ULTRASONIC CLAMP-ON FLOW MEASUREMENT OF NATURAL GAS, STEAM AND COMPRESSED AIR

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Abstract

Clamp-on metering of flowing liquids has been known since the 1960s, and measurements of natural gas flow using wetted transducers in contact with the gas has been known since the 1970s. The past decade has seen ultrasonic flowmetering technology gaining widespread acceptance in the petrochemical and chemical industry. Until now, a portable flowmeter using clamp-on techniques to measure the flow of industrial gases in steel pipes at low (under 8 bar or 120 psig) to medium pressure has remained elusive. This paper discusses clamp-on ultrasonic gas flow measurement equipment to measure low-pressure (above 4 bar or 60 psig) gas flow in metal pipes.

Some laboratory (air and gas mixture) and field (methane) calibration data, and industrial applications for gases, saturated and superheated steam and instrument air will be presented. These are mostly in the *P* range of 4 bar and higher, for steel pipe diameters in the range 3-inch to 30-inch (~75 to 750 mm), and bi-directional flow velocities up to ~135 ft/s (~40 m/s).

Introduction

Due to its advantage in accuracy, turndown ratio and no excess pressure drop, the current market for ultrasonic flowmeter technology is growing rapidly in both liquid and gas flow measurement. While the important feature of the ultrasonic flowmeter of *noninvasive* design has been well recognized and applied in *liquid* flow measurement since the 1960s, it has been difficult to achieve a practical clamp-on *gas* flowmeter for routine use on *metal* pipes.

When comparing with ultrasonic clamp-on *liquid* flow measurement, the major difficulty in clamp-on *gas* flow measurement comes from the fact that the ratio between acoustic impedance ρc of the metal pipe and gas is much greater than in the case of liquid. Symbols ρ and c are density and sound speed of the medium, respectively. The low ratio of the acoustic impedance of gas to steel means that only an extremely low portion of incident energy can be transmitted through the steel/gas interface. The acoustic impedance of air at ambient pressure is about 0.0004 Mrayls compared to 1.5 Mrayls for water. Even when air or gas is compressed at low to medium pressure, the impedance is still very small, usually not more than 0.015 Mrayls. For example, a typical natural gas has an acoustic impedance of about 0.0044 Mrayls at a pressure of 200 psig.

In a clamp-on flowmeter based on the principle of time of flight, two angle beam transducers are clamped on the pipe surface and spaced along the flow direction. Each transducer serves as a transmitter and a receiver alternatively in data acquisition and the sums and differences in transit time for the upstream and downstream directions are used to measure flow. For the same incident angle at the pipe/flow interface, one expects less than 0.2% of signal amplitude from 200-psig natural gas compared with water. Considering that there are more attenuation effects in gas flow due to molecular absorption and scattering, the received signal is even smaller. While little acoustic energy transmits twice through the metal/gas interface to provide information about flow, the rest of the acoustic energy is reflected and travels along or around the pipe as cross talk or coherent noise. The windowing of a short pulse as used in clamp-on *liquid* flowmeters is generally sufficient to eliminate the influence of the crosstalk. The reflected energy in clamp-on *gas* flow measurement, however, is so high that it not only interferes with the flow measurement by an early arrival of noise through the shortest path between the two transducers, it also bounces back and forth bouncing between the pipe structures such as flanges and potentially interferes with the flow measurement at later times. Furthermore, the Mach number in *gas* flow is usually higher than typical *liquid* flow, which causes higher jitter and acoustic beam drift up to a few degrees, which further reduces *SNR* (signal to noise ratio).

Laboratory Results and Discussion

To overcome these difficulties, a new clamp-on gas flowmeter (DigitalFlow™ GC868 system) was developed. In this system a new transducer, clamping configuration and signal processing technique were designed to improve *SNR* for gas flow measurement so that the signal can be chosen selectively and processed as it is in a typical clamp-on liquid transit time flowmeter to compute flow velocity. The system and improved waveform are shown in Figures 1 and 2. The frequency of ultrasound used in this work ranges from 0.2 to 1 MHz depending on application. Measurement is confined to the diagonal plane where an odd number of traverses are generally used to minimize the influence of the crosstalk.

Figure 1. A two-channel DigitalFlow™ GC868 Clamp-On Ultrasonic Flowmeter measures flow in two different pipes at the same time. It can also be used as a 2-path flowmeter.
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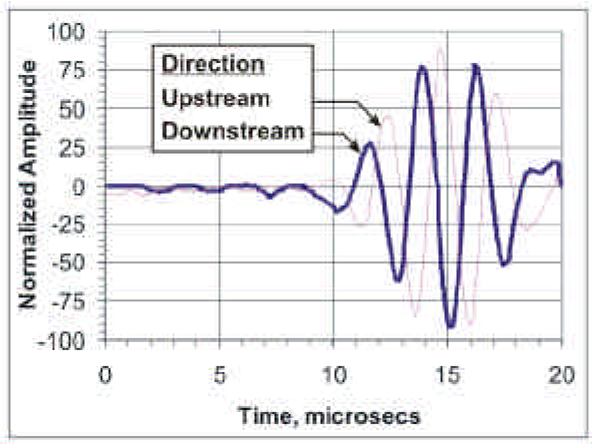

Figure 2. Upstream (*against* the flow) and downstream ultrasonic signals from DigitalFlow™ GC868, obtained when a pair of transducers was installed on a ϕ4-inch schedule 80 carbon steel natural gas pipeline. The natural gas was at approximately 200 psig pressure with flow rate of approximately 15 ft/s.

In the product development process, a systematic study was conducted in the laboratory. The repeatability and reproducibility of the system have been evaluated in a pressurized gas loop (see Figure 3). The loop was designed and built to serve as a Panametrics gas flow experiment and moderate accuracy calibration facility. Changing the frequency of the Spencer single stage turbine from 5 to 60 Hz varies the flow rate from 5 ft/s to 72 ft/s in the ϕ6-inch pipe. Velocities less than 5 ft/s are obtained by partially closing a valve in the ϕ6-inch section while the motor is set to 5 Hz. The standard deviation of the flow rate is better than 0.25% in the velocity range of 5 ft/s to 72 ft/s, which is characterized by a Panametrics 2-path *wetted* ultrasonic flowmeter IGM868. Higher velocity, up to 135 ft/s, can be obtained in a ϕ4-inch pipe when installed instead of the 10-foot long ϕ6-inch pipe in the lower section. The loop can operate at slightly over 120 psig of pressure. The compressed air and commercial inert gases argon and helium were used in the study. Argon and helium were mixed to the molar ratio of approximately 2:3 to obtain sound speed similar to natural gas (methane). The temperature of the flow was monitored but not controlled throughout the study.

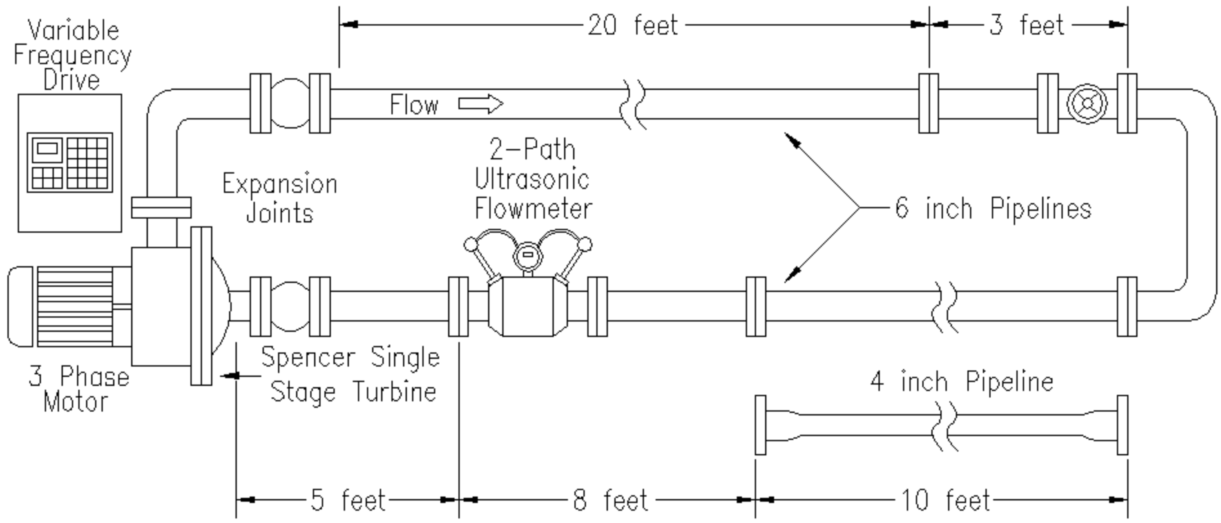

Figure 3. Schematic of the pressurized gas loop in Panametrics. The four elbows are installed in the same plane and a flow conditioner is inserted before the 10-foot section. The loop is capable of generating gas velocities from 0.5 ft/s to 75 ft/s at pressure range from ambient to 120 psig.

GC868 flowmeter was tested on the ϕ6-inch pipe in the top section and on a ϕ4-inch pipe in the lower section. The total length of the loop is less than 60 feet (<20 m) so that pressure drop and temperature difference are too small to cause a gas density difference of more than 0.5% between the instrument installation locations. Therefore all the calibration is based on velocity without pressure and temperature compensation. Data in Figure 4 shows flow measurement of two instruments clamped on the ϕ4-inch pipe and ϕ6-inch pipe at the same time, providing a self-consistency test of the technology. This is real time data logged in 5-second time intervals. Calibration of the flow velocity of compressed air and a pressurized gas mixture using a GC868 flowmeter is plotted against a Panametrics 2-path *wetted* ultrasonic flowmeter IGM868 (in Figures 5a and 5b). The standard deviation at each flow rate is less than 0.5% and their *K* factors (meter factors) are within ±2%.

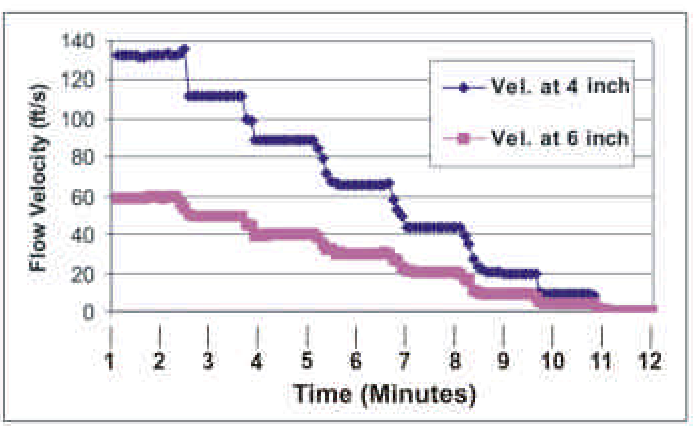

Figure 4. Raw data obtained from two GC868 flowmeters. One installed on a ϕ6-inch pipe in the top section and the other on a ϕ4-inch pipe in the lower section of the loop shown in Figure 3. The loop was filled with a mixture of argon and helium gases with a sound speed of approximately 1500 ft/s. The pressure was approximately 80-psig at ambient temperature. The data was logged in 5-second time intervals.

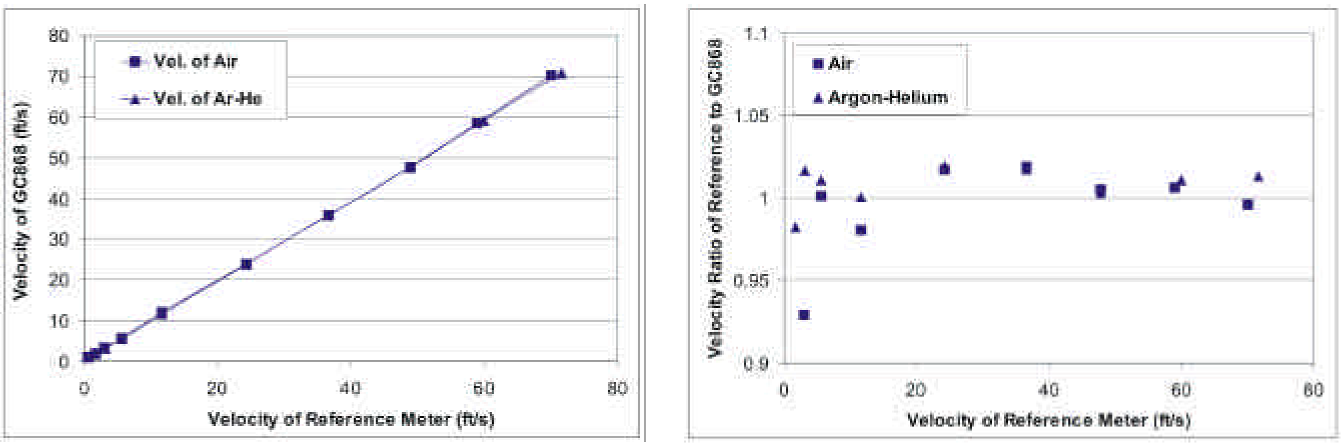

Figure 5. Calibration of a GC868 clamp-on against a 2-path *wetted* ultrasonic flowmeter IGM868. The gas was compressed air and argon-helium mixture respectively. Both sets of data were obtained at a pressure of approximately 60 psig at ambient temperature. (a) Velocity data is averaged over 4 minutes and the standard deviation is less than 0.5% at all velocities above 1.6 ft/s. (b) Ratio of velocity of IGM868 reference to that of the GC868 clamp-on flowmeter. Only the calibration above 5 ft/s is meaningful because the flow stability under 5 ft/s is difficult to maintain.

Signal to noise ratio is strongly dependent on the acoustic impedance $Z = rc$ and Z is approximately proportional to the square root of the molecular weight for gas when the intermolecular interaction is negligible at relatively low pressure. It is always easier to measure gas with higher molecular weight, when the intramolecular absorption of the ultrasonic energy is negligible. For a given gas, it is easy to understand that measurement becomes harder as the pressure drops. In Figure 6, the data was obtained when the same meter set up was used to measure gas flow at different pressures. The observed ±2% accuracy was reproducible in the tested pressure range. The sound speed measured by the GC868 has 0.5% uncertainty see Figure 7 for a real time data log in the 4 runs.

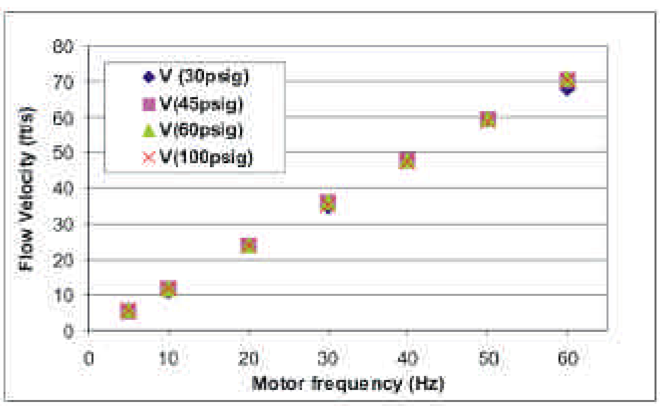

Figure 6. Flow velocity of argon-helium gas mixture measured at different pressures at the Panametrics pressurized gas loop. Flow velocity was varied by adjusting the motor frequency. Argon and helium were mixed at a molar ratio of approximately 2:3 with pressure starting at 100 psig and then depressurized in steps for repeated measurement.

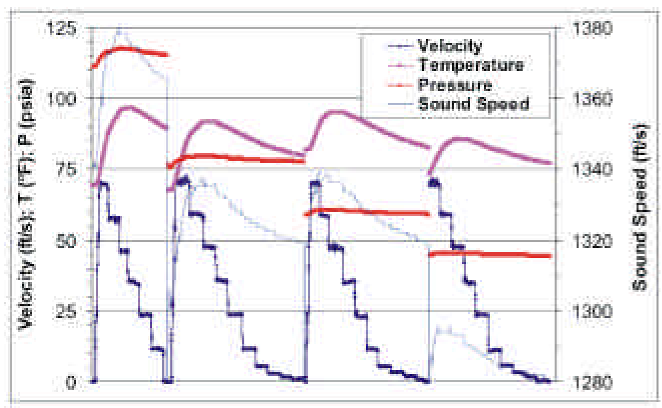

Figure 7. Real time data log of velocity and sound speed measured by GC868 flowmeter. Pressure and temperature were acquired using wetted probes connected to the instrument via 4-20 mA inputs. Data was recorded every 5 seconds on 4 different days in a row. The molar ratio of argon to helium gas was not strictly maintained throughout the test.

Since the ratio of sound speed between gas and metal pipe is so low, the refracted angle in the gas is generally less than 10 degrees. The direct consequence in clamp-on measurement of gas flow compared with a *wetted* ultrasonic gas flowmeter is that a much shorter transit time difference results from the same gas flow velocity. (For a *wetted*-transducer system the oblique path can be angled at 30°, 45° or even 60° to the normal.) Nevertheless, with cross correlation [1], the meter is able to measure natural gas flow velocity to a resolution of 0.16 ft/s in a ϕ4-inch pipe and 0.11 ft/s in a ϕ6-inch pipe in a one-traverse configuration. In case there is a major interest of low flow measurement, the instrument also allows the user to triple the resolution by using a 3-traverse transducer configuration (see Figure 8 for illustration).

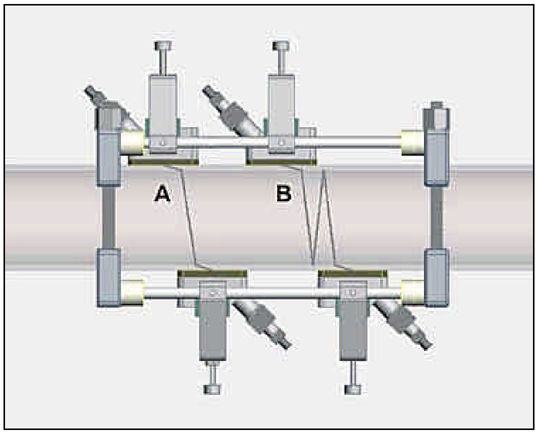

Figure 8. Transducers can be spaced in either 1-traverse (pair A) or 3-traverse (pair B) configuration using a single-channel flowmeter, depending on the application. The customer may also use a two-channel flowmeter installed on the same pipe to obtain a higher turndown ratio and better accuracy.

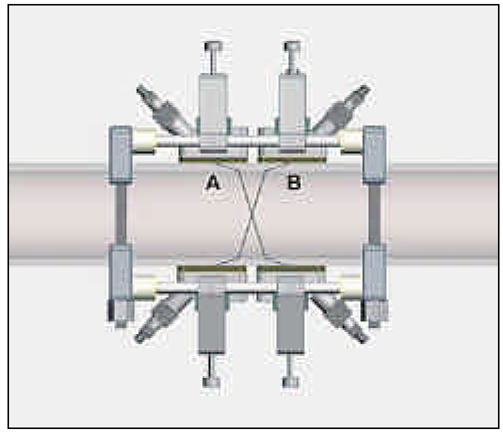

Figure 9. By averaging the results from a two-channel GC868 flowmeter with transducers installed in an X configuration shown here, an effective vee path is obtained to minimize the influence of crossflow.

It is thought that the small refractive angle inside the gas could also cause the instrument to be sensitive to crossflow. Since the instrument itself doesn't cause any disturbance to the flow profile, it could be used as a tool to study crossflow. However, it is more desirable to be less sensitive to the crossflow when functioning as a commercial flowmeter. Consider that a well developed flow profile in gas can only be established after very long straight run [2]. A study in Panametrics' gas flow laboratory was conducted to examine the influence of crossflow on accuracy at a typical application condition (10xID away from flanges and 10xID away from up- and down-stream elbow). Since the effect due to crossflow is much greater if the measurement is within the elbow plane [2], two pairs of transducers were clamped in the middle of the top 20-foot ϕ6-inch pipe section where the typical application condition is considered. There was no flow conditioner between the upstream elbow and measurement points. The two measurement points were separated by less than 2 feet and one measurement was co-planar and the other was orthogonal to the elbows. A dual-channel GC868 flowmeter was used to measure the velocities from the two measurement points simultaneously. A velocity difference between the measurement points would be observed if the meter accuracy were influenced by crossflow. The raw data and averaged velocity at each motor frequency, compared to the *wetted* ultrasonic flowmeter is plotted in Figure 10. The difference is 0.5% to 2.5% in the whole range, which indicates the crossflow influence is within the reproducibility of the instrument. It is also shown that a better accuracy can be obtained by averaging the two-channels, which is one of the most common configurations in *wetted* ultrasonic flow measurements.

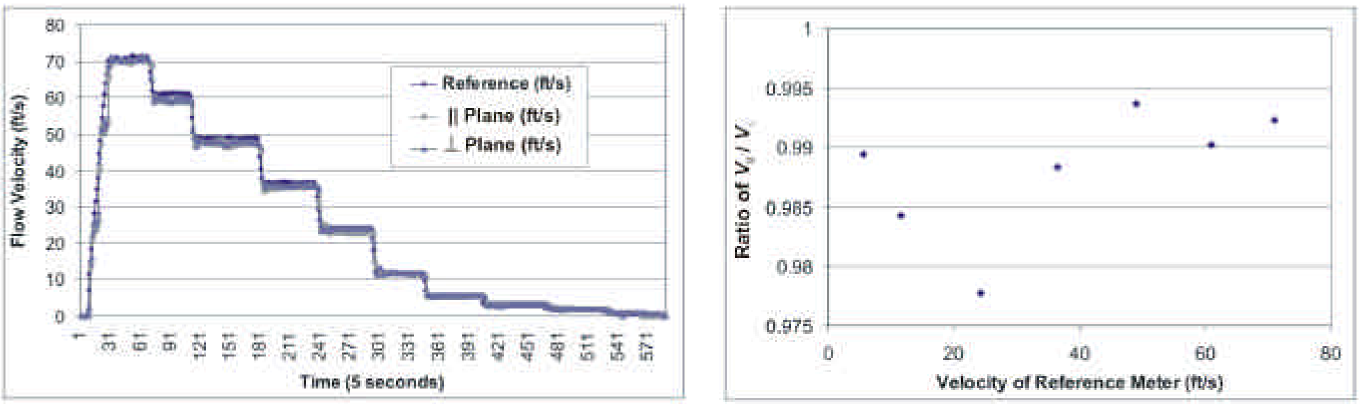

Figure 10. (a) Raw data from a two-channel GC868 flowmeter where the two-channels were installed in a configuration such that each measurement plane is aligned perpendicular or parallel to the plane of the elbows. The gas was an argon-helium mixture at 45 psig. Both sets of transducers were about 10 to 13 feet away from the elbows and there was no flow conditioner between the measurement points and elbows. The transducers were installed in a 1-traverse configuration. (b) The ratio of the mean velocities calculated from the data in Figure 10(a).

It is well known that the influence of crossflow is less in the vee path (2-traverse) configuration than in paths having an *odd* number of traverses [3]. While the vee path is a common practice in clamp-on *liquid* flow measurement, it is not favored in the clamp-on *gas* flow measurement due to the high coherent noise. If a good flow condition is impossible to meet, orthogonal plane is not accessible or piping configuration is very complex, an alternative to the vee path can be obtained by applying the X configuration as shown in Figure 9. Here, a two-channel GC868 flowmeter can be used to get an average flow from the two pairs of transducers installed in an X configuration as illustrated. These alternatives are among those used in the early days of *liquid* clamp-on flowmetering [3].

The GC868 flowmeter has demonstrated repeatable and reproducible results in the Panametrics laboratory. The system has also been evaluated in calibration facilities. A calibration in a high-pressure natural gas flow loop was conducted in the GTI meter research facility at Southwest Research Institute in San Antonio, Texas in May 2001. Two independent GC868 flowmeters were installed in the loop. There were carbon steel schedule 40 pipes at both locations with diameters of 12-inch and 8-inch. The ϕ12-inch installation was located upstream of the ϕ8-inch installation. The data was collected at the same time after instruments were programmed based on the pipe survey data conducted using an ultrasonic thickness gage, Panametrics model 36DL Plus, with a thickness resolution of 0.001 inch. In the case of an old pipe surface, a standard deviation of less than 0.005 inch in pipe wall thickness can be obtained, which gave us confidence in the pipe ID of better than 0.01 inch. Therefore the uncertainty of the cross sectional area should be less than 0.25%. The results are shown in Figures 11, 12 and 13.

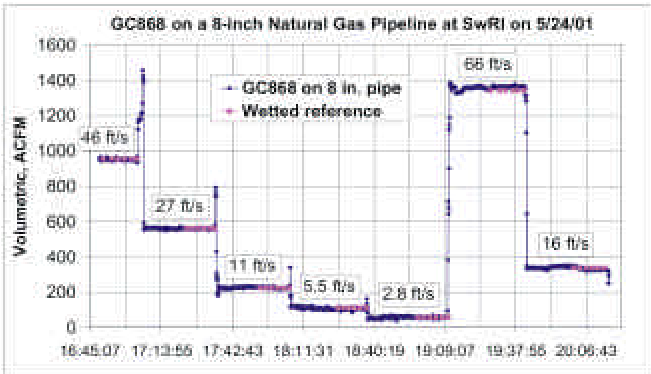

Figure 11. Raw data from a single-channel GC868 flowmeter installed on an 8-inch pipe versus reference data in GTI meter research facility at SwRI on May 24, 2001. Natural gas pressure and temperature were approximately 720 psig and 60°F respectively. Reference used pressure and temperature data acquired from wetted probes 30 feet downstream from clamp-on measurement point.

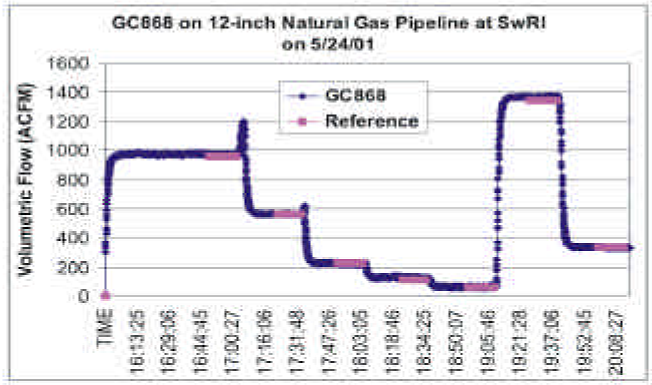

Figure 12. Data from a single-channel GC868 flowmeter installed on 12-inch pipe measured at the same time as the 8-inch pipe at GTI meter research facility at SwRI on May 24, 2001. This location was about 50 feet upstream from the other measurement point. The instrument was programmed with a different averaging mode.

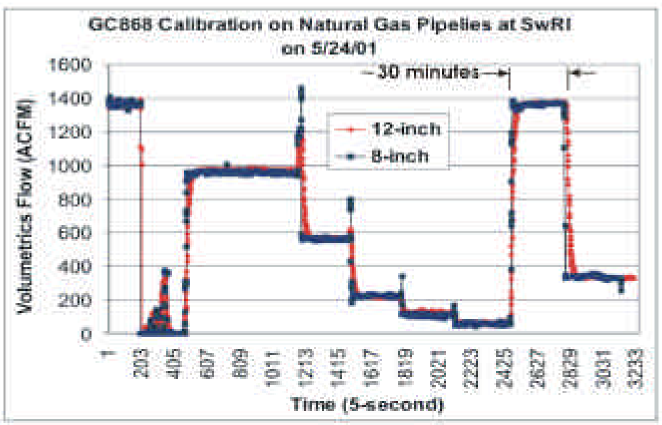

Figure 13. Data comparison from the two independent, single-channel GC868 flowmeters installed on the 8-inch and the 12-inch pipes measured at the same.

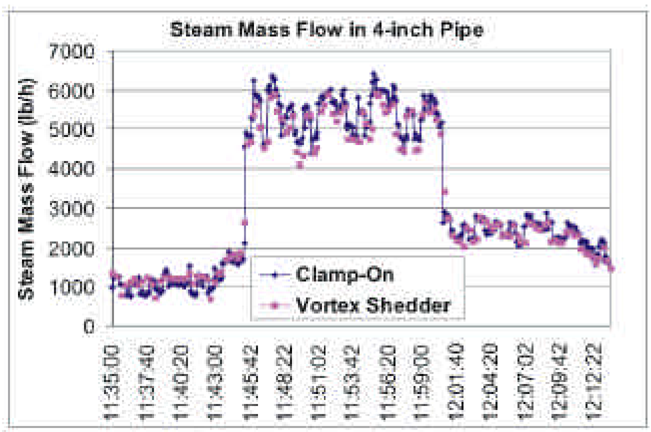

Figure 14. Data obtained from a 4-inch steam pipeline using a GC868 prototype flowmeter. Adjusting a valve varied the flow rate. Steam temperature was about 400°F and pressure was about 200 psig. A vortex shedder was about 5 feet downstream of the clamp-on meter.

Field Tests

In addition to laboratory tests, the meter has also been evaluated in various field tests [4]. They are mostly instrument airflow in ϕ3-inch to ϕ8-inch pipes at pressure of 6 bar to 8 bar and velocity from 0.5 to 40 m/s (1.5 to 135 ft/s). Some applications are bi-directional. The system is also used in natural gas transmission pipelines up to ϕ36-inch and steam pipelines from ϕ4-inch to ϕ12-inch (see steam data in Figure 14) and high temperature hydrogen gas (see Figure 15). There were brand new pipes and 80-year-old pipes including some egg shaped pipes. The numerous field tests have proven that product can work reliably in many cases and also brought in many practical issues specially related to clamp-on flow

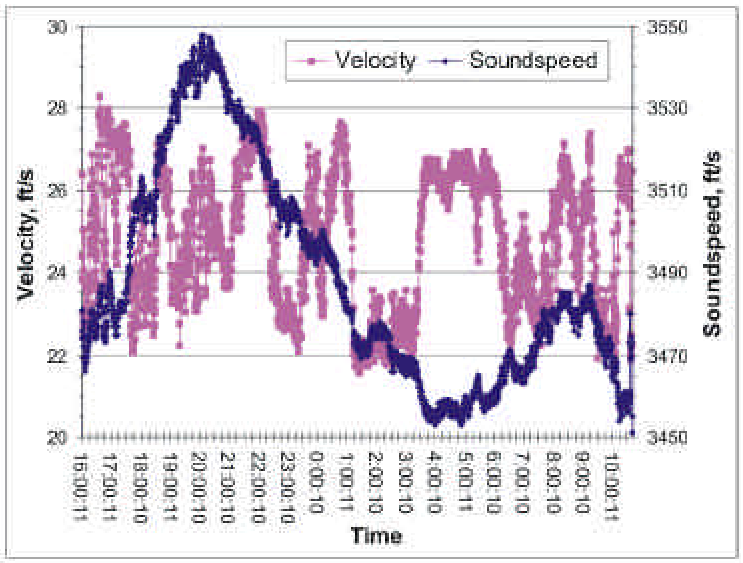

Figure 15. Hydrogen gas flow in a ϕ10 pipe measured using GC868 in a U.S. plant. Gas pressure is about 2300 psig and temperature is about 350°F.

measurement. Poor pipe wall conditions causes reduction in both acoustic signal and noise and generally results less *SNR* than newer pipes. Therefore, the minimum pressure of gas flow that can be measured by the instrument in poor pipe conditions needs to be higher than the pressure needed in good pipe conditions. The instrument is principally able to measure any gas as long as the fluid has a *Z* value greater than 0.002 Mrayls, assuming the gas doesn't contain highly attenuative molecules such as chlorine or high concentration of carbon dioxide. Acoustically, it should be able to measure hot gas, and it has been used to measure superheated steam up to 450° F (232°C) and even saturated steam at several sites using a narrow window. The influence of the liquid contents (e.g. condensate) and many practical issues related to high temperature are still under evaluation. Today, the standard product is limited to a maximum temperature of 302° F (150°C). One can find specification details at [www.panametrics.com].

Conclusion and Outlook

While users benefited from the non-intrusive and good repeatability characteristics of the clamp-on ultrasonic flowmeters, it is also desirable that any non-intrusive instruments provide good accuracy in absolute values. However, there are operational and installation effects that introduce bias to flow measurement in almost all types of flow meters, the convenience of the ultrasonic clamp-on flow meter should not be misinterpreted as a caution free meter. A thoughtful installation, operation is essential for obtaining an accurate flow measurement. While the *wetted* meter can be calibrated with a high precision spoolpiece and, if necessary, insertion of flow conditioners, the absolute accuracy of a clamp-on flowmeter strongly depends on flow profile and pipe conditions. It is required that clamp-on flow meter to be installed after a long straight run and on a typical round pipe so that flow profile can be considered as well developed. As it is found [5] that a carefully calibrated flow meter can become bias as pipe inner surface becomes contaminated and undetected. It is understandable that clamp-on flow meter can be biased when the pipe ID is unknown. However, a thoughtful installation of clamp-on flow meter without interruption of the flow involves a careful pipe survey using a high precision thickness gage such as Panametrics 36DL Plus, it not only can provide precise ID for ACFM calculation in flow measurement, it often provides additional information about the pipe for the users. Principally, the ultrasonic flow meter should also be able to perform self-calibration to adjust the possible bias due to typical pipe contaminations in the future

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