow rate offset was seen. This was not unexpected as the installation site did not contain 15 pipe diameters upstream and 5 diameters downstream from the flow meter. In order to correct for this offset, a meter calibration was performed at a NIST traceable flow calibration facility.

UWRL Calibration Tests – Facility Description

The **Utah Water Research Laboratory** (**UWRL**) is a research institution located as part of Utah State University in Logan, UT. The UWRL facility contains over 100,000 ft^2 of offices and laboratories. The flow meter calibration facility is housed in approximately 50,000 ft^2 of open space that is also used for various erosion and drainage type studies.

The facility has the capability of calibrating flow meters up to a 72-inch line size. A reservoir provides the water for the gravity fed flow calibration facility. A 48-inch line connects the reservoir to the facility and is capable of approximately 230 ft^3/s (103,000 gpm) water flow rate. Once in the facility, water is diverted to calibration sites based upon pipe size, flow requirements, and test requirements.

For the 24-inch flow meter calibration tests flow rates of up to approximately 50 ft^3/s (22,440 gpm, or 17.7 ft/s velocity) were possible. The facility has a National Institute of Standards and Technology (NIST) traceable weigh tank with a capacity of 230,000 lbs to used for the tests. When using the weigh tank reference flow rate accuracy is within 0.2% of actual flow. A magnetic flow meter and diverter valve are used to set the water flow rate prior to the test run.

The 24-inch flow meters were installed in the laboratory's 24-inch test line using a section of rubber lined pipe consisting of a 24-inch 90° long-radius elbow, a straight section of 24-inch pipe that was 71 inches long and a second 24-inch 90° long-radius elbow. Upstream of the rubber lined pipe was approximately 88 feet of straight 24-inch standard wall pipe with a flow straightener installed at the far upstream end. Downstream of the rubber lined pipe section was approximately 12 feet of straight 24-inch pipe followed by additional bends and pipe to direct the flow back to the test line supplying water to the weight tank.

The section of pipe that contained the flow meter under test was designed and built to be identical to the field set-up (in this particular case it was designed for the installation location found on the six salt water pumps, 24-inch Sch 20 with ¼-inch rubber liner pipe, with the downstream edge of the sensor band located 16-inches upstream from the elbow weld). Figures 6 through 9 illustrate the test line and location of meter installation.

Figure 6 Test Line (Flow Near to Far)

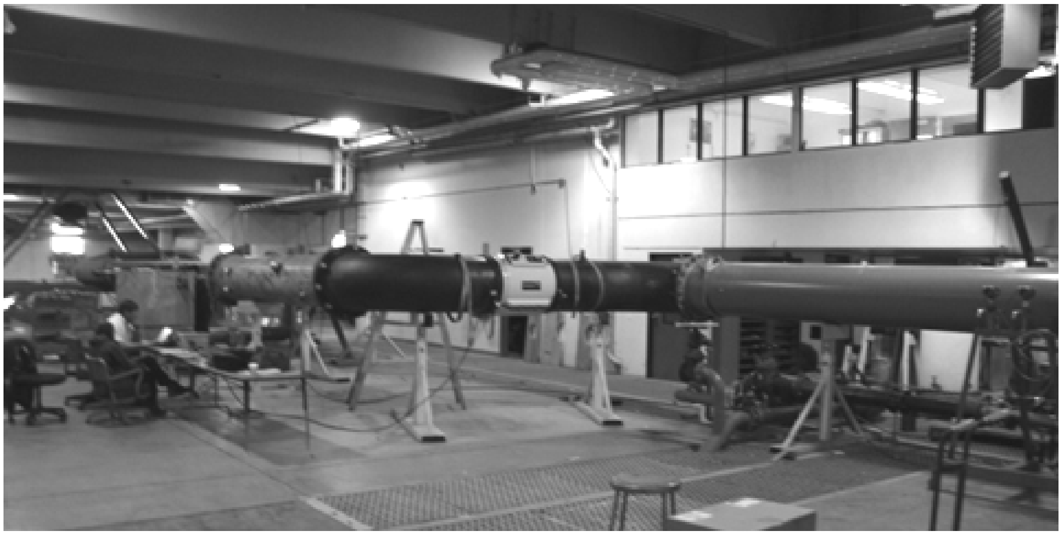

Figure 7 Test Line (Flow Right to Left)

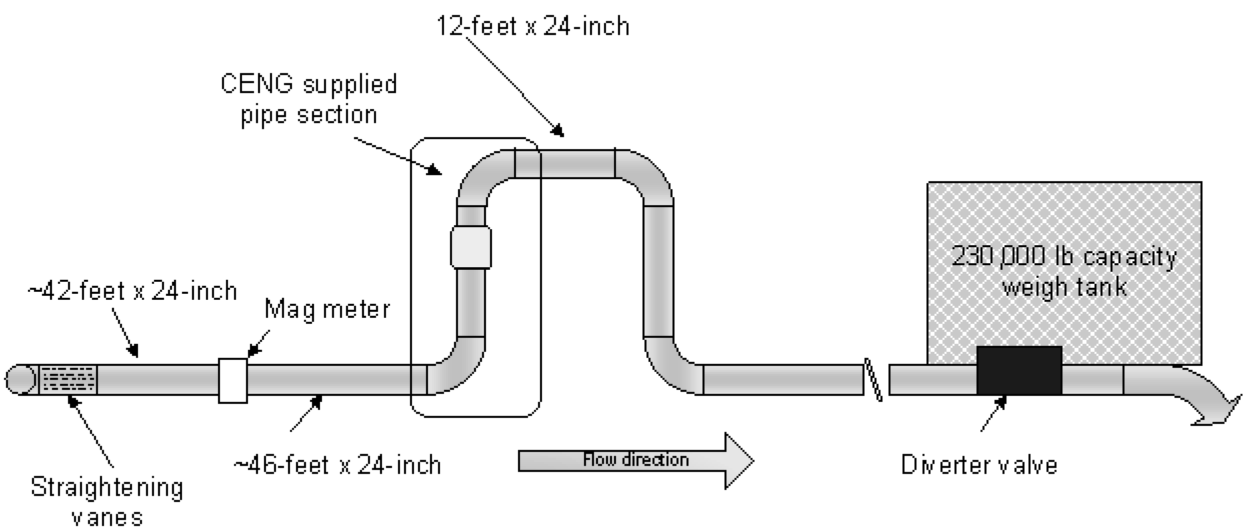

Figure 8 Flow Loop Schematic

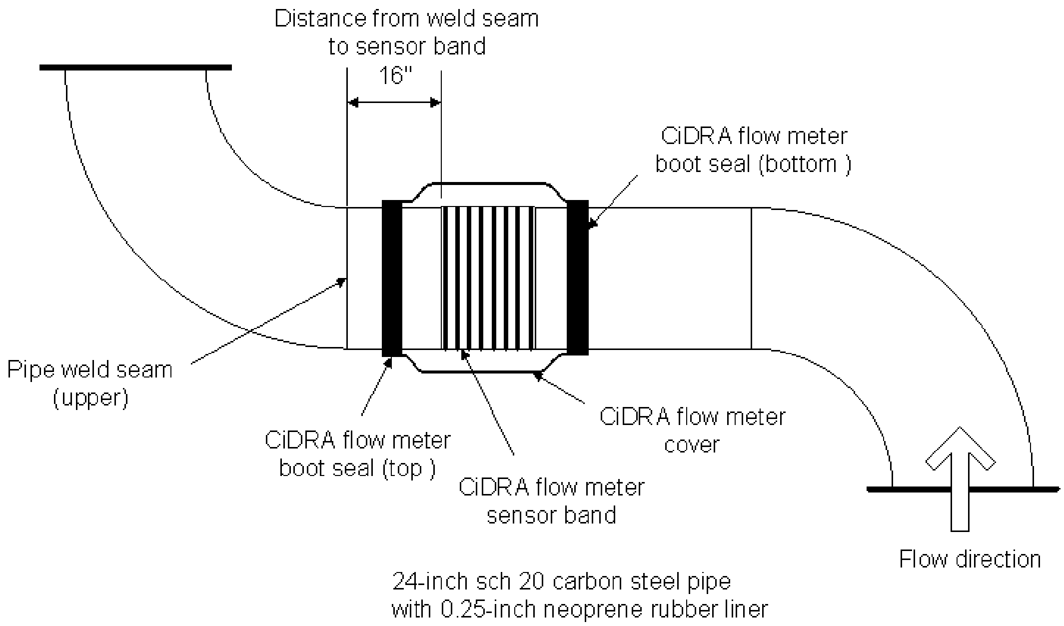

Figure 9 Test Pipe Designed to be Identical to Installation Pipe

UWRL Calibration Tests – Test Procedure

The *SONARtrac* flow meter uses 3 calibration coefficients (C0, C1, and C2) to correct flow rates.

The flow meter sensor band is recommended to be installed 15 pipe diameters downstream and 5 pipe diameters upstream of an elbow fitting to re-establish a uniform velocity head. If a highly accurate flow measurement is necessary and the previously mentioned straight pipe requirements cannot be met, then calibration testing can be conducted to correct the accuracy of the readings. Calibration coefficients may be universal from meter to meter, if the system characteristics, pipe geometry and installation location are identical. For this application, the calibration coefficients were validated on all sensor bands to ensure the reported flow rate accuracy is within ±2%.

Flow measurements were made using a weigh tank. The weigh tank is a primary flow measurement device that is regularly calibrated and traceable to NIST. Timing was completed using a PLC timer and temperature was measured using a digital thermometer.

The *SONARtrac* flow meters are equipped with a 4–20mA output. These outputs were averaged over the time period that the reference the flow was being measured.

The meter output was calculated using:

$$Q = \frac{range}{16}(mA - 4)$$

Where:
Q = flow passing through the meter (gpm)
Range = flow meter 4 - 20mA output upper limit (24,999 gpm)
mA = time averaged output of the meter being tested (mA)

The flow rate for the calibration and verification tests ranged from approximately 10,700 gpm to 22,000 gpm. Test procedure was as follows:

- Install the sensor head (sensor band #1, thermal blanket and cover assembly) on the test section of pipe. The downstream edge on the sensor band was located 16-inches from the pipe weld seam.
- Start flow at the low range flow rate of approximately 10,700 gpm and allow the flow rate to stabilize. An inline flow meter was used to set the approximate flow rate.
- Conduct flow rate calibration or verification runs to collect data.
    - Test durations varied from 70 to 150 seconds based on the flow rate since the weigh tank volume is fixed at 230,000 gallons.
- After completion of the test run, the total volume of water in the weigh tank was determined gravimetrically.
- The total water volume is compensated for temperature.
- Based on total water volume and test duration the reference flow rate is determined.
- The data are entered in a spread sheet and the percent difference between the flow meter under test and the reference flow rate measured by the calibration facility is determined.
- Repeat above procedure for each of the six flow rates that were used for the calibration tests.
- Calculate the *SONARtrac* meter calibration coefficients (C0, C1, and C2).
- Enter the calibration coefficients into the *SONARtrac* transmitter.
- Calibration test runs were then conducted at six flow rates on sensor band #1.
- The deviation from the NIST traceable flow rate was then calculated and entered into the calibration sheet.
- Remove sensor band #1 and install sensor band #2.
- Repeat verification tests for all meters.

The calibration coefficients were common for all sensor assemblies based on the sensor band #1 tests.

UWRL Calibration Tests – Test Results

A six-point calibration test was performed on each sensor band for a total of 42 test points. All test points were well within ±2%. Test results for the individual sensor bands are shown in Figure 10.

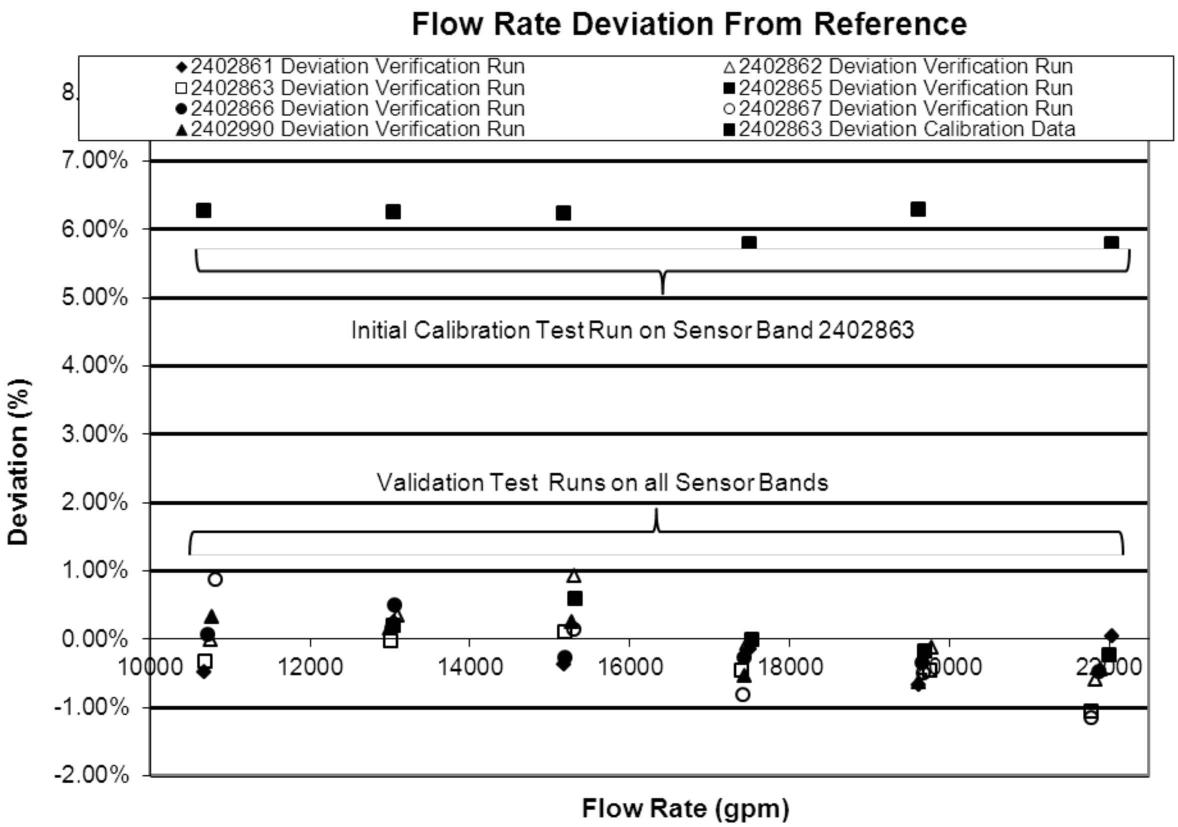

Figure 10 Seven Sensor Bands Calibration Test Results

FIELD IMPLEMENTATION

Flow meter sensor heads were installed in June 2011. Prior to installation the pipe exterior was sanded and painted to create a smooth uniform finish on the section of pipe where the sensor head was installed.

A two person installation crew installed all the sensor heads during a three day period. Typical meter installation time is 2 – 4 hours each.

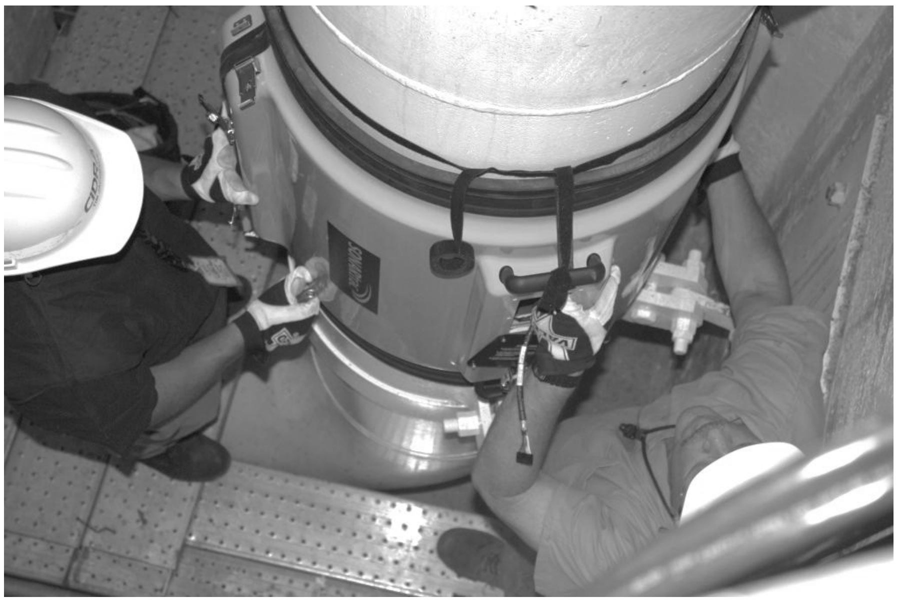

Figure 11 Sensor Head Cover Installation

CONCLUSION

SONARtrac volumetric flow meters are a new technology flow measurement device. They have been used on a wide variety of industrial process including mining, oil sands production, pulp & paper, food processing, fossil fired and nuclear power plants.

SONARtrac meters provide an alternative to other flow measurement technologies with the added ability of measuring entrained air fraction. Their ability to conduct flow measurements where the measurement location has less than ideal flow conditions has been demonstrated.

REFERENCES:

(1) Rothman, Paul; O'Keefe PhD, Christian, Thomas, Aaron "Application of Unique Sonar Array Based Process Monitoring Measurement Equipment for Minerals Processing Applications"