ULTRASONIC FLOWMETERS FOR PETROCHEMICAL PROCESS CONTROL

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ABSTRACT

The flow of gaseous and liquid hydrocarbons is now routinely measured ultrasonically. Ultrasonics has taken some twenty years to prove itself in nonideal industrial petrochemical process control applications. It has now reached the stage where many users specify ultrasonics when they want to achieve reliable, accurate measurements without loss of pressure; linearity despite wide turndown ratios; no moving parts; wide temperature range; portability. The ultrasonic flowmeter output can in general be in units of velocity, volumetric or mass flowrate. This presentation covers basic contrapropagation theory; flow profile; flare gas molecular weight, density and mass flowrate determination; liquid clamp-on applications; and limitations of the technology.

INTRODUCTION

Ultrasonic flowmeters have been used in oil exploration experiments downhole, over a mile deep, as well as in a Space Shuttle flight. The same principles that were utilized in these two unusual applications are in fact utilized in many mundane "down to earth" applications where liquid or gaseous hydrocarbon flows are to be measured. Applications include identifying which of several hydrocarbons is in a pipe at a given moment ("interface detection"), and accurately measuring the flowrate of each and every one of them. "Flowrate" includes flow velocity V, actual volumetric flowrate Q_a, volumetric flowrate Q_s referred to standard conditions (e.g., units of SCFM for gaseous hydrocarbons), and mass flowrate M_f. Thus, flow measurements can include density ρ, and if the hydrocarbon is a gas, this can include average molecular weight ($\bar{M}_w$) determination. Flare gas mass flowrate applications over the past ten years illustrate how one ultrasonic instrument can measure not only V and Q_a but also Q_s, ρ, $\bar{M}_w$ and M_f if pressure P and temperature T are known. For *liquid* hydrocarbon applications, it is often possible to measure V and Q_a using clamp-on transducers, for pipe wall temperature of about $\pm 200°C$. Above about 250°C, wetted or sometimes clamp-on buffer rods have been used. If the objective is *high repeatability* or *high precision*, flow profile can often be disregarded. For *high accuracy*, however, flow profile must be taken into account by one or more of the following interrogation methods: use of one or more special paths; sampling of 100% of the flowing cross-section; empirical calibration relating the ultrasonic flow velocity measurement V_p averaged over a particular path to the true area-averaged flow, $\bar{V}$. Limitations of presently-available flowmeters also must be considered, such as low-pressure propagation limits for gases; very thick wall, small-diameter limits for liquid clamp-on; response time; sampling rate relative to pulsations in unsteady flow; sources of attenuation and noise interference; memory/logging limits in portable flowmeters; accuracy limits based on availability of volumetric or gravimetric calibration facilities.

FLOW PROFILE CONSIDERATIONS

In the ideal situation of steady flow at ambient temperature in a long straight run of smooth pipe of known geometry, and of a size and at flowrates that are subject to verification in the controlled conditions of a calibration laboratory, gravimetric or volumetric calibration can be accomplished to 1/2% or better accuracy. Commercially-available ultrasonic flowmeters for liquids and for gases have evolved in which a variety of interrogation paths are utilized. These include both short-wavelength and long-wavelength interrogation of 100% of the flowing cross-section, as a means of minimizing the influence of flow profile on the accuracy. Other means of minimizing the uncertainties due to flow profile include the use of special points or paths such as (a) one or more quarter-radius points or (b) midradius chords where the local velocity nearly equals the mean velocity for developed turbulent flow profiles; (c) four-path Gauss-Chebyshev; (d) crossed diameters; and (e) chord segments when restricted access or high attenuation prevent a wall-to-wall diametral interrogation.

In cases that are sufficiently close to ideal so that the flow profile is expressible analytically, it is straightforward to relate the flow at *any point* to the mean. For example, according to the universal velocity distribution law for turbulent flow [H. Schlichting, *Boundary Layer Theory*, 7th Ed., McGraw-Hill (1979)],

$$\frac{V}{V_o} = \left(\frac{y}{R}\right)^{1/n}, \tag{1}$$

the ratio of the mean ($\bar{V}$) to the maximum (V_o) is

$$\frac{\bar{V}}{V_o} = \frac{2n^2}{(n+1)\,(2n+1)} \tag{2}$$

where y = distance in from the wall, R = radius of duct, and $n \approx 1.66 \log Re$ where Re = Reynolds number. The RHS of (2) may be interpreted as the on-axis meter factor K_o: $\bar{V} = K_oV_o$. Equation (1) assumes that the profile is a unique function of the Reynolds number.

It is similarly possible to relate the flow averaged over some particular *path* to the mean. If the path is a diameter,

$$\overline{V} = K_{dia}\ V_{dia} \tag{3}$$

where the diametral meter factor $K_{dia} = 1/(1.119 - 0.011 \log Re)$. In this case, if $Re = 10^6$, $K = 0.95$. If the path is a midradius chord, K_{mr} very nearly equals unity for $4000 < Re < 3.2 \times 10^6$. Values of K_{cs} for chord segments also have been calculated as a function of Re.

If one combines Eqs. (1) and (2) to solve for $\overline{V}$ in terms of V, it takes only a couple of steps to show that the mean is related to a local measurement of V at distance y in from the wall by

$$\overline{V} = V\left(\frac{y}{R}\right)^{-1/n} \frac{2n^2}{(n+1)(2n+1)}. \tag{4}$$

Where does $V \approx \overline{V}$? The answer is found by setting the non-V RHS portion of Eq. (4) equal to unity, from which

$$\left(\frac{y}{R}\right)^{1/n} = \frac{2n^2}{(n+1)(2n+1)}. \tag{5}$$

Solving for y/R,

$$\frac{y}{R} = \left(\frac{2n^2}{(n+1)(2n+1)}\right)^n. \tag{6}$$

Remembering that $n \approx 1.66 \log Re$, and also remembering that turbulent flows typically range between Re = 4000 and 3 000 000, we are concerned with n from about 6 to 10. Substituting a few n's into Eq. (6) one calculates:

n	6	8	10
y/R where $V = \overline{V}$	.245	.240	.237

What this means is that "local" measurements along short chord segments or measurements at a point, where the path or point is located 24% of the radius in from the wall (y/R = 0.24) sense a local value very close to the mean, to the extent that the actual profile can be represented by Eq. (1). As a practical matter, we can approximate this location as the "quarter-radius point."

DERIVATION OF TRANSIT TIME EQUATIONS FOR CONTRAPROPAGATION INTERROGATION

A rather simple derivation of the basic flow-sensing equation is possible if one imagines a fluid of uniform sound speed c flowing at a uniform velocity $V < c$ in a duct of cross-sectional area A, interrogated by two point sensors on the axis and spaced a distance L apart. The transit times in the upstream and downstream directions, respectively, are

$$t_1 = L/(c-V) \text{ and } t_2 = L/(c+V)\,. \tag{7}$$

The reciprocals of these transit times, multiplied by L, are

$$L/t_1 = c-V \text{ and } L/t_2 = c+V. \tag{8}$$

Accordingly,

$$V = \frac{L}{2}\left(\frac{1}{t_2}-\frac{1}{t_1}\right) = \frac{L}{2}\left(\frac{\Delta t}{t_1\,t_2}\right) \text{ and } c = \frac{L}{2}\left(\frac{1}{t_2}+\frac{1}{t_1}\right) = \frac{L}{2}\left(\frac{\Sigma t}{t_1\,t_2}\right). \tag{9}$$

The upstream-downstream time difference can be obtained from Eq. (7) as $\Delta t = 2LV/(c^2 - V^2)$. This can be expressed in terms of the Mach number $M_s = V/c$ for $M_s << 1$:

$$\Delta t = \frac{2LV/c^2}{1-M_s^2} = (2LV/c^2)\,(1+M_s^2+M_s^4+\ldots)\,. \tag{10}$$

ILLUSTRATIONS AND APPLICATIONS

The rest of this paper consists of illustrations related to the above ideas and to flowmeter applications in liquids and gases. Most of these illustrations are copyright by and reproduced with the permission of Academic Press [1] or Panametrics.

REFERENCES

1. L. C. Lynnworth, *Ultrasonic Measurements for Process Control*, 720 pp., Academic Press (1989).

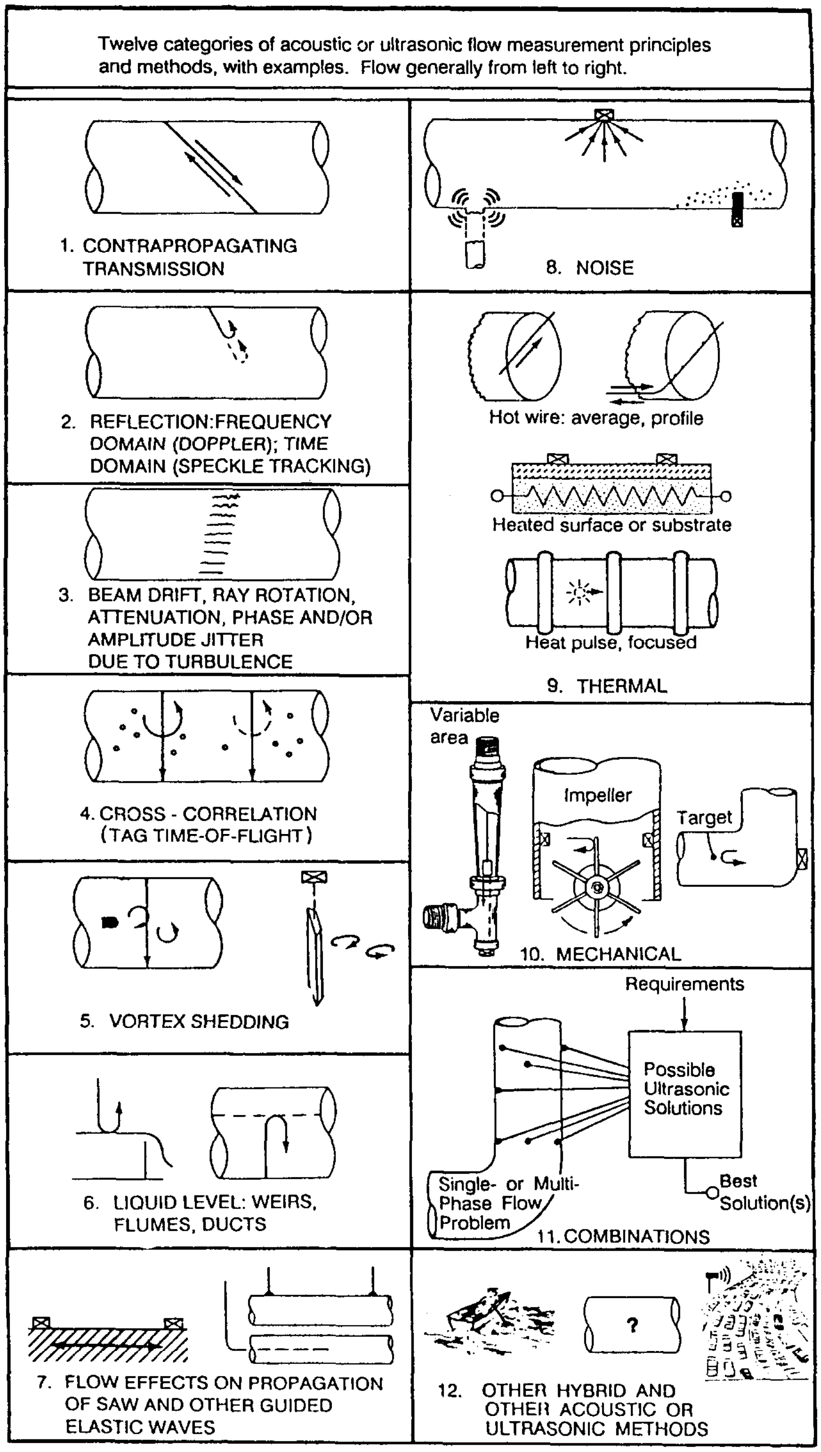


Figure 1 - Twelve categories of acoustic or ultrasonic flow measurement principles and methods, with examples. Flow generally from left to right (AP Fig. 2-1). ©1989 Academic Press; reproduced with permission.

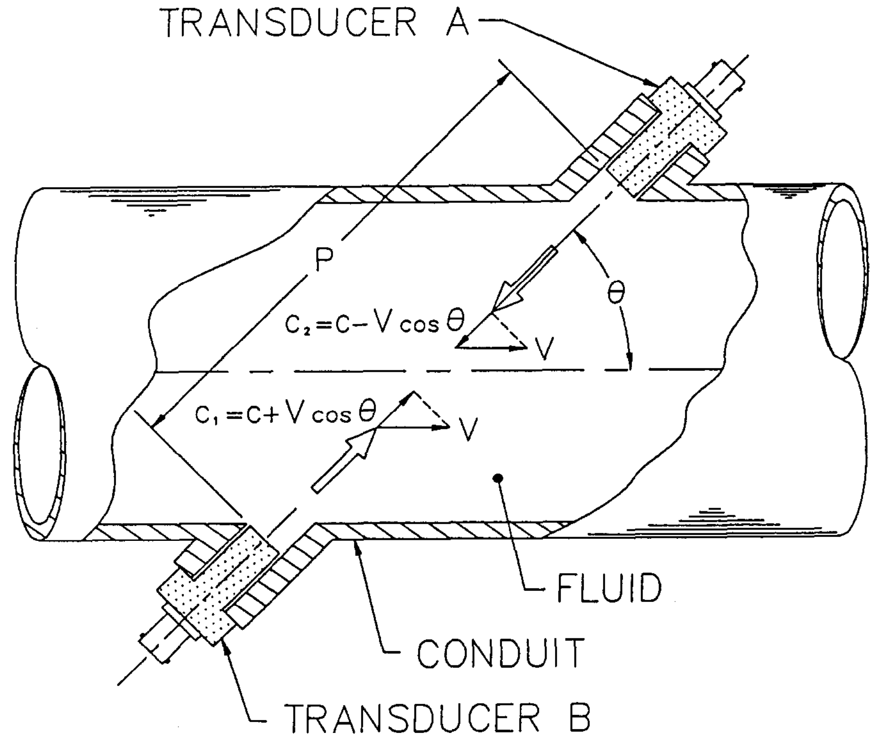


Figure 2 - Sound bursts are propagated alternately in opposite directions between a pair of transducers situated diagonally along the pipeline. The upstream signal is delayed and the downstream signal is speeded up by the moving fluid. Illustration adapted from Crouzet (AP Fig. 2-2). ©1989 Academic Press; reproduced with permission.

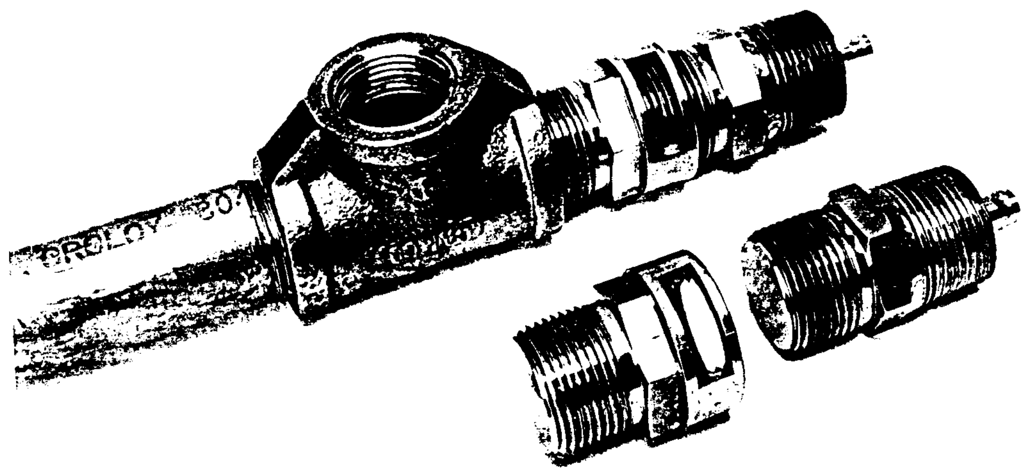


Figure 3 - Precision plugs accommodate removable transducers, while providing the controlled paths associated with wetted transducers (AP Fig. 3-30). ©1989 Academic Press; reproduced with permission.

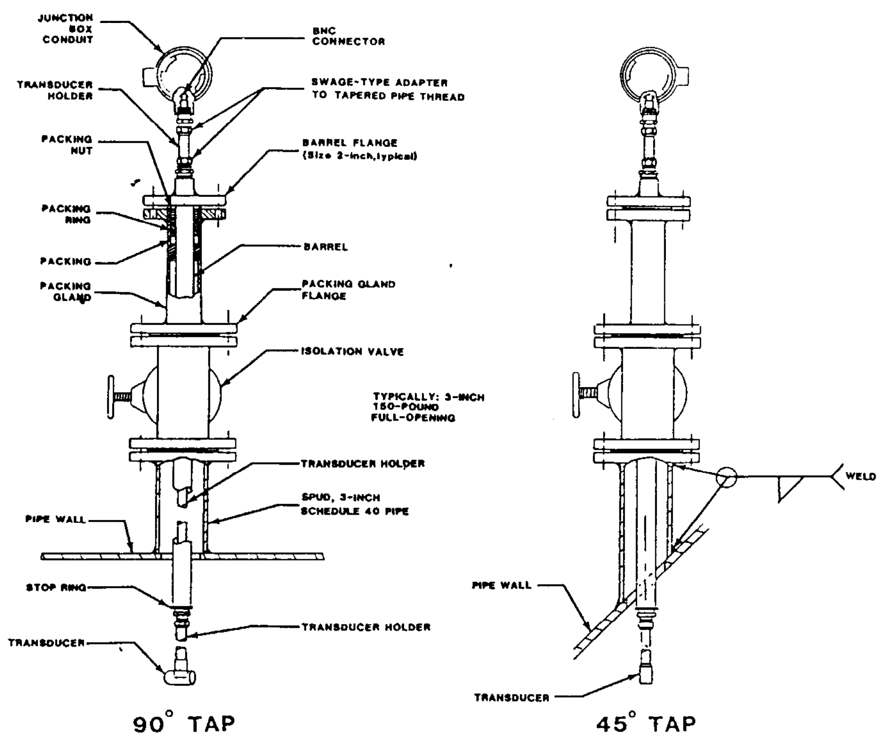


Figure 4 - Low-impedance (and high attenuation) of packing gland sealant contribute to acoustic isolation in a 100-kHz transducer holder used in flare gas flowmeters. After Smalling et al., 1984, 1986 (AP Fig. 3-37). ©1989 Academic Press; reproduced with permission.

Figure 5 - Example of PT868, a portable clamp-on (or wetted transducer) battery-powered correlation detection flowmeter. It was programmed in 1992 to operate as a transit time instrument when it is temporarily operated as a thickness gage. In 1993, new programs are expected to extend its operating modes to include reflection. This will be a multipulse tracking mode, different from the usual Doppler flowmeters, but nevertheless responsive to the flow velocity of scatterers in the fluid. Technical capabilities for this instrument include storage capacity for 40,000 data points, 20 site location parameters, on-line pipe tables, and graphic or alphanumeric LCD display.

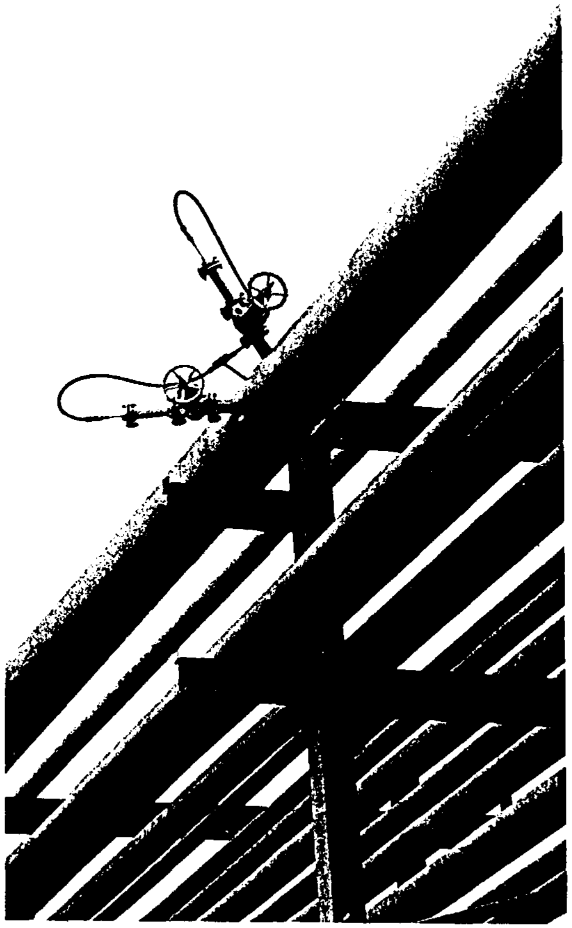


Figure 6a - Example of hot-tapped installation of flare gas flowmeter transducers in a 20-inch pipe despite access constraints imposed by nearby pipes.

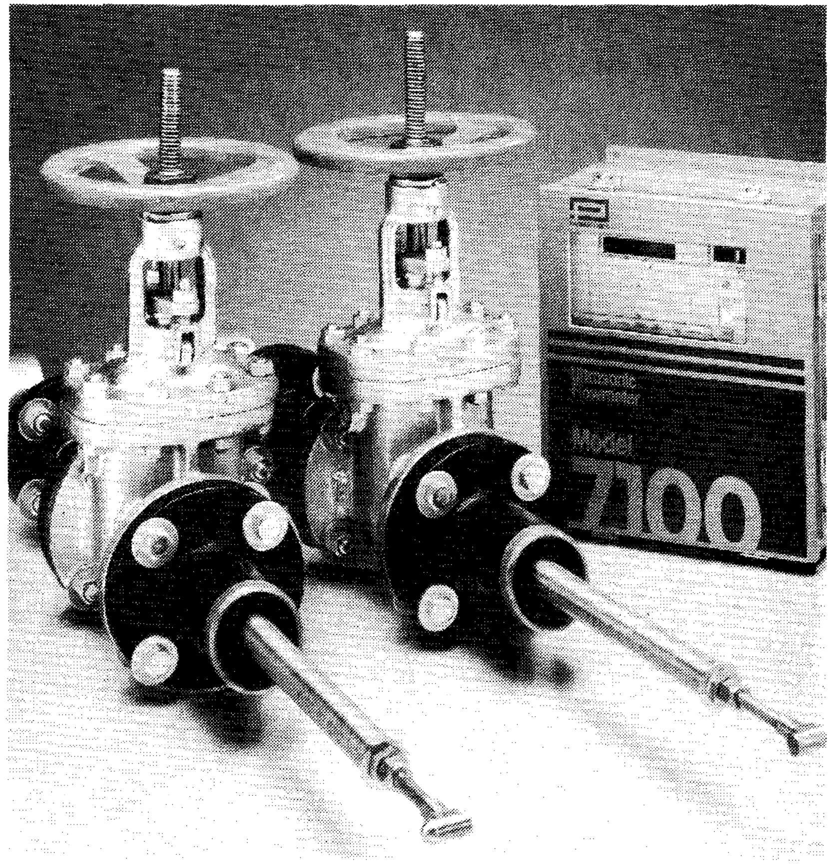
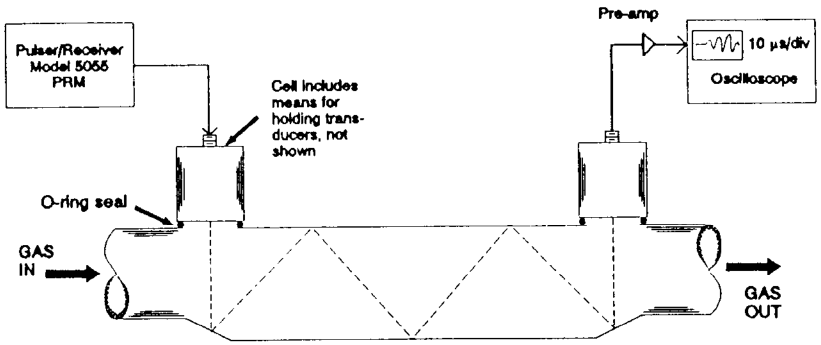


Figure 6b - Close-up of "bias 90" transducers and a flare gas flowmeter, Model 7100, that was introduced in 1984 to measure flow velocity V, sound speed c, compute gas average molecular weight M_w, and also the mass flowrate M_f if temperature T and pressure P are supplied to it as 4-20 mA signals.

(a)



Schematic of in-line plastic flowcell, zigzag interrogation.

(b)

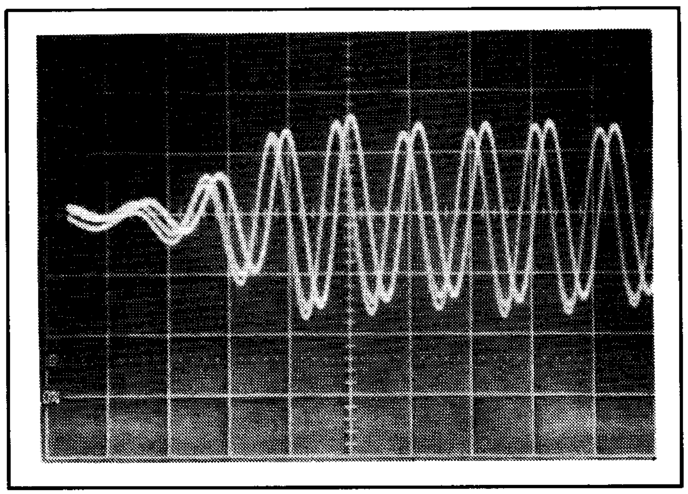
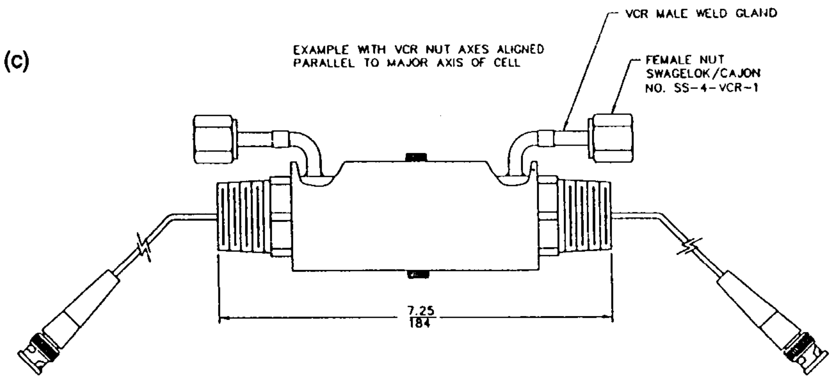


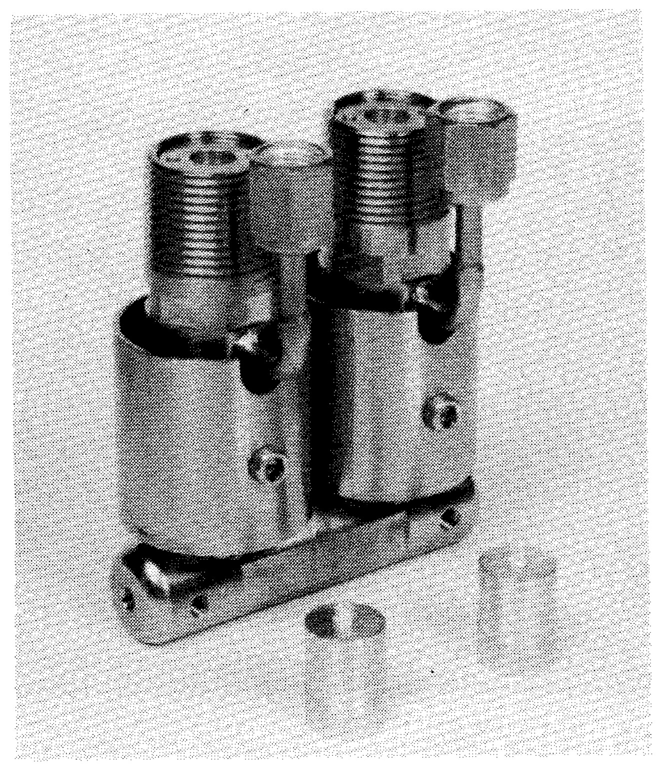
Figure 7 - Examples of small gas flowcells having a hydraulic diameter $D \sim 1$ cm to ~ 1 inch. (a) One of two plastic flowcell designs being evaluated in R&D studies of breathing dynamics and anesthetic gas concentration analysis. Reflector detail due in part to Yi Liu. (b) Oscillogram, double exposure, shows (right) waveform for still air, and (left) slightly-jittery waveform when air is exhaled in the direction of interrogation. The left-shifted waveform arrives earlier because of the combined effects of warmer air *and* flow. *Contrapropagation* is normally used to sort out these two effects. (c,d) Clamp-on for gases? No, not in general, but in some special cases (e.g. MOCVD applications) it is possible to build a small flowcell in which **all** the wetted parts are SS316/316L. The 100-kHz transducers are external, coupled or bonded outside the pressure boundary. Sound speed c yields average molecular weight of a binary (or pseudobinary) gas mixture, and hence the instrument (BG68) can determine the concentration (wt 5) of gas A in a mixture of A+B. Ref.: J. L. Valdes and G. Cadet, *Anal. Chem.* **63** (2) 366-369 (1991); ref. [1], pp. 576-579.

Below - Straight and U-Tube SS316/316L flowcells for concentration analyses of binary gas mixtures, based on sound speed c being a function of the average molecular weight M_w of the two gases A and B.

(c)



(d)



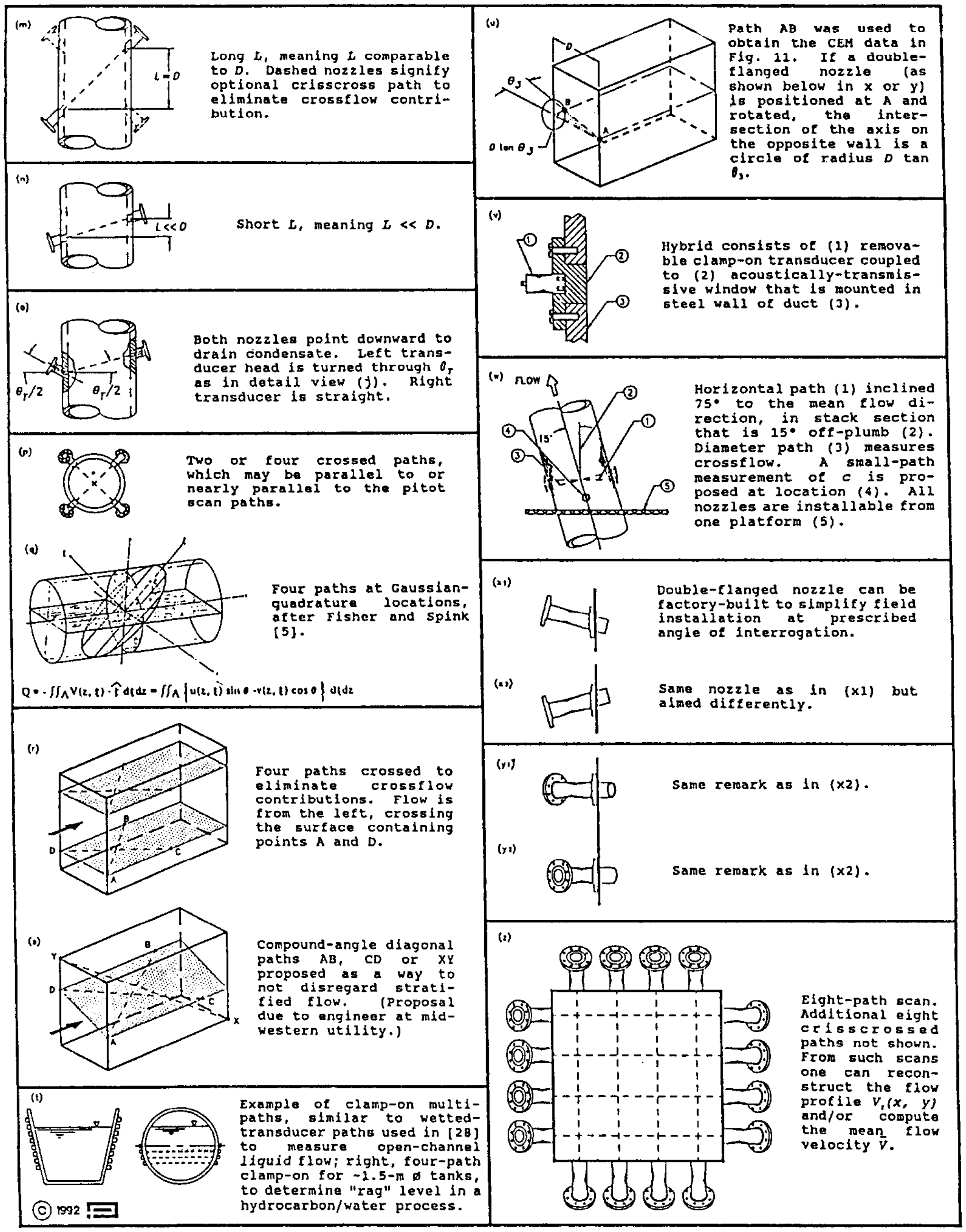


Figure 8 - Examples of long paths interrogated at f = 50 kHz, wall-to-wall, across-the-stack, in large stacks of hydraulic diameter D ~ 3 m (10 ft) to ~ 10 m (33 ft). Illustration from a paper by Lynnworth, et al., Point, Line and Area-Averaging Ultrasonic Flow Measurements in Ducts and Stacks, *Proc. 1992 Heat Rate Improvement Conference*, EPRI (1992). Flow velocity V≤ 30 m/s (~110 ft/s), typically, in 100+ megawatt coal-fired electric utilities.

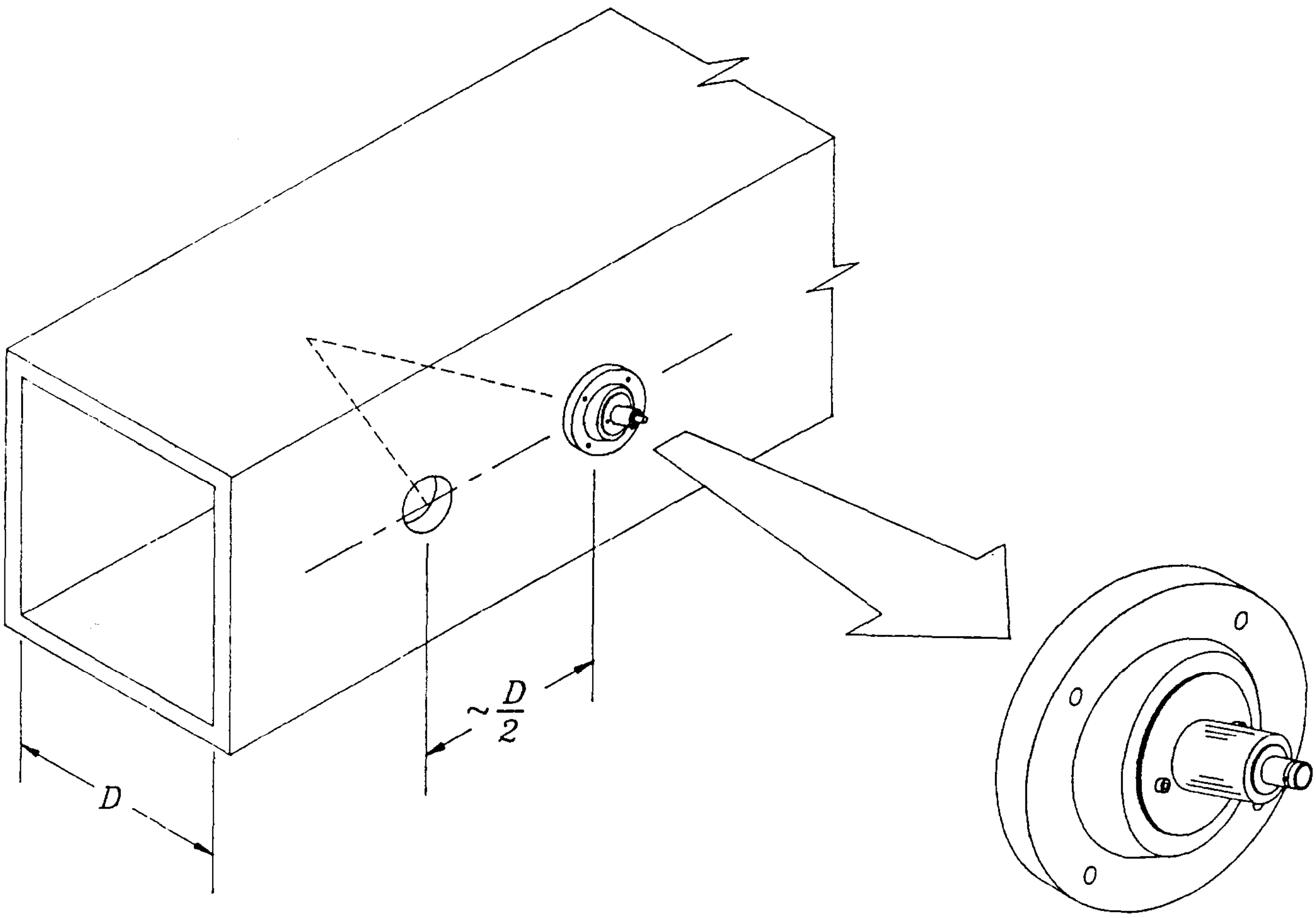
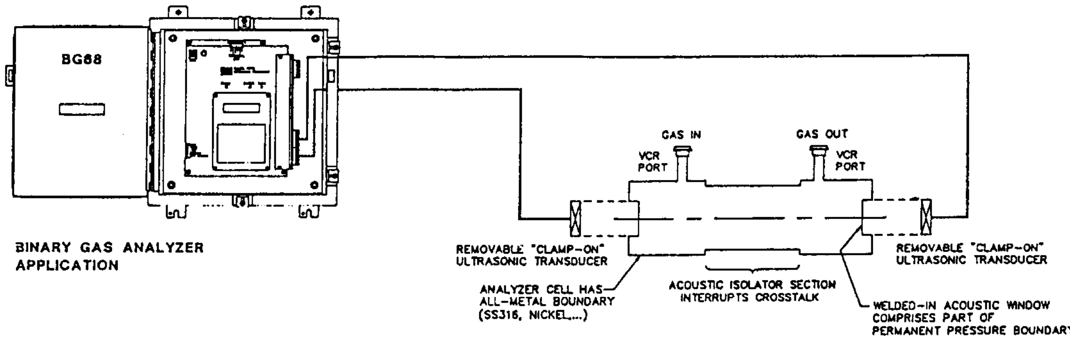
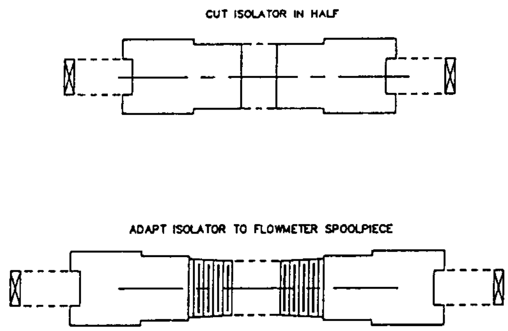


Figure 9 - Example of a small aluminum-housed flanged transducer similar to that used in Fig. 7a, b, c, mounted in a plastic (PVC) adapter. Such equipment is available to students and researchers for "plywood wind tunnel" flow tests. Each plastic adapter requires a 2-inch diameter hole through 3/4-inch plywood. Four drywall screws hold each adapter in place. The sound beam (50- or 100-kHz) enters the flowstream 15° to the normal, in the design illustrated. Flow is measured by using electronic intervalometers such as the general purpose equipment of Fig. 7a, or flowmeters such as a single-or four-channel GP68 or a four-channel CEM68, or equivalent. These transducers and adapters were developed for use in experiments on disturbed flow profiles and for other experiments on a particulate-laden air stream simulating air conveying 0.5 kg of air at high velocity ($V \leq 30$ m/s) in a small duct, $D \leq 0.5$ m ($\leq$ 20 inches).

Sound speed c in a binary gas mixture at temperature T yields gas concentrations X_1 and X_2. All-metal boundary means clamp-on transducers never touch the gas. Until a practical acoustic isolator was developed (patents pending), the clamp-on form of an ultrasonic binary gas analyzer could not be realized.



Below, right: Isolators screw (or weld) into a flowmeter spoolpiece, maintaining a sealed boundary. In the welded version, the boundary is all-metal. The transducers are clamp-on, same as for the analyzer cell. The transducers never touch the process gas. Now the upstream-downstream time difference yields flow velocity V, and sound speed c again yields average molecular weight and concentrations. Knowing gas temperature T, pressure P and spoolpiece duct area A, the instrument computes gas density ρ and mass flowrate M.



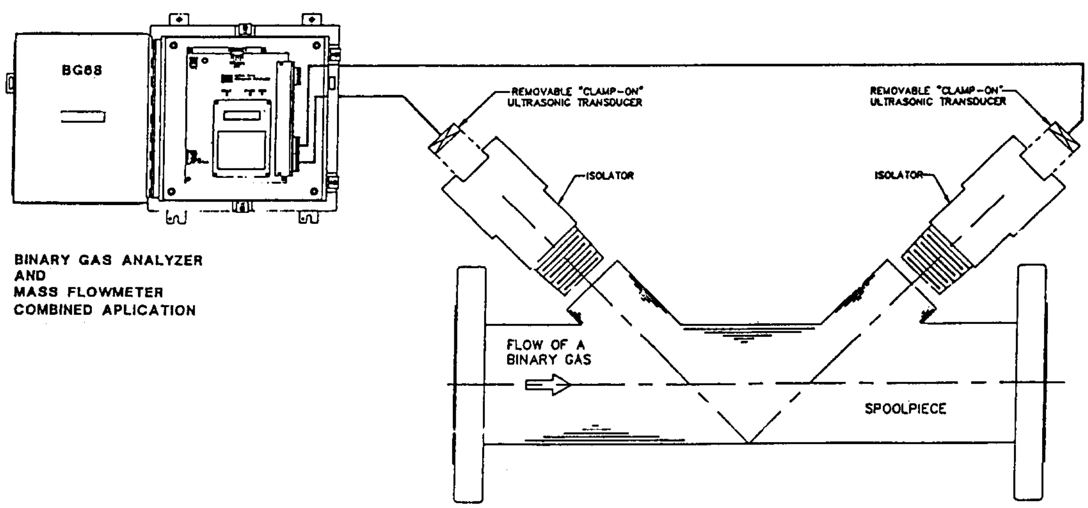


Figure 10 - Example of how the principles and components of some of the foregoing illustrations have been combined in a mass flowmeter. A commercial version of this concept was tested in 1992 on HCl/Cl_2 binary gas mixtures in a feasibility study. The wetted metal in this case was commercially pure nickel.