Excerpts from this ultrasonic report (UR-234) appear in the *Proceedings of the Texas A&M Symposium* (January 2002) in the following paper:

"Ultrasonic Flow Measurement: Technology and Applications in Process and Multiple Vent Stream Situations,"

by

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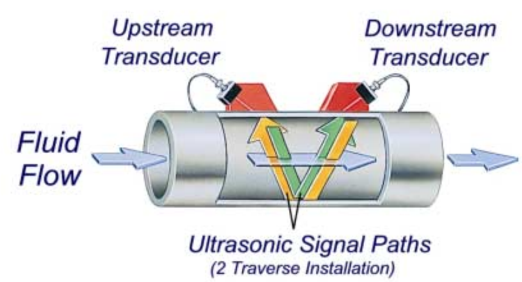
Instrument and process personnel are always looking for a better way to measure process flows. From simple steam flows to two-phase flows with entrained solids, the search is ongoing for technology that provides both accuracy and cost effectiveness. With today's environmental regulations requiring both more and more accurate flow measurements as well high-energy costs making fuel consumption a primary focus, traditional measurement techniques may be less than adequate.

One technology, which is gaining acceptance to meet the new needs in today's industrial marketplace, is transit-time ultrasonic flow measurement. (Box at right illustrates a common clamp-on configuration for liquids.) Considered by many skeptics to be too "new" of a technology, it has in fact been around since the 1950s or earlier for special applications. It has been available commercially (at least in Japan) since the 1960s. Panametrics commercial flowmeters were introduced at an ISA Show in 1979 and its flare gas ultrasonic flowmeter was introduced at this Symposium in 1984 by Smalling et al. Applications have grown rapidly in recent years as more people became aware of and confident in the performance of transit time ultrasonic flowmeters. Besides spanning temperatures between the extremes of cryogenic (-200°C) to very hot (500°C), ultrasonic transit time flow meters are used with gases, liquids and two-phase mixtures. Recently, clamp-on has been extended even to *gases* in steel pipe. So far, this last aspect requires that the gas have a sufficiently high acoustic impedance *Z*. For air, this typically means pressure $P > 4$ bar. In vent stack applications of the type to be described below, $P = 1$ bar so the solution was obtained with *wetted* transducers.



Transit-time ultrasonic flow meters, when applied to fluids of sufficiently high acoustic impedance *Z*, use two clamp-on or wetted transducers. One is installed upstream and one is installed downstream with respect to the flow direction. Each transducer transmits coded sound pulses received by the other transducer. The fluid flow increases the ultrasonic signal time of flight in the direction of flow and decreases the time of flight against the direction of flow. The difference in transit-times is directly proportional to the flow velocity.

Ultrasonic flow meters have among their useful characteristics, zero excess pressure drop, no moving parts and hence, little or no maintenance in many applications, bi-directionality, linearity and large turndown ratios, >>10:1. These characteristics are making ultrasonic flowmeters hard to ignore in light of the issues facing process and design engineers today. Unfortunately, textbooks often concentrate on the older technologies, e.g. orifice plates, venturis, so one might be led to conclude that ultrasound isn't proven yet; that it is hard to understand; why take a chance with something "new"?

Let's take a look at the characteristics of ultrasonic flow measurement and how these have proven beneficial in specific cases.

Turndown. Many engineers assume that turndown is not a necessary quality of a flow meter for routine plant flows. This is because many plants operate at relatively stable flow rates (±5% most of the time) once they are up and running. Why is it acceptable to be in the dark on process flow measurement during startup and shutdown of operating units? These are the most critical periods of process operation in regard to safety and environmental performance as well as production and product quality. Ultrasonic flow meters provide the highest turndown capability of all technologies used in modern instruments (see Fig. 1). This meter characteristic alone could lead to streamlined operational startups and shutdowns, which could minimize many kinds of losses.

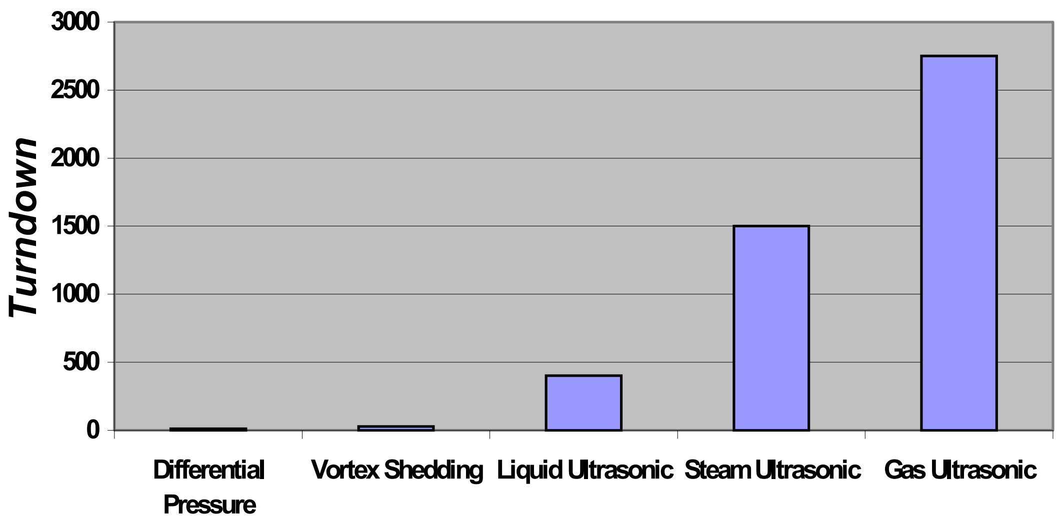


Fig. 1. Turndown Ratio of Some Common Flowmeter Types, Including Transit Time Ultrasonic Flowmeters

On a new plant, meters often need to be replaced after startup due to errors in design versus actual process operation. With the high turndown and, if required, virtual immunity to viscosity variations that ultrasonic multi-path flow meters possess, the only issue would be modifying the meter program after startup to obtain desired operating range. A *tenfold* change in viscosity introduces only a 1% change in the meter factor K of a diameter path (e.g. clamp-on) ultrasonic flowmeter, for turbulent fluids.

The main reason behind the large turndown is the linear response of a transit time flowmeter, in contrast to square law devices. Ability to measure laminar, transitional and turbulent flows may be contrasted with vortex shedding devices that are limited to approximately a 20:1 to 40:1 range of turbulent flows. [See Spitzer, 2001, page 380 for details.]

Pressure Drop. The ability to measure flow without any excess pressure drop is another characteristic of ultrasonic flow meters, and obviously quite different from Δ*P* devices. Everywhere in a process unit the pressure drop caused by flow measurement devices might be costing money – much of which is wasted needlessly. In many (but not all) cases, the Δ*P* might be interpreted as a Δ$ device. Consider cases where removal of a pressure drop such as an orifice plate could directly result in higher production rates. Whether you want to send more product through existing pipes or simply decrease the cost of production, ultrasonic flow meters often provide an economical solution, especially if "cost of ownership" is included in the calculation. The savings in energy alone when steam flow orifices were replaced with ultrasonic flow meters have already provided a generous return on investment in many plants. The savings depends on the cost of energy, and whether the pressure loss affects plant bottom line.

Window Into the Process. Ultrasonic flow meters can yield V and c information, i.e., flow velocity and speed of sound, respectively. Fluid soundspeed, which is a basic parameter used in the flow calculation, provides significant information on the process stream being measured. Soundspeed can sometimes identify the fluid's composition. This window into the composition of the process can transform a simple flow measurement into a useful operating and troubleshooting tool. This feature depends on the fluids being encountered, how many different compositions might exist, temperature compensation, etc. For a well-defined liquid such as water, at temperature far from 74°C, the sound speed correlates well with water temperature and density. The correlation also depends on pressure, but pressure exerts a rather small influence on sound speed.

[To provide a more general solution for liquid density ρ than is available based solely on c in liquids, investigators have proposed supplementary measurements such as the attenuation coefficient α (Babikov, 1960), or measurements of a reflection coefficient from a wetted reflective sensor. A recent example of the latter approach is due to Van Deventer (2001). This type of sensor yields Z, the liquid's acoustic impedance. Density ρ is then obtained by dividing Z by c. As far as the present authors are aware, however, practical commercial versions of liquid densitometers based on α or Z have not yet made it into the industrial process control field.]

Some other interesting aspects of ultrasonic flow meters are:

1. For clamp-on, no parts project into the pipe that can be plugged with solids and debris.
2. Measurement is generally not affected by process material coating the pipe walls (as long as pipe inside diameter is not affected).
3. Ability to measure bi-directional flow in a line.
4. No lead lines are required as with differential pressure based flow meters (such as orifice plates or wedge meters). Maintenance costs associated with draining lead lines for calibration or installing heat tracing to maintain temperature is eliminated.

The case studies that are presented below were taken from work performed by Panametrics Inc. at the Dow Chemical USA facility in Plaquemine, LA. They illustrate the flexibility of ultrasonic flow meters and how they can be successfully applied in a variety of applications.

Application # 1:
Transfer of Flammable Liquid from a Barge to a Storage Tank

Problems:

1. Need to monitor the product transfer rate to minimize the unloading time.
2. Need to stop the transfer as soon as the barge is empty to prevent over-pressuring the storage tank and releasing vapors to the atmosphere.

Solution:

Install an ultrasonic flowmeter and monitor the product flow and soundspeed.

Other solutions considered:

1. Use the derivative of the level to calculate the transfer rate and monitor the storage tank pressure to detect when the barge was empty. This was not implemented because the storage tank diameter was very large and the stability of the level indication did not make the derivative calculation an attractive solution. Stopping the transfer by detecting the pressure rise, when the storage tank vapor space was very small, was considered too risky to implement.
2. The use of a magnetic flow meter was considered, but could not be used since the liquid product was not conductive.
3. Flow and level switches were considered but were quickly dismissed in favor of analog signals.

Process conditions:

Pressure:	50 psig
Temperature:	Ambient
Flow:	0-500 gpm
Fluid soundspeed:	4000 ft/sec
Line:	10″ carbon steel

Flowmeter details:

Model:	Panametrics DF868
Transducer Frequency:	1 MHz
Output A:	0-500 gpm
Output B:	3000-5000 ft/sec

Fig. 2. Installation of DF868 Electronics

Fig. 3. Installation of Ultrasonic Transducers on 10" CS Pipe Transporting Flammable Liquid from Barge to Storage Tank

Results:

The flowmeter is functioning well. The flow indication allows a maximum transfer rate from the barge to the tank. The meter goes into a fault condition when the barge is empty because the transfer line is no longer completely full of liquid. The ultrasonic meter detects an error in soundspeed for liquid material and goes into fault. Detection of the flowmeter fault condition automatically shuts down the transfer before the storage tank over-pressures.

Application # 2:
Bi-directional Measurement of Air Flow at Atmospheric Pressure in Vent Line

Problems:

1. Determine volume of air flowing into each of 5 vessels through vent lines under normal operating conditions and measure the flow to atmosphere through same vent lines under abnormal operating conditions.
2. The air composition will vary in moisture content, temperature, and the amount of hydrocarbon vapors depending upon direction of flow.
3. Meters must function properly and accurately for control and environmental reporting purposes.
4. Redundant flow measurements required.

Solution:

Install an ultrasonic flowmeter spool piece on each vent line with 4 transducers. Each set of transducers programmed for bi-directional flow.

Other solutions considered:

1. Averaging pitot tubes were considered but the poor turndown capability and low differential pressure made this method of measurement impossible.
2. Thermal flow meters were considered but dismissed due to varying stream composition as well as polymer fines in the vent stream.

Process conditions:

Pressure:	0 psig
Temperature:	Ambient or slightly above ambient.
Flow:	-5000 to +5000 SCFM
Fluid soundspeed:	1150 ft/sec
Line:	16″ aluminum pipe

Flowmeter details:

Model:	GM868
Transducers:	100 KHz
Output A:	-5000 to +5000 SCFM
Output B:	-5000 to +5000 SCFM

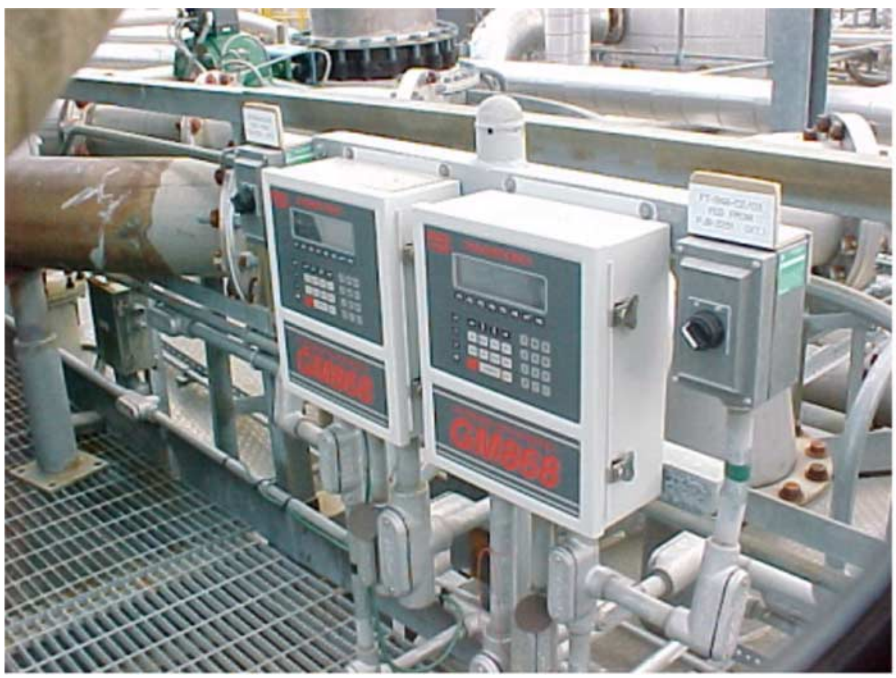


Fig. 4. Installation of Two Consoles, Each Containing GM868 Electronics

Fig. 5. Installation of Two-Path Ultrasonic Transducers on 16" Aluminum Pipe Measuring Bi-Directional Flow

Results:

The flow meters are functioning satisfactorily. Bi-directional flow measurement result is stable and sufficient for both process and environmental control.

Application # 3:
Vent Flow to Throx Unit (Thermal Heat Recovery Oxidizer – Waste Burner)

Problems:

1. Varying stream components, pressure, temperature and concentrations.
2. Saturated corrosive vapor.
3. Need to measure fluid velocity and volumetric flow.
4. Very low pressure.
5. High turndown required.
6. Trip function at low flow required.

Solution:

Install an ultrasonic flowmeter flanged spool piece on vent line with 2 transducers.

Other solutions considered:

1. A wedge flow meter was previously installed. The meter accuracy was affected too much by stream composition. A new flow meter solution was required. Therefore, the wedge meter was being removed.
2. A coriolis flow meter considered, but concerns over performance with so little pressure drop available eliminated this option.

Process conditions:

Pressure:	0-20 psig
Temperature:	50-125 ºF

Flow: 0-5250 ACFH
Fluid soundspeed: 1000 ft/sec
Line: 3″ titanium

Flowmeter details:
Model: GM868
Transducers: 100 KHz
Output A: 0 - 5250 ACFH
Output B: 750-1250 ft/sec

Fig. 6. Installation of Ultrasonic Transducers on 3" Titanium Pipe Measuring a Vent Stream with Continuously Varying Gas Composition to Throx Unit

Results:

The flow meter has been functioning without a problem since ~1998, i.e. for 3 years at the time of this January 2002 Symposium. It was hoped that the fluid soundspeed could be used as an indicator of the concentration of one of the two varying components in the stream, but both have similar soundspeed. With the two components having soundspeeds so similar to each other, it is impossible for the meter to differentiate them based on sound speed alone.

Concluding Remarks

These are just a few of the thousands of successful applications of transit time ultrasonic flow meters in industry. In some articles it is implied or stated that transit time is for clean liquids and Doppler is for "dirty" liquids. This incorrect myth assumes that sound can travel across a tilted-diameter path only through clean liquids. (If that were true, how would a Doppler soundbeam ever reach into the fluid far enough to scatter, and survive the return trip?) The incorrect statements also assume that the sound beam from a Doppler flowmeter cannot scatter from a clean liquid. Today, turbulence is sufficient to scatter ultrasound and some Doppler flowmeters can therefore work on clean liquids. Turbulence also enables *tag* flowmeters to work.

Maybe these statements about transit time for clean, Doppler for dirty, were true of the technology available in the 1960s, but the statements do not apply to today's flowmeters.

Correct statements for the transit time ultrasonic flowmeter would go something like this: transit time flowmeters work in gases, liquids and some two-phase mixtures provided a reasonable signal to noise ratio is obtained. For gases there is a further caveat: the flow should not exceed about Mach 0.1.

Clamp-on applies now to gases such as air at atmospheric pressure *in plastic pipe*, and in steel pipe, at pressures above about 4 bar. If the gas were argon, lower pressure would suffice, while for hydrogen or helium, higher pressure is needed, at this time. The 4 bar guideline depends on pipe condition, diameter and other factors.

As the technology continues to improve, these limits can be expected to change or vanish, meaning, the scope of applications will expand.

Repeatability for most transit time flowmeters usually is better than 1% and can be as good as 0.1%. Accuracy (or uncertainty) is a function of the profile uncertainty and other factors. Depending on the location and number of paths, accuracies can be 0.3%. This optimistic result has been achieved in some recent gas calibration tests, but the reader needs to understand, in the field, conditions at the site and the care exercised in installing the flowmeter may lead to a different accuracy figure. In the case of clamp-on, it is difficult and perhaps unnecessary to verify accuracy at the installation. An alternative is to "prove" the clamp-on at a calibration laboratory, but this usually means, on a similar but not necessarily identical section of pipe.

Acknowledgment

The authors acknowledge Panametrics' permission to excerpt portions from its copyrighted reports UR-226, 234, 260 and 266; and Dow's permission to report on several applications at their Plaquemine facility in Louisiana.

References for More Information

Asher, R. C., *Ultrasonic Sensors for Chemical Process Plant,* Institute of Physics Publishing, London (1997).

Babikov, O. I., *Ultrasonics and Its Industrial Applications*, Consultants Bureau, Plenium Press, New York (1960).

Miller, R. W*., Flow Measurement Engineering Handbook,* 3rd Ed., McGraw-Hill (1996).

Liu, Y., Lynnworth, L. C., and Zimmerman*,* M. A., Buffer Waveguides for Flow Measurement in Hot Fluids, *Ultrasonics,* **36** (1-5)*,* pp. 305-315 (February 1998).

Lynnworth, L. C., Clamp-On Flowmeters for Fluids, *Sensors*, **18**, (8), pp. 50-59 (Aug. 2001); Measuring Flow Under Tough Conditions Using Ultrasonics, *Control Solutions*, **74** (11), pp. 14-19 (2001).

Lynnworth, L. C., *Ultrasonic Measurements for Process Control, Theory, Techniques, Applications,* Academic Press (1989).

Papadakis, E. P., (Guest Editor), *Ultrasonic Instruments and Devices: Reference for Modern Instrumentation, Techniques, and Technology,* **23**, in the series *Physical Acoustics*, Academic Press (1999).

Scelzo, M., A Clamp-on Ultrasonic Flowmeter for Gases, *Flow Control*, **7** (9) pp. 34-37 (Sept. 2001).

Smalling, J. W., Braswell, L. D., Lynnworth, L. C., and Wallace, D. R., Flare Gas Ultrasonic Flow Meter, *Proceedings 39th Texas A&M Annual Symposium on Instrumentation for the Process Industries*, pp. 27-38 (January 17-20, 1984); Smalling, J. W., L. D. Braswell, and L. C. Lynnworth, *Apparatus and Methods for Measuring Fluid Flow Parameters,* U.S. Patent 4,856,321 (August 15, 1989); U.S. Patent 4,596,133 (June 24, 1986); U.S. Patent 4,754,650 (July 5, 1988).

Spitzer, D.W. (Editor), *Flow Measurement,* ISA, 2nd Edition (2001).

van Deventer, J., *Material Investigations and Simulation Tools Towards a Design Strategy for An Ultrasonic Densitometer*, Luleå University of Technology, Luleå, Sweden (2001); Van Deventer, J. A., *An Ultrasonic Density Measurement Technique,* Luleå University of Technology, 35 (1999).

Appendix A: Some background material and additional recent applications at sites other than Dow, Plaquemine LA

Fig. A1. Clamp-on Gas Flowmeter due to Shirley Ao. Patents pending. See Scelzo (2001).

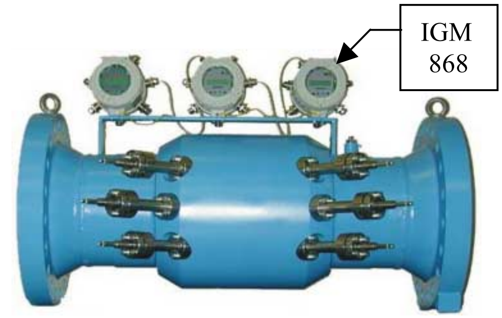


Fig. A2. The Cerberus Flow Measurement System used for PTB certification testing, developed by Jim Hill of Panametrics and Andreas Weber and Hans Kastner of RMG.

Fig. A3. Guided-mode clamp-on for ultrapure liquids in plastic tubing ≤ ϕ 25 mm, after Jim Hill and John Pell, U.S. patent 6,065,350 (May 23, 2000).

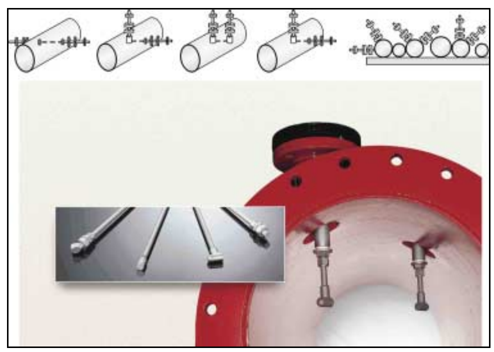
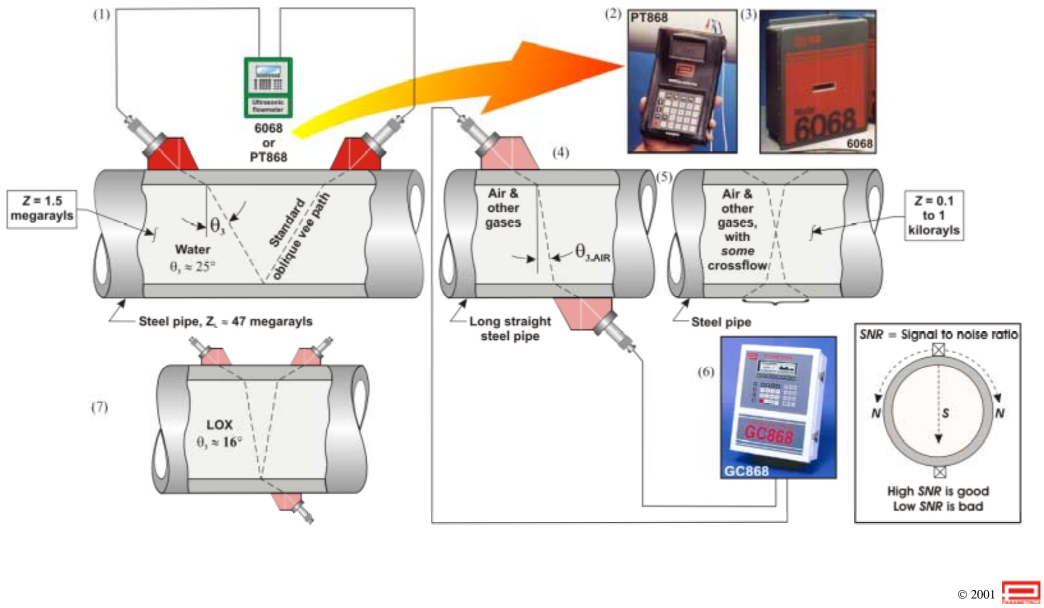


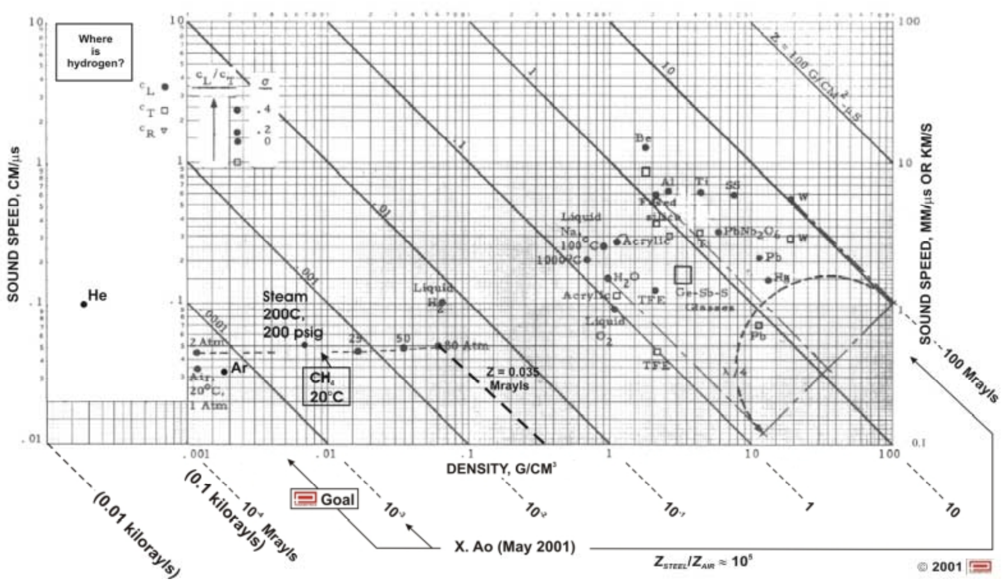
Fig. A4. Paths used in flare gas flowmeters, 1982-2002, after Smalling et al. (1984, 1989).

Now back to "background"

- Major differences … between gas & liquid …



Why not clamp-on for gases?



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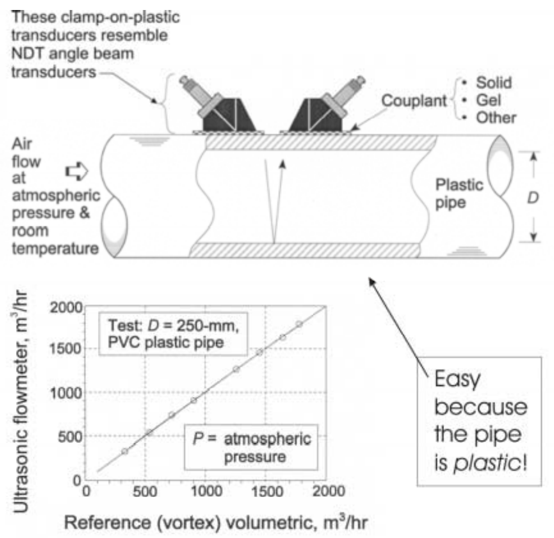
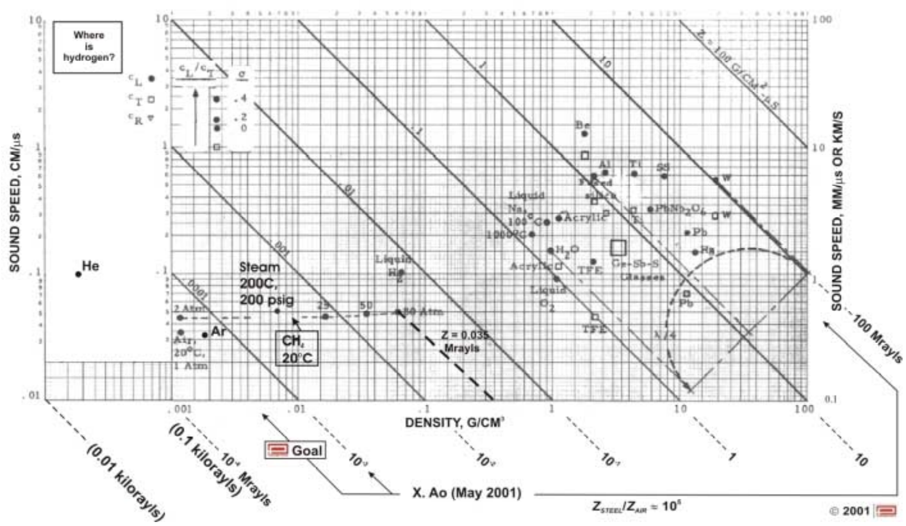
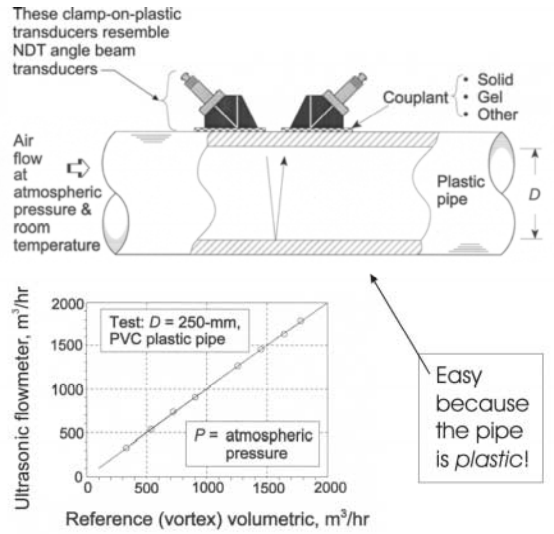


An easy clamp-on air problem, solved a few years ago by Oleg Khrakovsky.

Why not clamp-on for gases?

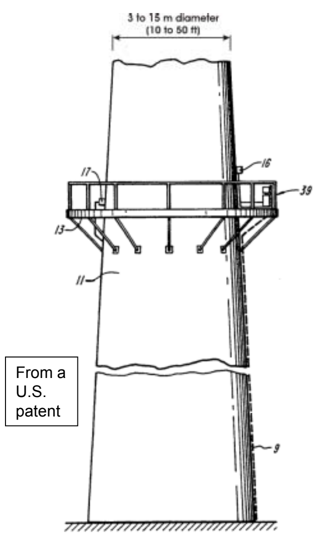


Why not clamp-on for gases?



An easy clamp-on air problem, solved a few years ago by Oleg Khrakovsky.

CEM = Continuous Emissions Monitoring



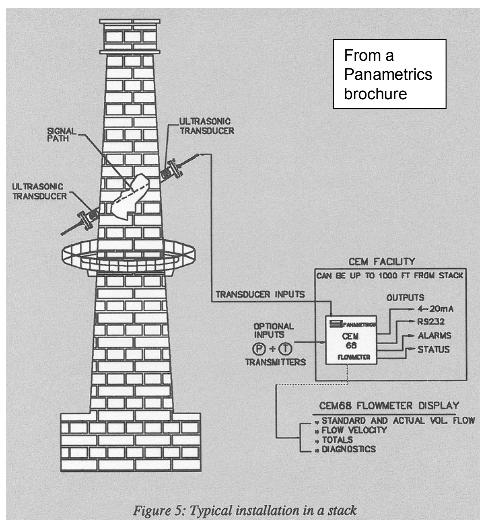


Figure 5: Typical installation in a stack

Example of a vent stack application in 1995, hot gas, two lined tees, oblique simple holders

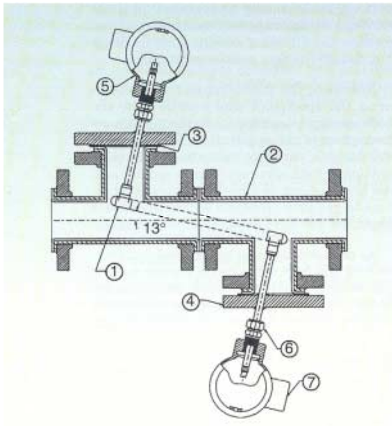


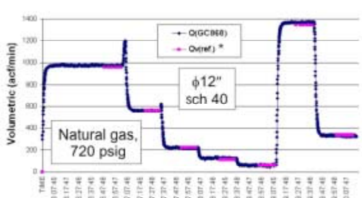
FIGURE 4. Titanium flare gas transducers adapted to a vent stack application where the temperature may reach 232°C. Legend: (1) T5-90 high-temperature transducer, 2 places. (2) 3-inch, 150-lb, heavy-duty PTFE-lined tee, 2 places. (3) 3-inch, teflon-enveloped gasket, 2 places. (4) 3-inch, 150-lb titanium grade 2, RF, blind flange, 2 places. (5) Junction box, 2 places. (6) 3/4-inch NPT(M) to 1/2-inch compression fitting, 2 places. (7) 3/4-inch NPT(F), 4 places.

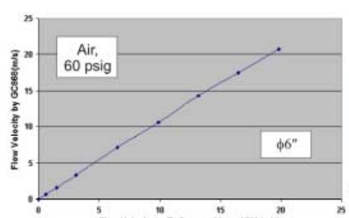
Ref: Lynnworth, L. C., Ultrasonic Gas Flowmeters, *m&c (Measurements & Control)*, **29** (5), pp. 92-101 (October 1995).

Not part of today's talk, but a peek at May 2001 Texas *clamp-on* gas calibration data … details @ next year's Texas A&M Symposium, maybe.

Steam pipe in NJ, ϕ6"

Beta site; equipment not yet available commercially for clamp-on steam



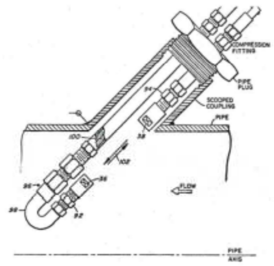


Clamp-on, steel pipes

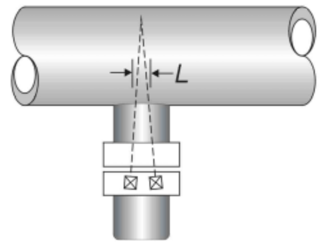
* Reference flow provided by GTI Metering Research Facility @ SwRI.

One port rather than two

(a) Proposal using an oblique port

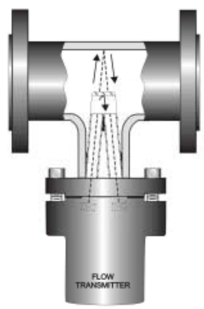


(b) ⊥ nozzle, vee path, echo off opposite wall of pipe



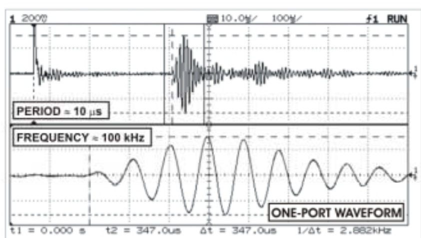
One-port Panametrics flowmeters, as of January 2002, were were considered experimental devices. Questions about commercial availability will be handled by the PCI R&D Division on a case-by-case basis, until they become standard PCI products.

(c) ⊥ nozzle, first and second reflecting surfaces



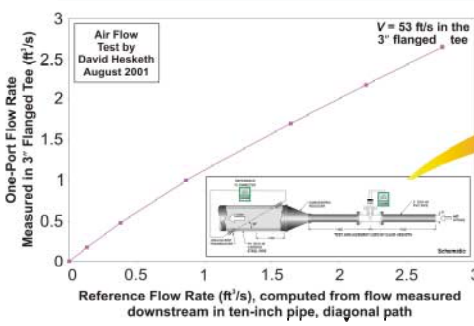
(d) ⊥ port, tested in flowing air in Panametrics R&D lab

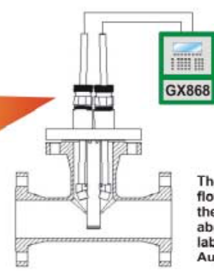
One port rather than two, *continued*.



One-port testing in a pipe of nominal diameter 3"
No flow, atmospheric pressure
Signal: 606.3 mV; Noise: 28.13 mV; *SNR*: 26.7 dB

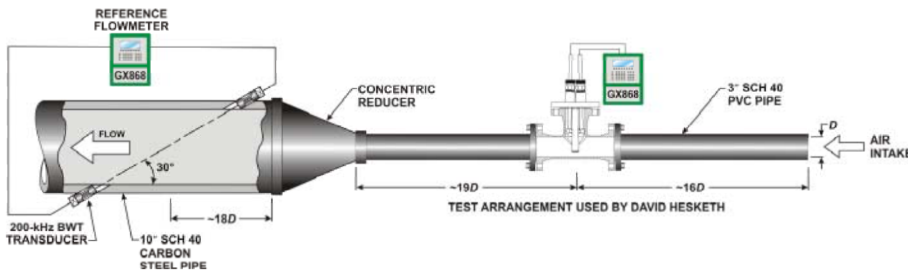
One-port Panametrics flowmeters, as of January 2002, were considered experimental devices. Questions about commercial availability will be handled by the PCI R&D Division on a case-by-case basis, until they become standard PCI products.





The maximum air flow velocity *V* in the 3 flanged tee was about 53 ft/s, in this laboratory test in August 2001.

One port rather than two, *continued*.



Conclusions from the Plaquemine Plant's Perspective

• Acceptance and utilization of transit-time flowmeters for process measurements are definitely on the rise. Although the present Plaquemine applications range in pipe size from 1 inch to 60 inches, the technology is often given first consideration for flow measurement in process lines that are 6" and larger.

• The technology is also given high consideration for all line sizes in special or difficult process applications such as high turndown, bi-directional flow, changing stream composition, saturated vapor, etc. One should keep in mind that gas applications in tube sizes down to 3/8" were demonstrated over ten years ago by the first presenter. Finally, the cem examples cited early in the talk showed smokestack diameters from 10 to 50 ft, in which high-velocity hot gas flows were measured ultrasonically about eight years ago. These applications collectively represent a *diameter turndown* of roughly $3 \times 12 \times 50 = 1800$. Taking into account lab tests on tubing diameter of 1/8" OD, and cem at the upper extreme, a case can be made for claiming with ultrasound, a diameter turndown capability over 5000. However, the equipment would not be identical over this entire range of diameters.

Conclusions from the Plaquemine Plant's Perspective, *continued*

- The reliability of transit-time flowmeters for process measurements is now proven to the point that the usage includes both control points and trip functions.
- The long-term cost of ownership for transit-time flowmeters is proving to be another advantage of this technology. The low pressure drop, low energy loss, minimal predictive preventive maintenance requirements, and high reliability are making the selection of transit-time flowmeters a valid option and a more frequent final flowmeter choice.

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