

**Ultrasonic Flow Measurement at High, Cryo or Ordinary Temperatures
Using Wetted and Clamp-On Transducers**

by

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Abstract

This paper explains the problems in measuring flow by the ultrasonic transmission method at *high* temperature, and offers solutions based on waveguide buffers. Buffer waveguides only a foot or so in length (~300 mm) convectively cool down enough at their “cold” end so that the ultrasonic piezoceramic transducer is not troubled by the temperature of a hot (300°C) fluid or hot pipe at the other end. The secret is to isolate thermally and economically, without corrupting the signal. Solutions are presented for compressional waves and for shear waves. These waves are used in wetted and clamp-on transducers, respectively. At ordinary temperatures such as normally encountered in water metering, flare gas and natural gas industrial applications the buffers are not necessary, at least not for thermal isolation. Ordinary clamp-on or wetted transducers generally suffice. They are installed on the pipe, or through factory-built spoolpiece ports or nozzles, or through cold- or hot-tapped ports utilizing, in the tapped cases, fixed or removable isolation valves. The number of *ports*, N_{PORTS} , can be zero to N , zero for clamp-on, $N \geq 2$ for multipath. The number of *paths*, N_{PATHS} , is $\geq N_{PORTS}$. The number of *chords*, N_C , is $\geq N_{PATHS}$. For example, for crossed clamp-on diameter vee paths, $N_C = 4$, $N_{PATHS} = 2$, and $N_{PORTS} = 0$.

Introduction

The basic problem in measuring by ultrasonics the flow of gases or liquids at *high* temperatures above 260 °C, is survival of the transducers or sensors that generate and detect the ultrasonic wave [6-9]. A secondary problem is coupling those waves into and out of the fluid (when *wetted* transducers are used), or coupling ultrasound into and out of the pipe (when using *clamp-on* transducers). Whether the transducers are wetted or clamp-on, it is also important to not disturb things too much, meaning, do not disturb the flow patterns nor the temperature too much. For example, local cooling at the transducer sites could cause solids to precipitate there, clogging the port or blocking the sound beam. This would be an undesirable side effect of the attempt to measure flow.

This paper’s remarks apply mainly to the *contrapropagation* method of ultrasonic flow measurement (Fig. 1). In the contrapropagation method, transit times are measured in the direction of flow, and later (or sometimes simultaneously), against the direction of flow. From the two measured transit times one can calculate the flow velocity V [1, 6-8]. At the low Mach numbers encountered in liquid flow, the time difference Δt is directly proportional to V . In steam and gas flows the Mach Number often exceeds 0.1. Here Δt is not exactly proportional to V but nevertheless, V is still calculable from the two transit times. The V is a line average along the ultrasonic path. In order to accurately take into account the flow profile, considerable care is exercised in the choice and weighting of the paths. The most general solutions available today utilize multipath sampling of the cross section. In custody transfer spoolpieces for large pipes subject to nonideal inlet conditions, it is not unusual to find four or five paths utilized. First we’ll consider temperature extremes (very hot, very cold). Then we’ll see about simplifying for *ordinary* temperatures.

What's the source of the high temperature problem?

Most types of ultrasonic flowmeters use piezoelectric transducers to generate and detect the waves. Just as special magnetic materials have been developed to retain their magnetic properties at high temperatures, so too have high Curie point ferroelectric or piezoelectric materials been developed that retain dielectric and other properties. Lithium niobate, for example, remains piezoelectric to about 1210 °C. But when the designer attempts to build a practical high-temperature

transducer using this material, several technical problems emerge: (a) unless excess oxygen is present, lithium niobate loses its own oxygen and no longer functions as an efficient electroacoustic transducer; (b) differential thermal expansion makes it hard to encapsulate the piezoceramic within a metal enclosure such as 316SS or Ti, such metals being typical for industrial flow applications. Electroding and damping are additional problems. Without damping, transducers tend to ring and their pulses get smeared out in time. This makes it difficult to accurately distinguish and time the upstream and downstream pulse arrivals.

While other ferroelectric or piezoelectric ceramics exist or are under development that retain their oxygen to the range 300 to 500 °C, or even higher, some or all of the other problems remain.

Is there no way to avoid these problems?

Buffer Waveguides: Wetted Type for Compressional, and Clamp-On Type for Shear Waves

In seismology, workers concerned with earthquake waves refer to P and S waves (primary and secondary waves). The terminology dates back to the 1800s, perhaps earlier, and is understandable if one notes that after an earthquake, at a recording site far away, two waves are received, separated in time. First comes the compressional wave, then the shear wave. If the earth were made of steel, and if the effects of temperature and pressure are neglected, the P waves would travel at a speed around 6 km/s and the slower S waves at 3 km/s. From the difference in arrival times, the distance to the source is calculable. In a hypothetical "steel earth" example, if Δt were 100 s the range would be 300 km. Data at two or more stations allows one to triangulate and locate the source. In a few moments we will see why the ultrasonic equivalents of P and S waves are important in measuring fluid flow at high temperature. (Briefly, the P waves correspond to the waves used in wetted buffers; the S waves, to the waves used in clamp-on buffers.)

Over fifty years ago, a relatively simple solution to avoiding high temperature at the transducer was already known to ultrasonic researchers. This solution was the buffer rod. The rod was usually solid metal, sometimes steel, sometimes SS, occasionally tungsten. The diameter was typically 12 to 25 mm. The outside was threaded or grooved to break up unwanted mode conversions. This solution worked well at high ultrasonic frequencies, say 2 to 10 MHz, where the rod radius was $>3\lambda$, λ being the ultrasonic wavelength in the rod. (Another solution, for the MHz range, is *clad* buffers [3].) At lower frequencies, however, unless the rod radius is increased, dispersion results. This means, just like white light is broken up by a glass prism in which different wavelengths travel at different speeds, low frequency *pulses* would be smeared according to the frequencies present.

If the industrial flow problem concerns gases or other media at high temperature, where the only frequencies that have a chance of successfully penetrating the fluid are low, meaning 0.1 to 1 MHz, and if the application does not allow a big port, then we must find a *small-diameter low-frequency buffer solution*. By "small diameter" we mean the buffer OD (outside diameter) should be in the range 12.7 to 33.4 mm and preferably not exceed 25.4 mm OD. [4, 7]

In 1995, confronted with the problem of buffering ultrasonic transducers subject to the constraints of (a) small diameter nozzle; (b) high-temperatures, up to 450 °C; (c) operating frequency ≤ 500 kHz, my colleague Yi Liu and I found ways of taking hundreds of wires and enclosing them inside a corrosion-resistant sleeve to create a rigid dispersionfree bundle. The rigid bundle is sometimes referred to as the BWT™ bundle waveguide technology system.

The resulting bundle forms a pressure boundary suitable for ultrasonic flow measurements of hot corrosive gases. It also works for hot liquids like molten asphalt, viscous liquids at *room* temperature requiring low frequencies below 1 MHz, and cryogenic fluids that have a tendency to flash. The low frequency penetrates the fluids despite their two-phase character. The KEMA-approved transducer is removable from the buffer, without breaking the pressure seal (Fig. 2). The portion of the BWT assembly within the insulated nozzle operates uncooled, at the fluid process temperature. The external portion can be as long as necessary to convection-cool down to a temperature such as 100 °C, well within the range of ordinary piezoelectric materials and constructions.

The first industrial application of the BWT transducers was in the Shell Per Plus refinery near Rotterdam. Buffers housed in SS, Ti or special alloys were used initially in about fifteen locations. Some locations had startup complications where first nitrogen, then hydrogen-rich (low-density) gas had to be measured from as low a pressure as possible (~10 bar) up to operating pressure = 209 bar, at temperatures over 200°C and be able to withstand 450°C during upset conditions. As the BWT bundle buffer worked well, its use was expanded to many other locations in the plant, and then to the next plant in the area that Shell constructed (Moerdijk). The BWT buffered transducers were subsequently used in steam tests conducted by Dow in Terneuzen, at $T = 340^{\circ}\text{C}$, 34 bar, ± 45 m/s steam flow. By mid-1999 there were over 100 BWT systems installed in gas and liquid flow measuring applications around the world.

Examples of BWT system applications are given in Table 1.

Table 1. Applications of BWT™ bundled waveguide <i>wetted</i> transducers in hot gases, hot liquids and other fluids.	
Fluid	Comments
Hot hydrocarbon gas	<ul style="list-style-type: none"> Hydrocarbon gas, 1 to 210 bar, normally 220°C, design 450°C, in thick-wall CS/SS pipes, $\varnothing 8'' - 16''$. Gas above atmospheric pressure, at $T = 165$ to 200°C.
Steam	<ul style="list-style-type: none"> Dow Terneuzen, $\varnothing 4''$, 340°C, 34 bar, $V = \pm 45$ m/s bidirectional pulsed steam flow in sootblower. FTPA (Feedthrough PanAdapta®) one-piece buffer, flanged near its midpoint, and of sleeve OD = $\frac{1}{2}''$ (12.7 mm) or 1'' (25.4 mm).
Hot liquid	<ul style="list-style-type: none"> Short or long residue e.g. heavy hydrocarbon mixture, temperature to 270°C and pipe up to $\varnothing 12''$. Very viscous at 20°C, moderately or not viscous at high temperature. Water, 220°C, contaminated with entrained gas.
Other	<ul style="list-style-type: none"> Liquid of high viscosity at <i>ordinary</i> temperature. Cryogenic liquid which flashes occasionally.

What About Clamp-On for High or Cryo Temperatures?

Around 1996, EDF (Électricité de France) initiated a project at Panametrics, to develop high-temperature clamp-on transducers that could be used to measure the flow of superheated water in steel pipe. Temperature was 260°C and pressure, 60 bar. Clamp-on transducers for contrapropagation flowmeters generally introduce the ultrasonic waves *obliquely*. In theory, one way to do this could be to use the BWT bundle at an angle. However, as the compressional wave velocity was 5 km/s in the steel BWT buffer, the refracted angle in the hot water would be too small for most applications. The small refracted angle is a consequence of Snell's Law, applied to hot water where the sound speed is only about 1 km/s. Instead, suppose we select a *shear* wave as the incident wave, in order to have a *slower* incident velocity (3 km/s, like in seismology example above) and a proportionately larger refracted angle in the hot water. The shear wave theoretically offers the possibility of a refracted angle larger by a factor of about 5/3, compared to what is achievable using incident compressional waves at the same oblique angle, say 60°. Only one set of problems now remained: how to produce shear waves, obliquely incident, having a shape easily timed to ns or sub-ns precision, and at frequencies from 0.5 to 4 MHz? The answer turned out to be *another waveguide*. This time, instead of using many thin wires, we used one thin plate. The plate has certain topological features for generating reference echoes or for measuring temperatures at corresponding points, but overall it resembles a small hockey stick. "Hockey stick" has become its name. Its acronym is OKS. The OKS waveguide in Fig. 3, Fig. 4(c) and Fig. 5 has a length in the direction normal to the pipe of about 250 mm and a thickness of 6.4 mm. Of this length, the 75-mm nearest the pipe is insulated. The rest, like the BWT system outside the nozzle, is cooled by convection so that the temperature to which the piezoceramic is exposed is <100°C. [See Fig. 3(g).]

Examples of appropriate applications for the OKS are given in Table 2, organized as a function of pipe diameter. The liquids were superheated water (260 to 271°C, 60 bar) if not otherwise identified.

Applications of OKS on pipes *smaller* than 3 inches (75 mm) are possible, depending on ultrasonic frequency, pipe material, wall thickness, fluid conditions and accuracy requirements. No field tests, however, had been conducted on pipes of diameter < 3 inches (< 75 mm) at the time this article was prepared.

Table 2. Examples of OKS <i>clamp-on</i> applications at various pipe sizes.*		
Nominal Pipe Size		Liquid; comments
Inches	mm	
3	75	(a) Belgium (Thiange 3), running over two years, three points (XMT868). The water temperature $T = 285$ deg C. OKSs were calibrated at Eau de Paris at room temperature in order to be qualified prior to installation in the plant. (b) US nuclear utility, two blowdown pipes, CS, sch 40, 25 to 400 gpm, running since plant restarted in May 1999. OKS selected because of turndown ratio and ease of retrofit. OKSs were calibrated at Alden Research Laboratory at room temperature in order to be qualified prior to installation in the plant. See Fig. 6.
4	100	EDF installed two pair of OKS, where water temperature was 300°C.
6	150	(a) Emergency back-up just in case previously-installed intrusive devices were to fail (plant in Pacific Northwest). (b) <i>Cryogenic</i> application at KOGAS plant in Korea: liquefied propane gas, -150°C. (c) EDF: water temperature was 300°C.
8	200	Flexicoker plant in TX: SS321 pipe; OKS replaced venturi, which tended to clog.
10	250	(a) Forsmark Unit 1 in Sweden: Heavy wall, SS, 2 MHz, paths available at $\pm 45^\circ$, better than 1% agreement with venturi, and with ultrasonics yielding much wider turndown ratio. Installed September 1998. (b) Atochem @ Serquigney (Normandy): oil, 330 deg C, working >6 months (c) Hybrid GC spoolpiece (Fig. 5) yielded $\pm 0.33\%$ error band for $Re = 0.47 \times 10^6$ to 1.3×10^6 (R&D multipath project). (d) Secondary-flow swirlsensors; multipath no-hole spoolpiece: water tests @ room temperature; liquid level R&D laboratory project in support of industrial clamp-on liquid level application in 12" and 28" pipes, in harsh environment, brought to our attention by PN Services.
14-18	350-450	EDF conducted trials lasting eight months or longer, on various large steel pipes, in nuclear and/or fossil-fueled plants. Figure 3(f) shows one of the earliest test installations. Modern clamps apply the coupling pressure in a simpler way, using one of: pipe riser clamps, two-piece split collars, welded-on yokes [(Fig. 3(c) or Fig. 4(c)]. The pipe riser clamp accommodates one or two yokes. [Two-yoke version: Fig. 3(e).]
>100	>2500	Canadian nuclear plant's downcomer, which has a large, thick-walled ~cylindrical shape, has an annular passageway ~3 inches (75 mm) between inner and outer wall. Outer wall is CS, ~2 inches (50 mm) thick. AECL installed OKS transducers in late-summer 1998 and measured not only the water flow but also determined that a second phase (entrained steam) was <i>not</i> present.

*One customer's field service personnel have used OKS on ~50 different applications. In these cases, none of which are included in above list, the test generally is quick, $\leq 1/2$ -hour. Pipe sizes ranged from $\varnothing 4''$ to 16". Hydrocarbon liquids ranged in temperature up to about 360°C. Permanently-installed example from St. Croix, Virgin Islands, running since January 1997: heavy vacuum gas oil, 275°C, SG = .77, $\nu = 0.5$ cS, carbon steel pipe, 10" sch 40, $c_3 \approx 700$ m/s, measured (with DF868) volumetric flow rate $Q = 1260$ gpm, using $f = 1$ MHz, and 2 traverses (vee path).

Table 3. Summary of BWT and OKS buffered waveguide transducers and guidelines on where to use them; some limits.* In field-proven applications, pipe diameters have ranged from one inch to nearly one meter.		
Internal characteristics or application	BWT bundle waveguide technology	OKS (Hockey Stick)

Icon		
Ultrasonic wave type and speed	Compressional, $c \approx 5000$ m/s	Shear, $c \approx 3000$ m/s
Clamp-on or wetted?	Wetted	Clamp-on
Maximum temperature	500°C	500°C (360°C for 250-mm OKS size)
Minimum temperature	-200°C	-200°C
Maximum fluid pressure	210 bar (3045 psig)**	> 100 bar (> 1450 psig)***
Material at the hot end	316 SS, Ti, other corrosion-resistant alloys	Usually 1018CS; sometimes 304SS or 316SS
Fluid media	Gas, steam, liquid, two-phase but still sonically conductive	Liquid; liquid plus small percentage of gas phase
Frequencies available in 1999	0.1, 0.2, 0.5 and 1 MHz	0.5, 1, 2 and 4 MHz
What to avoid? (Limits known or of concern as of 31 August 1999. Check again after Y2K.)	Multi-phase highly-scattering media (unless Transflexion® stroboscopic scattering mode were to apply); pipe ID < 10 mm <i>might</i> be a problem unless <i>axial</i> path flowcell is practical.	Gases; same as limits listed for BWT bundle. Field performance not yet established on pipes smaller than $\phi 3''$ (75-mm ID).
Patent Status on 31 August 1999	U.S. patent no. 5,962,790 (Oct. 5, 1999). Other patents pending in US and abroad.	Pending in US and abroad.

*This table does not list accuracy, mainly due to the difficulty of conducting calibrations at high temperatures such as 260°C. BWT and OKS transducer systems have been qualified for particular high-temperature applications based on accuracy demonstrated at ordinary temperature. This is typically followed by evaluation in the field at high temperature, sometimes for periods of one or more years. Wetted and clamp-on buffered accuracy are comparable to that obtained with their non-buffered transducer counterparts, usually to within a factor of two or better.

**Maximum allowable pressure in some cases depends on the flange material and the temperature. In some BWT designs the maximum allowable pressure may be as high as 5000 psig near room temperature.

***Higher pressures mean thicker pipe wall. This could impose a crosstalk-induced limit, if the fluid were so attenuating that crosstalk noise N , around the pipe, exceeded the strength, S , of the fluid-borne signal.

Clamp-On Coupling for Temperature Extremes

Over twenty years ago, Henry Karplus at the Argonne National Laboratories demonstrated *soft metal foil* as an effective long-term (> 5 yr) couplant in ultrasonic flowmeters, in his work to 600°C on liquid sodium. The best choice for the material of the foil in a given situation depends on technical and cost factors. Technical concerns include intergranular corrosion, if the foil's melting point is too close to the operating temperature. In tests of *short* duration, $\lesssim 1$ hr, typically associated with feasibility tests or flow surveys, satisfactory economical couplants might be aluminum foil, or anti-seize grease. For *permanent* coupling (usually desirable, because of the inconvenience of recoupling at high temperature and perhaps in a radioactive area), foil metals other than aluminum are generally preferred. A *low*-melting-point foil was found to be easy to install and use at cryogenic temperatures, using the OKS to solve a clamp-on flow problem that previously had been quite troublesome. Until the foil and OKS were introduced, this job at a Korean liquefied gas facility (-150°C) required recoupling at frequent intervals, especially following thermal cycling.

The metal foil is normally supplied as a strip 6.5 mm wide by 100 mm long. It is bent to conform to the OKS foot shape and taped just prior to use, around the foot of the OKS, using two small strips of electrical tape. The tape strips are removed or burn away after installation, but they've done their job. The foil is already clamped in place, using a 1000+ kg force that is readily obtained by torquing the pressure screw that is part of the clamp. [Figure 3(c).]

Again, for quick trials, anti-seize couplant suffices, and here, as coupling pressure can be modest, a "room temperature" clamp suffices [Fig. 3(a)] aided by an aluminum block that centralizes the OKS. To minimize crosstalk we have found it best to place OKS transducers on opposite sides of the pipe. Sometimes this is an inconvenience, and sometimes there can be undue responsiveness to crossflow. If the latter is a problem, then two sets of transducers are used, making an X configuration. The average velocity is the sought V . The difference yields the crossflow velocity V_x .

Sometimes the OKS pair are installed at room temperature and the soft metal foil couplant isn't soft enough to couple at reasonable coupling pressure. A solution in this case, first demonstrated by one of our colleagues (Peter Kucmas) and one of the authors (Per Fredriksson) in a 1998 startup at Forsmark Unit 1 in Sweden on 10-inch SS heavy wall pipe, was to wet the metal foil with a drop of glycerine couplant. This traditional ultrasonic couplant couples fine at room temperature and evaporates later, at high temperature, leaving no residue. The same glycerine solution was used during a scheduled shutdown in a 1999 "cold" startup on $\varnothing 3$ " schedule 40 carbon steel blowdown pipes at a US nuclear plant. Temperature later reached 271°C. Coupling then depended on the soft metal foil, which by this time was dry. Periodic checking of the received waveform showed that coupling has remained constant for months.

As another approach to finding a permanent couplant, consider welding. The OKS, typically made of CS1018 but in principle manufacturable of any standard engineering material such as 316SS, can be held in place against the pipe with one of the standard clamps illustrated. Clamped this way, it can be tack welded. The clamp is then removed. Full-penetration fillet welds along both sides of the OKS foot then provide complete coupling that is unlikely to decouple over the life of the pipe [Fig. 4(c)]. Weld-on OKS transducers and welded-on yokes (instead of removable clamps) might make the OKS system easier to use in some applications. But welding to an operational pipe is not allowed in many cases. If contemplated, code and safety issues must be addressed for the particular case at hand.

What About Hybrids (Calibratable Spoolpiece with Removable OKS Transducers)?

Hybrids combine features of wetted and clamp-on transducers. Hybrid spoolpieces like the one in Fig. 4(c) *could* utilize welded-on OKS transducers or welded-on yokes.

Recall that the BWT wetted buffers, originating as a solution for high-temperature flow problems, ended up solving some problems at room and cryogenic temperature too. Regarding the OKS clamp-on buffers, we have already mentioned the *cryogenic* application in Korea. Are there any other clamp-on spinoffs for the OKS?

First, consider that the KEMA-approved transducer portion of the BWT system is removable while the buffer itself remains permanently in the pipe nozzle, as the permanent pressure boundary. This is not unlike the PanAdapta® precision plug concept shown on p. 168 in [7]. Some 1800 were in use by mid-1999, mostly for *ordinary* temperature. Referring again to the BWT buffer system, Figure 2(b), the KEMA-portion is sort of a clamp-on. (In fact it is normally epoxied in place at the end of the BWT buffer, but can be removed using two wrenches, and later reinstalled or replaced.)

Second, consider the introductory remarks about multipath for a more general solution under bad flow conditions.


Let us now observe that each pair of thin OKS transducers can be arranged to interrogate a narrow, well-defined region. Four OKS pairs can thereby provide a GC (Gauss-Chebyshev) quadrature solution to integrating flow over the cross-section of a calibratable spoolpiece. This concept, illustrated in Fig. 5 (a, b), was tested in water at room temperature by our colleague Brita Dean last year, and yielded an error band of $\pm 0.33\%$ for the $\sim 3:1$ Reynolds Number (Re) range 0.47×10^6 to 1.3×10^6 in its first calibration test [2]. This accuracy by itself perhaps is not remarkable. However, it was done with *no holes for the multipath transducers*. All transducers were removable clamp-on OKS types. As the internal notches for this design are triangular and only penetrate radially about 5 mm or less, depending on location, it seems reasonable to surmise that they disturb the flow less than the traditional ports of $\varnothing 30$ mm or so, that are associated with transducers of $\varnothing 25.4$ mm, for example. Although this hybrid spoolpiece was tested only at room temperature, its design is not limited to room temperature. Incidentally, in those tests, Brita Dean also used another form of the OKS [Fig. 3(b), middle], clamped in a plane perpendicular to the spoolpiece axis, and measured swirl. In that configuration the OKS transducers are referred to as swirlsensors. Recognizing that the swirlsensors interrogate in a thin sheet

perpendicular to the pipe axis, much as the OKS hybrids interrogate in the thin GC planes, there is a possibility for sensing *liquid level* in the swirlsensor plane. This too has been demonstrated. Laboratory swirl and liquid level test results obtained in 1997 by our former colleague Lena Steingard are shown on p. 380 in [8]. Of these three spinoffs (hybrid GC spoolpiece, swirlsensor, liquid level), R&D activity is presently aimed at the first. Although the OKS transducers are released and available commercially, and work with commercially available flowmeter consoles such as Panametrics PT868, DF868, and XMT868, the unreleased R&D items are not yet available except on special order from Panametrics' PCI R&D Division. (These '868 flowmeter instruments are the work of our colleague Saul A. Jacobson and his engineering staff.)

To obtain the best results with clamp-on, it is recommended but not absolutely required, that the pipe be flat and smooth under the OKS' feet. Both OKS transducers should be parallel (Fig. 6). As the OKS transducers are normally manufactured with flat feet, the pipe, ideally, would have two parallel flats at 180°, say at 3 and 9 o'clock. Flats, however, are not absolutely necessary, as the metal foil can be supplied thick enough to make up the theoretical gap. Those who have used ultrasonic clamp-on flowmeters at room temperature know that the gel or grease couplant supplied by the manufacturer similarly fills up the air gap between transducer and pipe. What's different about the metal foil, is that it doesn't dry out, doesn't get washed away, and doesn't run away when it gets hot. Early tests at EDF, for example, during an eight-month high-temperature trial on one pipe, showed no change in coupling. Similar results have been reported for the cryogenic Korean application, which has been running with no maintenance for six months since it was started up early in 1999.

Simplifications, Options, Examples at *Ordinary* Temperatures

At ordinary temperatures such as normally encountered in water metering, flare gas and natural gas industrial applications the buffers are not necessary, at least not for thermal isolation. Ordinary clamp-on or wetted transducers generally suffice. They are installed on the pipe, or through factory-built spoolpiece ports or nozzles, or through cold- or hot-tapped ports utilizing, in the tapped cases, fixed or removable isolation valves. The number of *ports*, N_{PORTS} , can be zero to N , zero for clamp-on, $N \geq 2$ for multipath. The number of *paths*, N_{PATHS} , is $\geq N$. The number of *chords*, N_C , is $\geq N_{PATHS}$. For example, for crossed clamp-on diameter vee paths, $N_C = 4$, $N_{PATHS} = 2$, and $N_{PORTS} = 0$.

Clamp-on. From the perspective of the flowmeter designer, water in plastic, glass, or metal pipe is a simple, routine application, provided (a) the pipe isn't too small, (b) flow rate is not too low nor too unsteady, and (c) accuracy and response time requirements are not unreasonable. Subject to these and perhaps a few other caveats, *simple clamp-on solutions exist*, e.g., Fig. 7. If this standard solution is applied in two orthogonal planes, we have the case corresponding to $N_C = 4$, $N_{PATHS} = 2$, and $N_{PORTS} = 0$. In the end view the paths preferably lie at $\pm 45^\circ$ to a vertical axis: . They look like the letter X inside a circle.

If in fact the X paths lie in plane \perp axis of the pipe, the contrapropagation method yields not axial flow V_z but the crossflow components V_{X1} and V_{X2} . Their vector resultant is the crossflow, V_X . Our colleague Brita J. Dean last year found in one such test, V_X was proportional to V_z , in the Re range 0.47×10^6 to 1.3×10^6 [2].

What about clamp-on for *air*? The main problems are impedance mismatch, small refracted angle, and acoustic crosstalk around the pipe. However, if the pipe is sufficiently attenuating, e.g., PVC, solutions resembling Fig. 7 exist. Crosstalk is reduced by using an *odd* number of traverses. A larger number of traverses also helps by increasing the axial interaction length L , and allowing more time for pipe ringing to subside. An example of clamp-on test results with ordinary air flowing in PVC pipe is given in Fig. 8.

Hybrid. As a transition to *wetted* transducers for ordinary temperature, consider the PanAdapta® permanently-installed precision plug and removable transducer (Fig. 9). Some 1800 of these were in use earlier this year. The fixed plug can be made of a special alloy if required for corrosion resistance. The external transducer, removable-with-two-wrenches, can be housed in 316 SS for most environments. It functions like the Kema-approved transducer shown earlier and associated with the BWT bundle [Fig. 2(b)].

Wetted. For water or other *liquids*, the transducer can be as simple as a hex head pipe plug that contains a piezoceramic element near its radiating end, and an electrical connector at the opposite end. For air and some other gases, the outline can often look as simple as Fig. 10, but inside, there may need to be adequate acoustic isolation to defeat or diminish crosstalk. One such isolation scheme, adequate for *low* and *steady* pressure, uses soft O-rings

(Fig. 11). The T7 transducer depicted in Fig. 11 was used in air circulation measurements conducted at WPI (Worcester Polytechnic Institute), reported in [4]. For higher or pulsatile pressure, axial restraint may use methods other than soft o-rings. Our colleague Toan H. Nguyen's solutions are embodied in steam [10] or gas transducers such as Panametrics types T9 or T11, respectively. These are usable in ordinary air too.

Inside the sealed metal case, the "air" transducer is typically impedance-matched. As an example of the waveforms obtainable when such transducers are installed in a multipath spoolpiece, Fig. 12 shows 200-kHz received signals for diameter and off-diameter paths in a $\varnothing 6$ " (150 mm ID) spoolpiece. In this air example the ports in the thick-walled spoolpiece were simply pipe-tapped 3/8" NPT and the transducers were threaded in, sealed with teflon tape. In other situations, face seal or flanged and gasketed ports or nozzles may be required by code or to meet safety regulations.

Spoolpiece Examples. Spoolpieces have some obvious advantages over clamp-on. They can be calibrated. The paths can be predetermined and they are not limited to small refracted angles, nor are the refracted angles a function of sound speed c_3 in the fluid. The most important advantage, namely, the possibility of being calibrated, in fact does not rule out clamp-on, if we allow the concept of "hybrid" to be considered. This observation applies for diameter paths and even for off-diameter paths [Fig. 5(a, b)].

Although a number of manufacturers have obtained excellent results with diameter, midradius and GC (Gauss-Chebyshev) path combinations, questions remain for complex installation effects and short upstream runs. Two of the multipath spoolpiece designs that we investigated in recent years are shown in Fig. 13. These two designs contain either some provision to directly measure secondary flow components, or, by reflection, minimize the effect of crossflow. Data currently being acquired by our colleagues Jim Hill and Bill McGrath, in collaboration with Hans Kastner, Andreas Weber and others at RMG, Butzbach, are expected to yield by early next year, optimized solutions to meet GERG 2, AGA or other harmonized standards or specifications.

Hot-Tapped Flare Gas Examples. Even before the first public announcement fifteen years ago by Exxon's Jack W. Smalling, of Exxon and Panametrics work on flare gas ultrasonic flow measurement at Exxon's refinery in Baytown Texas, the "bias 90" and other hot-tapped geometries had proven themselves to be effective solutions to installing sensors in crowded pipe racks. [6, pp. 294-302] The method of hot-tapping normal or oblique to the pipe surface, allowed optimization of the path for a given set of installation constraints. For the "bias 90" the chordal segment was shorter than wall-to-wall. The meter factor K was calculated by integrating across presumed Nikuradse (power law) profile. The "bias 90" arrangement is compared with a standard tilted diameter path and a rather axial-inclined gas path in 3" lined pipe, in Fig. 14. That figure also includes a small-pipe gas flow sensing geometry due in large part to our colleague Maurits A. Zimmerman of our NL office. For most of these gas flowmeters the final transducer design is the work of our colleague Toan H. Nguyen (Waltham).

Conclusions

- Clamp-on, wetted and hybrid solutions exist for many fluid flow situations: gas, liquid, standard atmosphere, hazardous environment, etc. At this time, clamp-on is generally limited to liquids, and to atmospheric-pressure air in *plastic* pipe.
- Temperature extremes (cryo or very hot) can be handled by buffering the piezoelectric transducers that generate or detect compressional or shear waves. This extends clamp-on and wetted transducer applications down to cryogenic levels, -150° or lower, and up to 300°C or higher.
- A spoolpiece offers advantages of calibration, path control, and precise placement of transducers. These transducers are usually wetted but they can be clamp-on, at least for liquids.
- Ordinary temperature allows considerable variety in the approach, providing the designer with opportunities to optimize the path, the type of penetration (if any penetration is required at all), ultrasonic frequency, wave type, etc.

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