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Paper 3.1

Evaluation of Clamp-on Ultrasonic Gas Transit Time Flowmeters for Natural Gas Applications

V. C. Ting, ChevronTexaco Exploration and Production Technology Company
X. Shirley Ao, GE Panametrics

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V. C. Ting
ChevronTexaco Exploration and Production Technology Company
Houston, TX, USA

and

X. Shirley Ao
GE Panametrics
Waltham, MA, USA

ABSTRACT

This paper presents the results of meter performance tests of the Clamp-on Ultrasonic Gas Transit Time Flowmeter GC868 now manufactured by GE Panametrics. Evaluation tests were conducted during the week of December 3, 2001, at the Colorado Engineering Experiment Station, Inc., (CEESI) Wet Gas Test Facility in Nunn, Colorado, USA. The objective of these evaluation tests was to determine the accuracy of clamp-on gas flowmeters at field operating conditions where gas is dry and/or contains a small amount of entrained liquid.

The clamp-on ultrasonic gas flowmeter was introduced commercially in 2001. Its transducers clamp on the outside of the pipe wall and cause no pressure drop despite wide rangeability. Since no tapping or cutting of the pipe wall is required, permanent installation costs are significantly reduced. Clamp-on ultrasonic gas meters are suitable for monitoring, control, and diagnostics applications. Advantages such as shorter tube length requirement, lighter meter weight, zero pressure drop, ease of installation and lower unit cost will contribute to capital expenditure (CAPEX) and operating expenditure (OPEX) reductions. It also appears or has been shown to be useful for metering of erosive, corrosive, and toxic gases, and/or metering in many applications where penetrating the pipe wall is undesirable. In the future, it can also be developed for *subsea* applications, where cost reduction could be significant. Besides flow velocity *V*, the meter measures gas sound speed *c.* Sound speed may be interpreted in terms of gas temperature *T* or average molecular weight *MW* in suitable situations.

The meter evaluation tests were conducted at the following conditions:

- One meter was mounted on 10.16 cm (4-inch) schedule 80 pipe and the other meter was mounted on 15.24 cm (6-inch) schedule 80 pipe.
- Natural gas nominal pressures: 14.5, 41.4 and 75.8 bar (210, 600, and 1100 psia).
- Gas velocities: 3 to 18 m/s (10 to 60 ft/s).
- Liquid/Gas mass ratio: 0, 0.006 and 0.012.

Test results indicated that the meters measured dry gas flow velocities within $\pm$2% uncertainty. When gas is entrained with low liquid rates at liquid gas mass ratio LGMR<1.3%, clamp-on meter measurement uncertainty remains in the same range as a dry gas meter, except at lower pressure and gas velocity.

INTRODUCTION

Application of ultrasonic meters for natural gas flow measurement has been known since the 1970s and became generally acceptable for large volume custody transfer measurement in the 1990s. Most ultrasonic meters for *gas* flow measurement use intrusive/invasive transducers, where the transducers are *wetted*, i.e., in contact with the gas stream. Ultrasonic flowmeters using clamp-on transducers were developed and have been used in *liquid* flow measurement since the 1960s. In the past five to ten years, clamp-on gas flow measurements occasionally were used at low pressure in plastic pipe or high pressure in steel pipe. Since 1999, Vedapuri [1] has reported a series of laboratory studies on wet gas using an ultrasonic clamp on method. Commercial ultrasonic flowmeters using clamp-on techniques to measure gas flow in steel pipes were introduced by Panametrics in the fall of 2000 [2]. Panametrics was acquired by GE in July 2002, and is now referred to as GE Panametrics.

Clamp-on ultrasonic gas meters are suitable for monitoring, control, and diagnostic applications. The transducers are easy to install since they clamp on the outside of the pipe. Other clamp-on features such as shorter meter tube length requirement, no excess pressure drop, lighter meter weight, and lower unit cost contribute to lower capital and operational expenses. The clamp-on gas flowmeter is an appropriate candidate for metering erosive, corrosive, or toxic gases, and/or in any application (within an approved operating envelope) where penetrating the pipe wall is undesirable. In the future, flow rate measurements along a subsea pipeline, in principle could be developed using clamp-on ultrasonic technology for flow assurance, reservoir monitoring, and flow control at a lower capital and operating cost.

ChevronTexaco evaluated two commercial clamp-on meters under controlled conditions at the Colorado Engineering Experiment Station, Inc., (CEESI) Wet Gas Test Facility located in Nunn, Colorado, USA, during December 2001. The unit consisted of an electronics console, clamp-on ultrasonic transducers, connecting cables, and a clamping fixture that mounts on the pipe as shown in Figure 1.

Fig. 1 – Clamp-On Ultrasonic Gas Flowmeter

Most industrial ultrasonic gas flowmeters utilize transit time or the time of flight ultrasonic flow principle to measure the difference in travel time between pulses transmitted with and against the fluid flow and beamed at an angle in the pipe. The GE Panametrics ultrasonic clamp-on gas meter [3] used a patented Correlation Transit-Time detection technique to detect the time of flight through the metal pipe wall. The meter specifications claim velocity accuracy of ±2.0% for a single path meter in 1.52 to 30.48 m/s (5 to 100 ft/s) ranges in air flow measurement. Ultrasonic clamp-on meters have operated reliably over a 100:1 turndown ratio despite only 10*D* upstream straight run.

CLAMP-ON ULTRASONIC GAS FLOWMETER

The principle of the transit time ultrasonic flowmeter is well known and is widely used in wetted ultrasonic gas and liquid flowmeters as well as in clamp-on liquid flowmeters. In a typical single path configuration, a flowmeter measures flow velocity using two identical transducers located upstream and downstream, respectively. Each transducer typically transmits and receives in an alternating manner so that flow velocity can be calculated based on the transit time sums and differences.

The long-thought *apparent* limitation in clamp-on metering of gas flowing inside a metal pipe is due to practical difficulties in signal transmission through the gas/pipe interfaces. The GE Panametrics Model GC868 flowmeter overcomes the acoustic impedance mismatch difficulty and measures gas flow velocity in metal pipes even when gas is at low pressure, e.g., six barg for *MW* near 29. Since the limit is imposed largely by the signal to noise ratio, the specification on the gas to be measured is determined mostly by the magnitude of acoustic impedance Z, where $Z = \rho c$, the product of the density □ρ and sound speed c of the gas. Z needs to be equivalent to or higher than the value of acoustic impedance for air at 6.2 barg (90 psig). In a typical pipe condition, the GC868 flowmeter measures air/nitrogen gas at a minimum pressure of 6.2 barg (90 psig) or natural gas at a minimum pressure of 13.8 barg (200 psig). The measurable flow velocity is from 0 to 0.1 in Mach number (0 to 40 m/s in natural gas) depending on the pipe size and accuracy requirement. The ideal flow condition is a dry gas flow at condition of acoustic impedance $\rho c \geq 0.004$ Mrayls in typical pipe with relative roughness $\epsilon/D < 0.001$. The meter location should have at least 10*D* straight run upstream *and* downstream and should be at least 10*D* from any flanges.

To some extent the 6.2 barg is a guideline for air flow in common steel pipes of schedule 80 or schedule 40. In titanium pipe thinner than schedule 40, two or three barg probably suffice. As we go to press, lab results on thin-wall Cu or SS tubing indicate that one-barg air can be measured in some cases.

While the clamp-on flowmeter features convenience and low cost of meter installation, it encounters more uncertainties than a flowmeter built as a prefabricated spoolpiece. For instance, it was demonstrated in the field that the meter was able to measure air flow at a pressure of 2.1 barg (30 psig) and even at lower pressure in relatively new pipes, but had difficulty measuring at 6.2 barg (90 psig) in old pipes. The specified minimum pressure of 6.2 barg (90 psig) for measurable airflow is based on typical pipes. The rule of thumb is that any deviation from typical conditions, i.e., deviations such as distorted pipe shape, corroded pipe inner surface, or the presence of a high percentage (2% or higher) of highly attenuating molecules in the gas flow, such as Cl_2 or CO_2, will require higher line pressure to assure the meter functions reliability.

Once the pressure reaches an acceptable level, the accuracy should be maintained unless there is not enough straight run and the effective pipe cross-section area is significantly changed from the input diameter. Both factors cause offset in volumetric flow measurement. However, a second channel can be used to reduce flow profile error [3] and the cross-section area can be determined accurately by a careful ultrasonic pipe wall thickness measurement prior to meter installation. Although the current meter does not have the capability of updating the effective ID to monitor the pipe wall inner surface buildup, sound speed measured by the GC868 has been used as a trouble-shooting parameter when it is combined with known sound speed. The relative roughness, ϵ/D, is an error factor for all flowmeters measuring velocity; however, ϵ/D less than 0.005 is still within the GC868 accuracy specification.

It is well known that sound speed c measured by the intrusive ultrasonic clamp-on gas flowmeter can be used to detect the change of mean molecular weight in gas flow since c is approximately proportional to $1/\sqrt{MW}$ for given pressure and temperature. (Sound speed c also depends on the ratio of specific heats.) For instance, the flare gas flowmeters by GE Panametrics are widely used to locate the source of gas leaks in a piping network based on *MW* [4]. The clamp-on ultrasonic flowmeter, besides measuring V, also measures small changes in the speed of sound for diagnostic applications.

FLOW SYSTEM

Test Facility and Setup

Evaluation of the clamp-on ultrasonic gas meters at dry and slightly wet conditions was conducted at CEESI's Wet Gas Flow Loop. Figure 2 shows an aerial view of the facility. The flow loop utilized lean natural gas and decane liquid as the process fluid to circulate in a 10.2-cm and 15.2-cm closed-loop piping network. A charging compressor and circulating compressors are used to circulate gas in a pressure range between 6.9 and 82.7 bar (100 and 1200 psia) and temperature 2.7 to 27ºC (5 to 50ºF) above the ambient temperature.

Fig. 2 – Aerial View of CEESI Facility, courtesy and permission of CEESI

A reference gas turbine meter was used to accurately measure the circulated dry gas flow rates. Liquid flow rate and density were measured by a coriolis meter and injected into the gas stream by positive displacement pumps. After the liquid is injected into the gas stream, wet gas flows through the test section where the ultrasonic clamp-on meters were installed on the 10.2 cm and 15.2 cm pipes as shown in Figure 3. Coriolis meters were used to measure the mass flow rate and the density of the returned liquid. When the injected liquid mass flow rate is equal to the return liquid mass flow rate, the system is at a steady state condition where data can be acquired. Wet gas flows through the test sections and returns to a gas/liquid separator. At the exit of the gas/liquid separator, liquid returns to the storage area and gas is directed into the upstream header of the circulation compressors.

With the ability to independently control and measure both the gas and liquid flow rates accurately, the effect of dry gas and wet gas on the ultrasonic clamp-on meters can be determined. The CEESI wet gas flow measurement system uncertainty in gas and liquid flow velocities is estimated at 1%.

The meters were set up as a single path meter with triple-traverses. Pipe wall and diameters were surveyed by using a Panametrics wall thickness probe and profiler. The transducers and fixtures were installed according to the manufacturer-recommended procedures and were mounted at the three and nine o'clock positions. Figures 4 and 5 show the pictures of two meters installed on the 10.2 cm and 15.2 cm pipes at the CEESI Wet Gas Flow Loop.

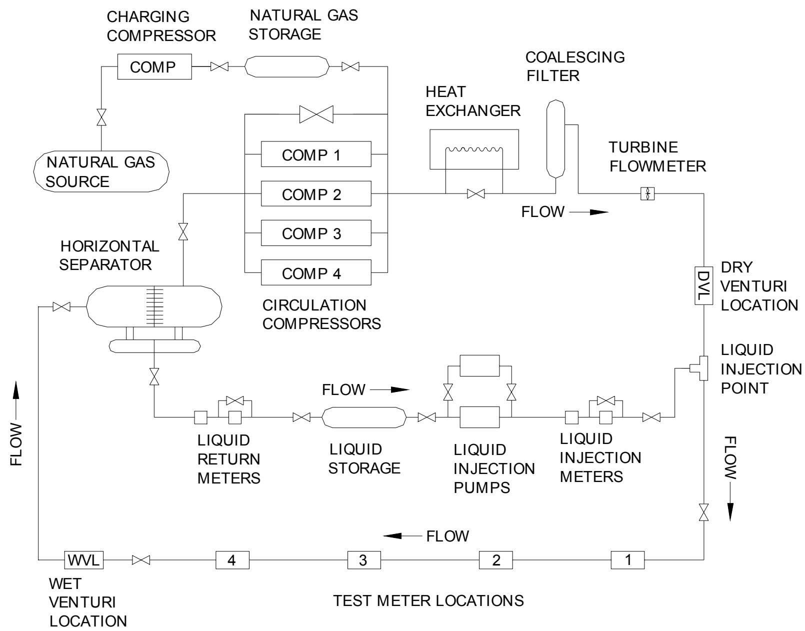

Fig. 3 – Ultrasonic Clamp-on Meter Testing Schematic – 10.2-cm Meter Located Between Test Meter Locations 2 and 3; 15.2-cm Meter Located Downstream of Wet Venturi Location (WVL)

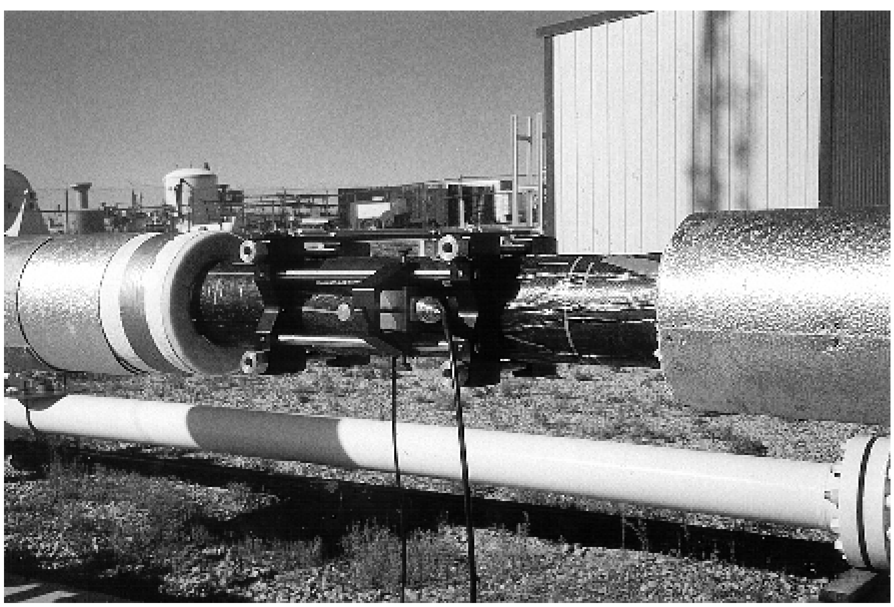

Fig. 4 – 10.2-cm Ultrasonic Clamp-on Meter Installed at CEESI Wet Gas Flow Loop

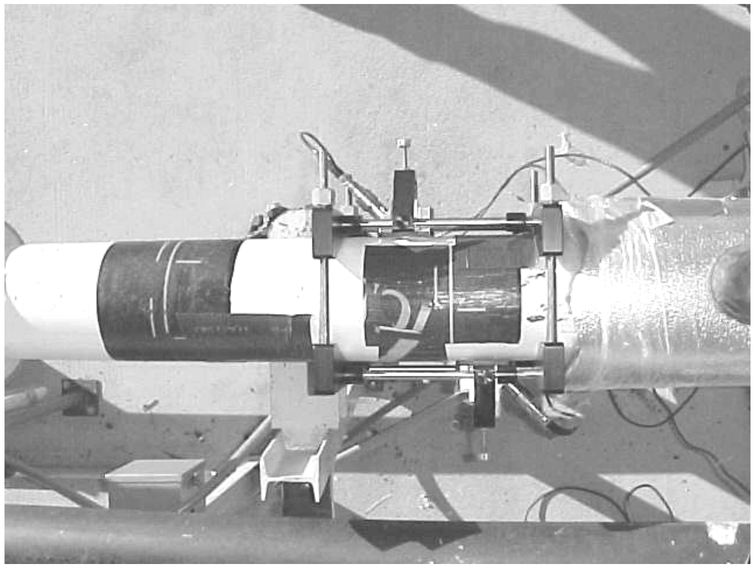

Fig. 5 – 15.2-cm Ultrasonic Clamp-on Meter Installed at CEESI Wet Gas Flow Loop

Test Conditions:

The following test conditions were selected for the clamp-on ultrasonic meters:

- A single path with triple traverse meter was mounted on a 10.16 cm (4”) pipe section and another meter was mounted on a 15.24 cm (6”) section. Both sections are schedule 80 pipes and over 10*D* upstream straight pipes.
- Processed natural gas of nominal pressures 14.5, 41.4 and 75.8 bar (210, 600, and 1100 psia).
- Dry gas tests at nominal gas velocities of 3.05, 6.10, 9.15, 12.19, 15.24 m/s and 18 m/s (10, 20, 30, 40, 50 and 60 fps) in the 10.16 cm (4-inch) schedule 80 test section.
- Wet gas tests at velocities of 3.05, 9.15, 15.24 m/s (10, 30, and 50 fps) at the 10.16 cm (4-inch) schedule 80 test section.
- Liquid/Gas mass flow ratio of 0.006 and 0.012

Table 1 shows the results of diameter survey of the 10.2 cm and 15.2 cm pipe using an ultrasonic thickness gauge, GE Panametrics 36DL Plus.

Table 1 – Pipe Diameter Survey

Pipe	Average OD (inches)	Average ID (inches)	Average Wall (inches)	ID Standard Deviation
Φ4 sch80 CS	4.50	3.798	0.351	0.003
Φ6 sch80 CS	6.625	5.775	0.425	0.003

RESULTS AND DISCUSSION

For ease in identifying the meters on the 10.2 cm and 15.2 cm locations, we denote the clamp-on meter located on the 10.2 cm pipe as Meter A and on the 15.2 cm pipe spool as Meter B.

Dry Baseline Tests:

Figures 6 and 7 are the performance plots for the ultrasonic clamp-on gas Meters A and B at nominal 14.5, 41.4, and 75.8 bar (210, 600, and 1100 psia) dry conditions. Deviations of gas meter velocity readings from CEESI's reference gas turbine meter are plotted. The historical reference, turbine meter calibration plot, Figure 8, shows that the meter has a ±0.37% uncertainty at the 95% confidence interval.

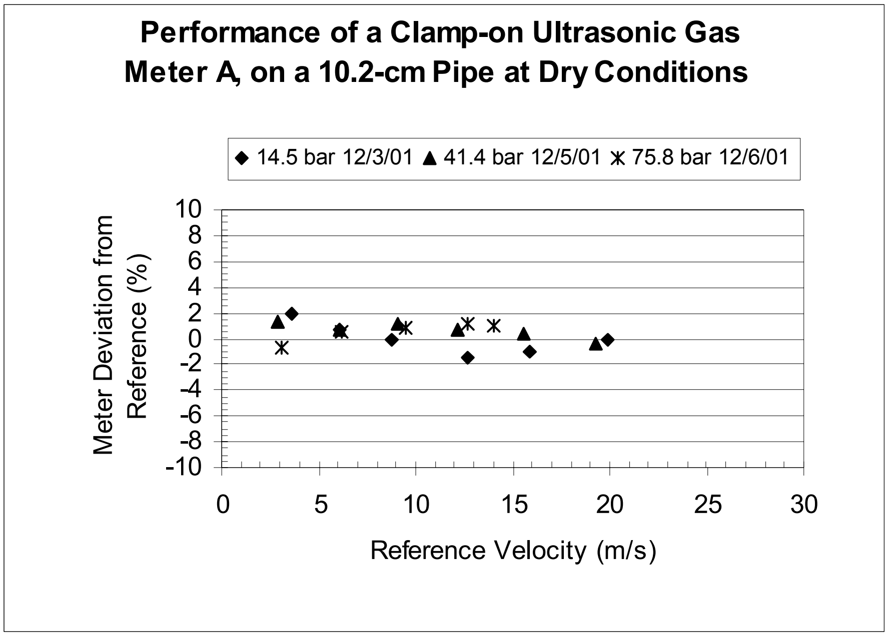

Fig. 6 – Performance of a Clamp-on Ultrasonic Gas Meter on a 10.2 cm Pipe at Dry Conditions

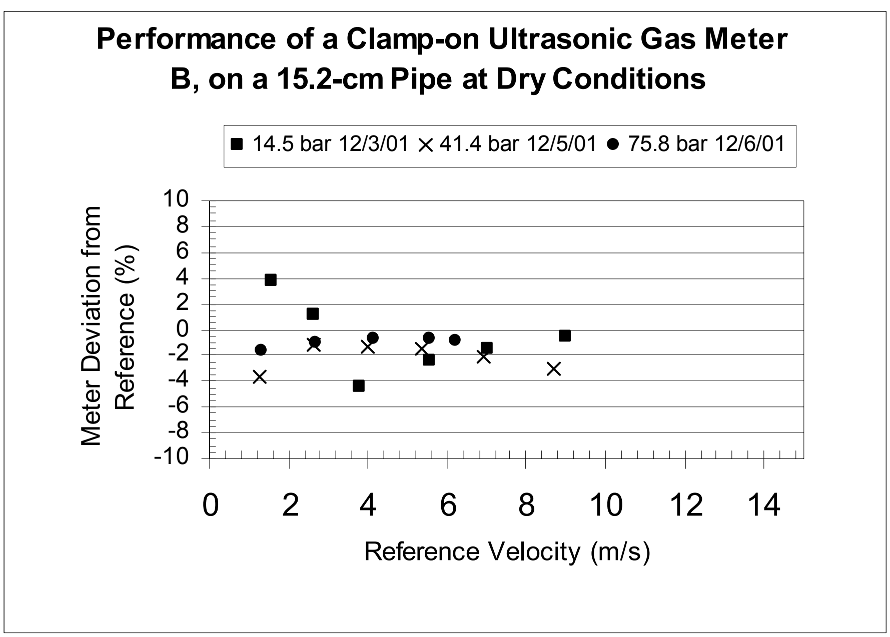

Fig. 7 – Performance of a Clamp-on Ultrasonic Gas Meter on a 15.2 cm Pipe at Dry Conditions

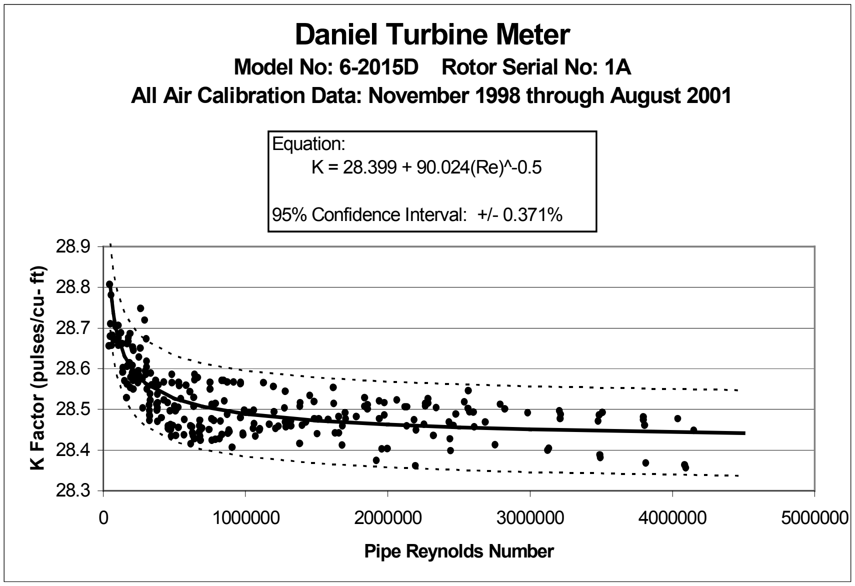

Fig. 8 – CEESI Dry Gas Turbine Reference Meter Calibration Curve

A gas meter velocity deviation from CEESI's dry gas reference velocity is defined as:

Velocity Deviation from Dry Reference Flow (%) = $(V_{Ultrasonic} - V_{Dry}) / V_{Dry} * 100\%$ (1)

where $V_{Ultrasonic}$ is the velocity reading from the ultrasonic meter, and V_{Dry} is the reference gas velocity calculated by dividing reference turbine meter mass flow rates by the product of gas density and meter cross-section area.

Both Meters A and B were installed in series and tested simultaneously. Figure 6 shows the meter deviation from the dry reference meter for Meter A. All data points are within ±2% of the reference flow velocity. Test results for Meter A located on the 10.2 cm (4-inch) pipe section agreed with the manufacturer's accuracy specification of ±2% for a single path meter.

For the Meter B tests, the meter performance is also within the ±2% window at 75.8 bar as shown in Figure 7. However, four data points for Meter B at lower pressures exceed the manufacturer's specifications of ±2%. The performance of Meter B located on the 15.2 cm (6-inch) pipeline at 14.5 bar shows more instability, falling outside the ±2% specification at low and high gas velocities. It is also noticeable that Meter B is located at a longer distance downstream from the reference meter.

Wet Gas Tests:

Testing for wet gas meters was conducted at conditions similar to the dry baseline tests. Liquids were injected at various liquid rates, ranging from a liquid gas mass ratio (LGMR) of 0 to 2%, or Lockhart-Martinelli Number (X) from 0 to 0.004. Both Meters A and B were installed in series and performance data were collected simultaneously.

LGMR and X is defined as:

Liquid Gas Mass Ratio (*LGMR*)
= Liquid Mass Flow Rate / Gas Mass Flow Rate × 100% (2)

Lockhart-Martinelli (X)
$= (M_g / M_L) \times [\sqrt{(\rho_L / \rho_g)}]$ (3)

where M_g = Gas mass flow rate
M_L = Liquid mass flow rate
ρ_g = Gas density
ρ_L = Liquid density

In order to characterize wet gas metering performance, we define ultrasonic clamp-on meter performance in terms of wet gas velocity deviation from dry flow rate:

$$\text{Wet Gas Velocity Deviation from Dry Reference Flow (\%)} = (V_{Ultrasonic} - V_{Dry}) / V_{Dry} \times 100\% \quad (4)$$

where $V_{Ultrasonic}$ is the wet gas velocity reading from ultrasonic meter, and V_{Dry} is the reference dry gas velocity calculated by dividing reference turbine meter mass flow rates by the product of gas density and meter cross-sectional area.

Figure 9 shows the effect of wet gas velocity deviation from dry reference flow at 14.5, 41.4, and 75.8 bar (210, 600, and 1100 psia) for Meter A located on the 10.2 cm (4-inch) pipe. At low liquid entertainment rates where LGMR is less than 1.3%, the effect of liquid entrainment is still within the deviation of the dry gas meter performance variation of ±2% for all tests. No significant liquid entrainment effect was detected for Meter A at low liquid rates.

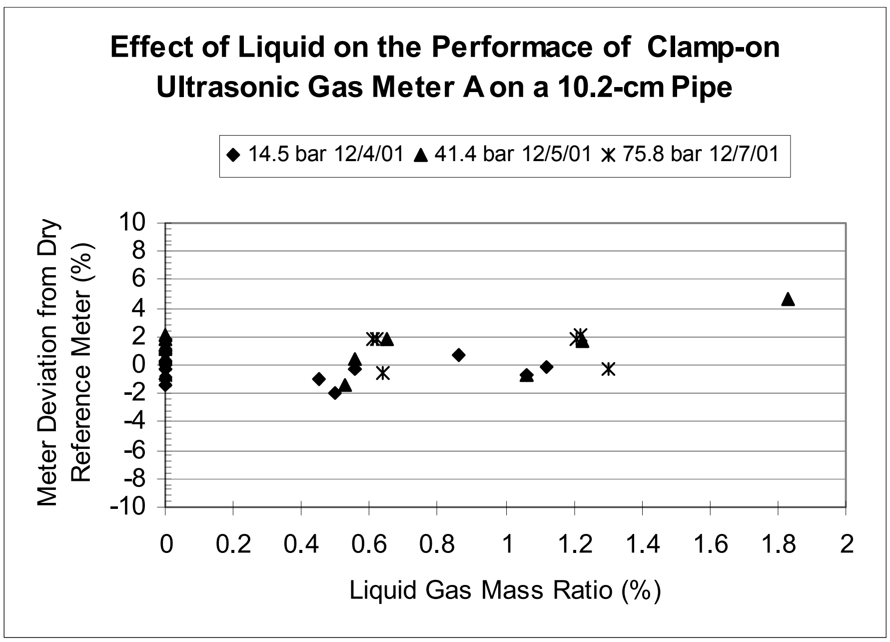

Fig. 9 – Effect of Liquid on the Performance of a 10.2 cm Clamp-on Ultrasonic Gas Meter

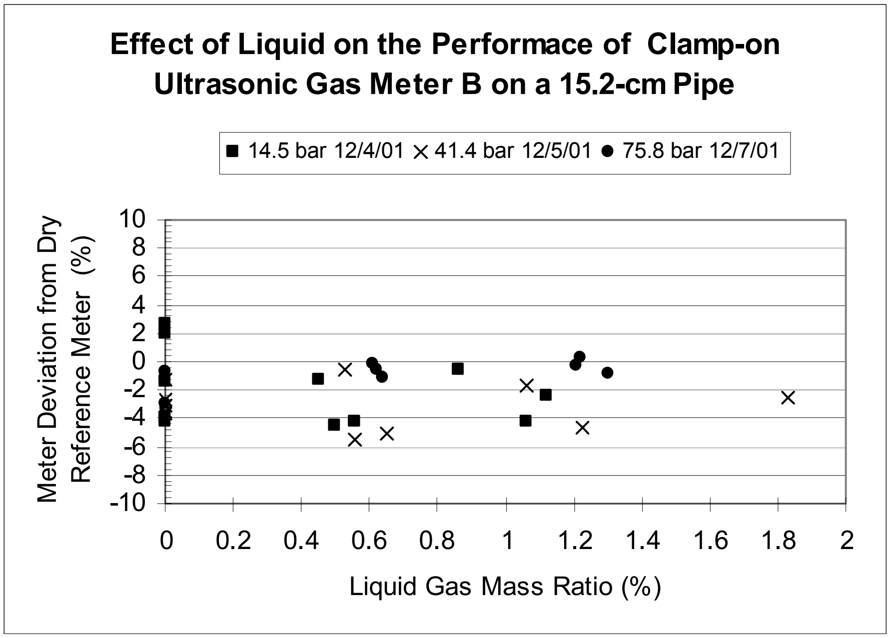

Fig. 10 – Effect of Liquid on the Performance of a 15.2 cm Clamp-on Ultrasonic Gas Meter

Wet gas velocity deviation from the dry reference meter for the clamp-on ultrasonic Meter B, located on the 15.2 cm (6-inch) pipe, is shown in Figure 10. Test results indicated that the effect of liquid on the performance of gas flow measurement of Meter B is also within the same deviation range of dry gas flow except for a few lower data points at 14.5 and 41.4 bar. The gas flow measurement deviation is higher. Again, the long distance between Meter B and reference could have contributed to the error especially when velocity is low.

The entrained liquid in clamp-on gas flow measurement by GC868 introduces two major effects. One could disable the meter by introducing high noises, the other produces positive offset in actual flow rate due to a change on the pipe cross-section area since the GC868 only measures velocity in one plane. The first effect does not occur in typical gas flow applications unless the liquid content is very high, and the second effect may be reduced by using an additional channel along another plane to correct the affected area.

A combined wet gas meter performance plot to show the wet gas velocity deviation from dry reference meter as a function of Lockhart-Martinelli numbers is also presented in Figure 11.

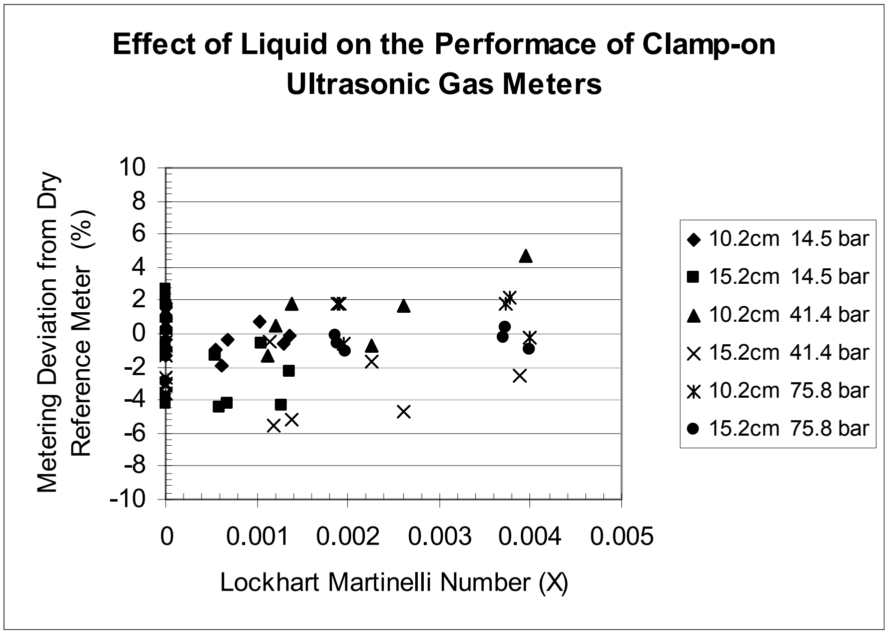

Fig. 11 – Effect of Liquid on the Performance of Clamp-on Ultrasonic Gas Meter as a Function of Lockhart Martinelli Number

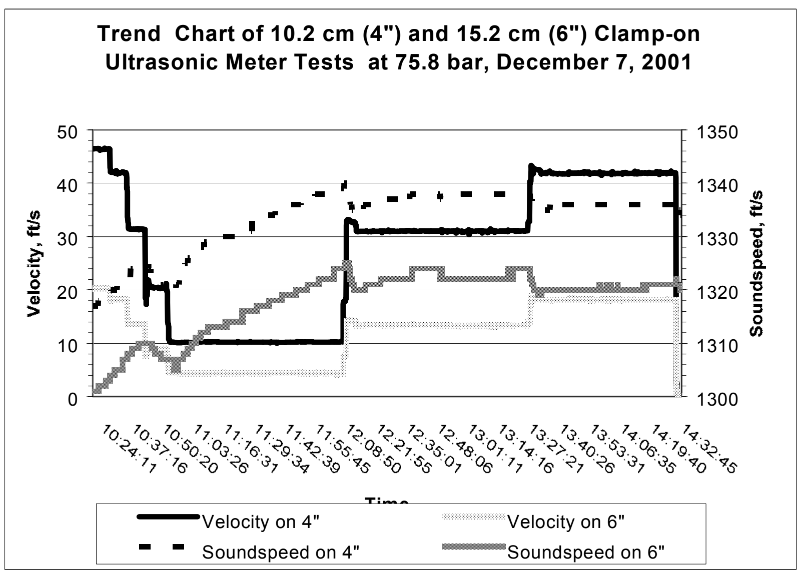

Fig. 12 – Trend Chart from GC686 Flow Computer During Evaluation Tests at 75.8 bar

Figure 12 shows an example trend chart from the GC-868 flow computer recording both clamp-on Meters A and B at 75.8 bar. Actual gas velocity and speed of sound recorded from 10:24:11 to 14:34:20 on December 7, 2001, during CEESI testing are presented.

CONCLUSIONS

Based on test results conducted at CEESI's Wet Gas Flow Loop, the following conclusions can be drawn using the December 2001 version of the GC868 clamp-on gas ultrasonic transit time flowmeters:

1. The clamp-on gas meter can be used for monitoring, control, and diagnostics applications especially where the cost, space, and weight of using conventional spoolpiece or hot-tapped insertion meters are prohibitive.

2. Meter accuracy within ±2% can be achieved for dry gas flow providing installation procedures are followed and pipe conditions are within the recommended specifications. The clamp-on meter performs best at a higher pressure.

3. When gas is entrained with low liquid rates at LGMR<1.3%, clamp-on meter measurement uncertainty remains in the same range as a dry gas meter, except at lower pressure and gas velocity.

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