FLOW TECHNIQUES, INDUSTRIAL

Ultrasound is widely used in industrial flow measurement. Compared to other flow measurement techniques, ultrasonic systems have unique advantages. Common ultrasonic techniques such as transit-time and Doppler introduce no resistance to flow beyond the resistance of the pipe containing the flow. Systems utilizing clamp-on transducers do not contact the flow, allowing flow measurement of a wide range of fluids. Furthermore, ultrasonic techniques do not require the fluids to have special electromagnetic or optical properties. Applications vary from the measurement of clean water to sewage, from corrosive chemicals to salad dressing. Flows can be measured in pipes from under 1 mm to more than 5 m in diameter, or in open channels from small irrigation and drainage channels to canals and rivers. Setups vary in complexity from small hand-held devices to permanent multisensor plant-monitoring installations. Proper equipment selection results in a meter with low cost of operation requiring little or no maintenance.

Early attempts to employ ultrasound for flow measurement were not always successful (1,2). Among the difficulties was a lack of understanding regarding the sensitivity of ultrasonic meters to various flow and media parameters, inadequate signal processing technology, and transducer materials problems. Modern meters are able to employ relatively powerful, inexpensive digital signal processors to support sophisticated signal detection and flow monitoring algorithms. Equally important is the research into acoustics and materials of the last several decades, allowing the fabrication of reliable transducers with predictable characteristics. These developments are jointly responsible for the steady increase in ultrasonic flow metering. Earlier comprehensive reviews of the field include works of Lynnworth (3,4). A description of different techniques and applications is given in the following sections.

CLASSES OF ULTRASONIC FLOW MEASUREMENT TECHNIQUES

Several methods employing ultrasound to measure flow exist. Among the more common methods are the transit-time, Doppler, speckle-tracking, and open-channel techniques. Transit-time devices employ the difference in rate of propagation when sound travels with and against flow. Transit-time meters are typically used in clean liquid and gas applications. Doppler devices employ the shift in frequency of an echo from a moving target. Doppler devices require some form of scattering material in the flow to generate echoes, making them particularly applicable in multiphase situations. Speckle-tracking devices also rely on moving scatterers in the fluid, but they use time-domain methods (e.g., cross-correlation) to measure flow rate. Open-channel devices place obstructions in the flow path with a known relationship between head (the difference in water level upstream and downstream of the obstruction) and flow rate. Open-channel meters are commonly used in irrigation and wastewater systems.

A few less common methods are also noteworthy. Correlation or flow-tag devices detect features in the acoustic signal sampled at two points a known distance apart, and they estimate velocity based on the time it takes for a feature to move from the upstream to the downstream station. Vortex shedding meters employ a bluff body in the flow, which induces vortices in the flow at a rate proportional to the flow rate. These vortices are then detected ultrasonically. A flowswitch can be designed which uses the noise generated by fluid moving through a pipe. A transducer monitors the sound level in the pipe, and the switch closes when the sound intensity exceeds a threshold.

Lastly, the acoustic properties of the flow can be monitored to determine the composition of the flow. Changes in speed of sound are an especially sensitive indicator for many applications. A change in speed of sound in the flow can indicate the passage of an interface between two different fluids (5). Contamination of the flow due to a leak can also be detected by speed of sound changes (4).

FLOW PROFILES

Understanding the properties of flow through a filled pipe is important to the design of an accurate flowmeter. Assumptions about the flow profile are made in most devices, and these assumptions limit the ultimate accuracy of the meter. A short description of some of the properties of closed pipe flow which influence ultrasonic flowmeters is given here. A thorough examination of closed pipe flow is given in Ref. 6.

Fluid moves though a filled pipe with a nonuniform flow profile. The shape of the profile can vary greatly, but two simplified cases are important and illustrative. Low-velocity flows through long, straight pipes develop laminar flow, with a characteristic parabolic flow profile. High-velocity flows become turbulent, and the flow profile tends to a flatter, more

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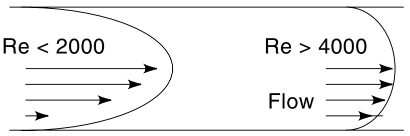

Figure 1. Flow profile tends to flatten from parabolic profile with increasing velocity. The Reynolds number predicts the shape of the flow profile.

uniform shape (see Fig. 1). Low- and high-velocity flows are distinguished by the Reynolds number of the flow, given by

$$\mathrm{Re} = \frac{VD}{\nu} \tag{1}$$

where V is the velocity, ν is the kinematic viscosity, and D is the pipe diameter. As a rule of thumb, low-velocity flows are those for which Re is less than 2000, while high-velocity flows have an Re greater than 4000. For $2000 < \mathrm{Re} < 4000$ the flow profile is unpredictable.

These idealized profiles assume long, straight, smooth runs of pipe. Pipe elbows, obstructions to flow, vibration, rough surfaces, and multiphase conditions can disturb the profiles. While some meters are more tolerant than others are, the disturbed profile tends to reduce the accuracy and repeatability of the meter. For this reason, flowmeter manufactures generally recommend certain lengths of straight pipe upstream and downstream from the meter. Typical values are 20 diameters upstream and 5 downstream of the meter. While these values are usually sufficient to achieve reasonable profiles, flow straighteners or conditioners may be needed in some cases. These consist of many vanes parallel to the desired direction of flow. The vanes have the effect of dampening any swirl or other nonuniformity in the flow.

MEASUREMENT TECHNIQUES

Transit-Time Methods

A transit-time meter uses the apparent difference in speed of sound when an acoustic pulse travels between fixed transducers through a moving medium. To measure the speed of sound, two transducers are situated such that the acoustic path joining them has a significant component parallel to the flow. Figures 2, 3, and 4 illustrate common arrangements. These illustrations are merely descriptive and do not depict all the possible variations and details. Some designs employ multiple reflections off the pipe walls, and nondiametrical paths can be employed. In operation, the transducers act alternately as transmitter and receiver. The upstream transducer will launch a pulse into the flow, which will be received by the downstream transducer after some delay t_d. This operation may repeat one or more times. The transducers then switch roles, with the downstream transducer sending and the upstream transducer receiving a pulse after a delay t_u.

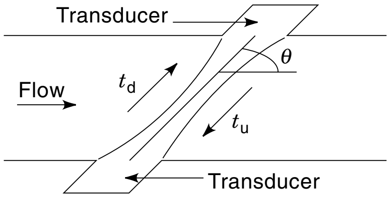

Figure 2. Schematic drawing of a transit-time flowmeter. Sound travels faster to the downstream transducer than away from it.

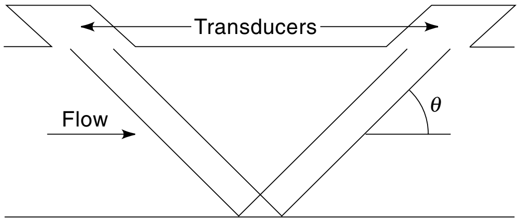

Figure 3. Reflections off pipe wall may be used to increase the acoustic path length.

For conditions where the flow velocity V is much smaller than the speed of sound in the medium c, the apparent speed of sound will increase or decrease by the component of V parallel to the direction of sound propagation (see Fig. 5). This leads to the equations

$$t_d = \frac{l}{c + V_p} + \tau \tag{2}$$

$$t_u = \frac{l}{c - V_p} + \tau \tag{3}$$

$$V = \frac{V_p}{\cos\theta} \tag{4}$$

where V_p is the component of flow parallel to the path of propagation and l is the path length between the two transducers. τ is a fixed delay determined by the electronics and any intervening stationary material. While either Eq. (2) or (3) could be solved for V_p, this is seldom done in practice because, in general, c depends on temperature and other variables and may not be known with sufficient accuracy to produce a meaningful estimate of V. Equations (2) and (3) can be solved for V_p independent of c:

$$V_p = \frac{l\,\Delta t}{2(t_d - \tau)(t_u - \tau)} \approx \frac{l\,\Delta t}{2t_d t_u} \tag{5}$$

where $\Delta t = t_u - t_d$. The approximation assumes the delay τ is negligibly small.

Computation of V by this method demands the ability to measure small differences in propagation time. For instance, given $\theta = 45$, a 1 m/s water flow through a 10 cm pipe pro-

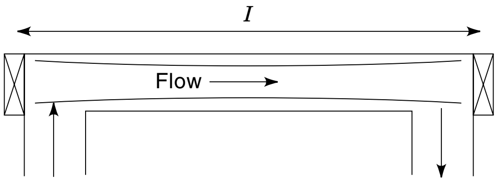

Figure 4. Arbitrary acoustic path length may be achieved with an axial transducer arrangement.

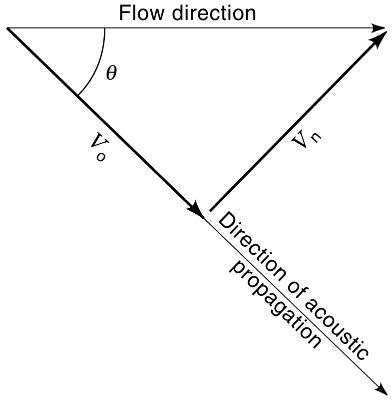

Figure 5. Vector diagram of acoustic path components relative to flow.

duces a Δt on the order of 100 ns. For slow flows or narrow pipes, using an axial transducer arrangement or multiple reflections within the pipe to increase the path length can increase Δt.

Sing-Around Method. Another transit-time approach involves using the received signal to trigger the transmission of the next pulse. A first pulse is launched, and its reception launches the next pulse. The pulse is said to "sing around" the system as it propagates through the pipe to the receiver, through the electronics back to the transmitter. The frequency at which pulses are sent can then be used to estimate the velocity through the relation

$$\Delta f = f_\mathrm{d} - f_\mathrm{u} = \frac{1}{t_\mathrm{d}} - \frac{1}{t_\mathrm{u}} = \frac{2V_\mathrm{p}}{l} \tag{6}$$

where the fixed delay has been neglected for simplicity.

Once the path-averaged flow velocity V has been found by any of the above methods, the volumetric rate of flow Q can be found through the relation

$$Q = AKV \tag{7}$$

where A is the cross-sectional area of the pipe and K is the meter calibration factor. K is dependent upon the flow profile. For a diametrical path and idealized flow profiles, $K = 0.75$ for laminar flow ($\mathrm{Re} < 2000$); while for turbulent flow, K becomes dependent on velocity through the relation (3)

$$K = \frac{1}{1.119 - 0.011\,\log(\mathrm{Re})} \tag{8}$$

Sound paths other than the diameter may be used to reduce sensitivity to flow profile. A midradius chord path is least sensitive to the difference between laminar and turbulent flows (7). Multichord systems are capable of averaging flow over a greater area and exhibit less sensitivity to disturbed flow profiles. K may also be determined by field-testing. Many systems can compensate for K varying as a function of V.

Transit-time meters are best suited to measuring flow of clean fluids and gases. The major requirement is that the fluid have sufficiently low attenuation and scattering to allow the reliable transmission of a pulse across the flow. "Sufficiently low" varies from meter to meter and tends to drop year by year as more sensitive and sophisticated receivers are introduced. Systems now available are able to monitor the quality of the received signal in addition to the usual flow measurement duties. Should the signal appear unreliable, the system can take appropriate corrective steps. These may then reject single measurements which represent a greater-than-expected variation from the previous measurement (8). This can be useful in minimizing the effect of bubbles on measurement. Another transit time system (9) can track changes in the speed of sound of the fluid. This prevents the received signal from straying outside the measurement window should flow conditions change.

The transit-time method is the most accurate of the ultrasound techniques, with typical claimed accuracies of 1% to 2% of flow (2,9), Some multichord systems achieve accuracy of 0.25% of flow (10).

Doppler Methods

Anyone who has every noticed the change in pitch of the horn as a train speeds by is familiar on some level with the Doppler shift. Since its discovery in 1842 by Christian Doppler, it has been widely used in radar, astronomy, sonar, and biomedical imaging as well as in flowmetering. Doppler systems employ the shift in frequency of a wave emitted by a moving object to estimate its velocity. For more information on Doppler methods, see FLOW TECHNIQUES, MEDICAL.

In a Doppler flowmetering system, the moving objects are inhomogeneities in the flow, which act as scatterers of ultrasound. These may be either particles of different phase than the main flow (e.g., solids or bubbles in liquid flow) or disturbances of the flow itself, such as vortices. Manufacturers usually specify minimum and maximum percent scattering material by volume necessary for proper meter operation. A minimum value is required to generate a detectable echo signal. A maximum is set to ensure that the beam penetrates the flow sufficiently to produce an accurate reading. Field-testing is often necessary to determine if the flow possesses adequate acoustic characteristics, since the scatter properties depend on the size and composition of the solids. A typical specification (11) calls for 25 ppm scattering material of >30 μm solids or bubbles minimum, 1% by volume maximum scatterer content.

If sound of frequency f is reflected from a body moving with velocity V, the echo received will undergo a frequency shift given by

$$\Delta f = \frac{2 f_\mathrm{c} V \cos\theta}{c} \tag{9}$$

where θ is the angle between the sound beam and the direction of flow. Δf can be measured by mixing the received signal with the transmitted and low-pass filtering:

$$d(t) = \mathrm{LPF}\{\cos(2\pi f_\mathrm{c} t)\cos(2\pi(f_\mathrm{c} + \Delta f)t)\} = 0.5\cos(2\pi\Delta f t) \tag{10}$$

The frequency of the low-pass signal is then proportional to the flow velocity.

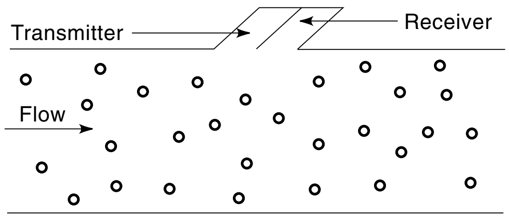

Figure 6. A dual-aperture Doppler system, which relies on scattering media in the flow.

The simplest realization of a Doppler system is a dual-element continuous-wave (CW) device (Fig. 6). Two transducers are set in a single housing. The transducers are arranged such that the transmitter and receiver beam patterns are set at an angle θ to the pipe wall, and they overlap to the greatest degree practicable. The transmitter emits a constant frequency sound wave into the flow. The reflected signal is detected by the receive crystal. The received signal is mixed with the transmitted frequency and is low-pass filtered. The output frequency of the low-pass filter is proportional to the flow rate. The problem with this system is that the received signal is weighted according to the scatterer distribution in the flow. This may not be known. Furthermore, there is no method for selecting a single radius of the pipe at which to estimate velocity. In spite of this shortcoming, the CW method remains popular due to its low cost and reasonable accuracy once calibrated.

Some of the shortcomings of the dual-element CW arrangement can be overcome with techniques that allow the sampling of specific regions within the flow, either through transducer focusing or through range gating.

Beam-Gated CW. In this arrangement (Fig. 7), the two transducers are located on opposite sides of the pipe. The beam patterns are arranged to intersect at a specific radius within the pipe (typically the center). The operation of the transmit and receive elements remains the same as in the dual-element CW system. The beams intersect within a limited volume, and thus the received signal yields velocity information only for that volume. This reduces the effect of changes in scatterer concentration on the velocity estimate by limiting the volume over which they influence the measurement.

Pulse Wave. Rather than utilizing a CW, a tone burst can be used to isolate a region within the flow. A single transducer is used to launch a tone burst into the flow. A fixed time later, the same transducer samples the reflected signal. This is repeated many times in rapid succession. The echo, $r(n, t)$, will undergo a phase shift due to the motion of the scattering material such that

$$r(n, t) = A\cos\left(2\pi f_c t + 2\frac{nTV}{c}\right) \tag{11}$$

where n is the pulse number and T is the time between pulses. If $r(n, t)$ is sampled at the same time after the launch of each pulse, the $2\pi f_c t$ becomes a constant phase factor, and a discrete-time cosine signal in n is developed. The frequency of this signal may be substituted for Δf in Eq. (9) to determine V. A limit is imposed on the maximum velocity that can be unambiguously determined by this method due to the discrete-time nature of the signal. If the term TV/c exceeds $\pi/2$, the sampled signal will be aliased, and the measured velocity will actually decrease with increasing real flow velocity. Care must be taken to ensure that this does not happen in practice. For a more complete discussion of pulse-wave Doppler, refer to Flow techniques, medical.

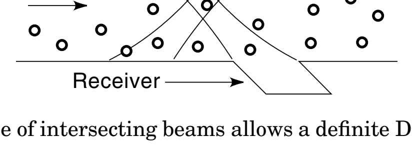

Figure 7. Use of intersecting beams allows a definite Doppler sample volume to be selected.

As in transit-time devices, the product of velocity, cross-sectional pipe area, and a calibration factor K gives the volumetric flow rate. Determining the K factor is more difficult in split-aperture CW systems, since the flow profile and the scatterer distribution play a role. Doppler systems typically achieve accuracies of 1% (2).

Speckle-Tracking Methods

Speckle-tracking techniques provide an alternate method to measure flow in a scattering fluid. A typical system (9) employs transmit and receive transducers mounted in close proximity, similar to a Doppler system. The transmitter fires short pulses into the fluid. After a delay to interrogate the proper depth, the receiver records a short period of the echo signal. This process is repeated several times in rapid succession, on the order of 1 ms to 10 ms between each burst. Each received signal contains echo energy from moving and stationary targets. By subtracting the "average" signal from each echo, the signal due to flow may be obtained. One echo signal is selected as a reference and is cross-correlated with the others. By tracking the correlation peak across the several echoes, the motion of the fluid may be estimated from one echo to the next. This information, coupled with the time between echoes, gives an estimate of the fluid velocity. Refer to Flow techniques, medical for more information.

Pseudorandom Noise. The 1988 patent of Jacobson et al. (12) describes flowmeters, both transit-time and speckle-tracking, using pseudorandom noise technology. The mode of operation for these meters is the same as for tone-burst flowmetering equipment, but the use of pseudorandom noise allows improvements in signal-to-noise ratio (SNR) and velocity resolution. The Jacobson patent describes a system in which a tone burst is modulated by an 11-bit Barker code before transmission into the flow. The Barker code multiplies each one-cycle segment of the tone burst by ± 1, depending on the bit value, one or zero, of the Barker code for that segment. The Barker code was selected because signals thus modulated have narrow autocorrelation peaks with low sidelobes, compared to simple tone bursts. The received signal is filtered by correlation with a copy of the transmitted signal. The filtered signal will have a sharp peak at the time corresponding to receipt of the transmitted waveform. This sharp

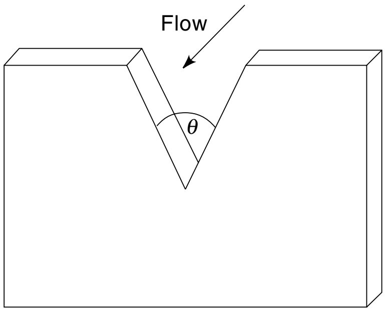

Figure 8. The V-notch weir is used for flow rates under 20 L/s. Theta is typically 60° or 90°.

peak provides the dual function of providing a distinct reference point to calculate the time of flight, as well as providing the greatest SNR possible from a linear filter.

Other speckle-tracking techniques have been developed for biomedical applications and may see future application to industrial flow measurement. Interested readers are referred to Refs. 13 and 14.

Methods for Open Channels and Partially Filled Pipes

The methods described thus far require the pipes containing flow to be completely filled for proper operation. There are many cases where this is not always true. Furthermore, there is frequently a need to measure flow through an open channel. Purely ultrasonic and hybrid approaches can be used to measure flow in these situations.

Weirs and flumes are often used to measure flow rate in open channels. Some of the most common types are illustrated in Figs. 8 through 11. These devices have well-characterized relationships between head and flow rate.

A weir is a dam across a channel with an opening of a specific shape at its top that passes the flow. The most common types are the rectangular, V-notch, and Cippoletti weir. The Cippoletti weir has a trapezoidal opening whose sides have a slope of 4 : 1 rise : run. These three types are depicted in Figs. 8 to 10. V-notch weirs are typically used for flow rates below 20 L/s. Rectangular and Cippoletti types are used for larger flows, with the only restriction being that the head should be kept less than 30 cm to maintain accuracy. Each type has a characteristic head-to-flow relation, given by the equations (2)

$$Q_{\mathrm{r}} = 94.2(L - 0.2H)H^{1.5} \tag{12}$$

$$Q_{\mathrm{v}} = 70.1\tan(0.5\theta)H^{2.5} \tag{13}$$

$$Q_{\mathrm{c}} = 95.2LH^{1.5} \tag{14}$$

where Q_{r}, Q_{v}, and Q_{c} are the flow rates in L/s for the rectangular, V-notch, and Cippoletti weirs, respectively.

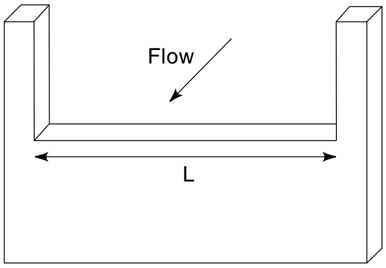

Figure 9. The rectangular weir can handle arbitrary flows, limited only by its width.

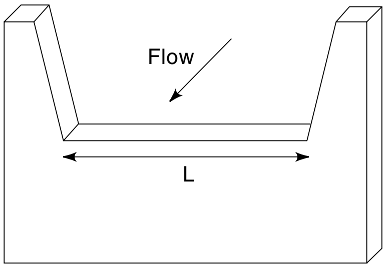

Figure 10. The Cipoletti weir's sloped sides simplify the head/flow relation.

The Parshall flume shown in Fig. 11 has the advantage of lower head loss versus a weir for a given rate of flow. The flow is roughly proportional to the 1.5 power of the head.

Given the relationship between head and flow rate, the problem of measuring flow reduces to the problem of level measurement. This can be achieved ultrasonically though pulse-echo time-of-flight measurements to the air–water interface. The measurement may be made either from below, through the fluid, or above, through the air. Through-air measurements require temperature compensation, because the speed of sound in air is a sensitive function of temperature, varying roughly 1% per kelvin.

Typical installations (15,16) use a transducer and thermometer mounted over the flow connected to a pulser-receiver and a computer. The user provides information on the type of weir or flume used, and the computer calculates the flow rate based on head and temperature. Open-channel methods achieve accuracies in the range of 2% to 5% of flow (2).

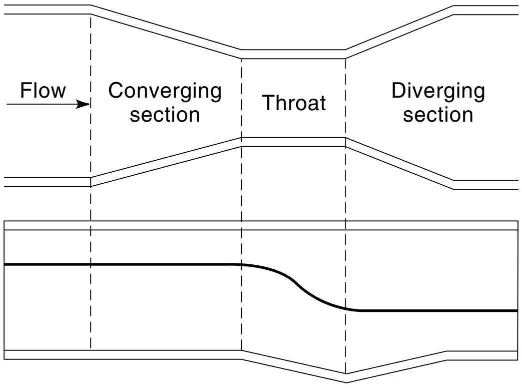

Figure 11. The self-cleaning Parshall flume incurs a lower head loss for the same rate of flow as a weir.

In instances where it is impractical to install a weir or flume, a combination of velocity and flow height measurements may be used to estimate flow. A transit-time or Doppler meter may be installed low in the channel to provide a velocity estimate for a given chord. As long as the flow is well developed, this chordal velocity can be related to the average channel velocity. An ultrasonic level sensor is then employed to measure the flow head. The average velocity is multiplied by the flow area, which is supplied as a function of height to yield a flow estimate. If the flow level drops to the point where the velocity transducers are no longer submerged, the computer can switch to a mode in which the flow is estimated by height alone. Accuracy suffers considerably in this mode, however, since many conditions besides head will affect the flow velocity.

The weir/flume and velocity/area techniques may be combined to expand the range over which an accurate reading may be obtained. For instance, a small flume may be set in the bottom of a larger channel. In this arrangement, low flows are carried and measured entirely by the flume. Larger flows flood over the flume and are measured using the velocity/area method.

Vortex-Shedding Meters

Vortex meters use the Karman sheet phenomenon (3) to measure flow velocity. An obstruction, termed a bluff body, is placed in the flow. When the flow is of sufficient Reynolds number, vortices will be shed from the bluff body. These vortices will be shed at a rate inversely proportional to the diameter of the bluff body and proportional to the flow. The Strouhal number S is the proportionality constant relating the quantities:

$$f = \frac{SV}{d} \tag{15}$$

where d is the diameter of the bluff body and f is the frequency at which vortices are shed.

Ultrasound can be used to detect the passage of vortices. Transducers placed on opposite ends of a diametrical path will record fluctuations in attenuation as the vortex passes. By noting the frequency with which the disturbances occur, and given knowledge of the bluff body dimensions, flow rate may be calculated.

Vortex meters can have very good accuracy (17), better than 1% of flow. They do require that the flow be above a certain minimum Reynolds number. They also provide some resistance to flow, due to the bluff body.

Correlation Methods

Correlation flowmeters work by detecting fluctuations in some flow parameter at an upstream station and measuring the time required for the fluctuation to appear at the downstream station. The parameter correlated is not always restricted to ultrasonically detectable properties.

A generic configuration involves two stations situated a known distance apart. Each station consists of transmitting and receiving transducers on opposite sides of the pipe. A signal, either CW or pulsed, transmitted across the pipe will experience random variations in phase and amplitude. These variations are due to a number of factors, including the passage of variations in fluid mixture (changes in component ratio), eddies, and other forms of turbulence and variations in temperature. The received signal upstream is monitored for strong variations in phase and/or amplitude, and time is measured until the same disturbance appears downstream.

The upstream and downstream units must be close enough together so that fluctuations in the flow characteristics responsible for the observed signal change do not dissipate before their effect can be observed at the downstream station. On the other hand, the stations should be far enough apart that accurate timing of the passage of the disturbance is possible.

Correlation meters generally exhibit poor accuracy compared to other ultrasonic types.

Flow Interface Detection

Large pipelines, as used in the petroleum industry, often carry a variety of products in sequence. That is, one product is sent through the pipeline for a period of time, followed by another. One product may immediately follow another, or a water plug may separate them. To successfully recover the product from the end of the pipeline, which may be many miles from the source, a method is needed to distinguish one product from another.

Zacharias (5) reported on the use of speed of sound as a method for distinguishing one product from another in 1971. He notes that there is a linear relationship between specific gravity and speed of sound for hydrocarbon fuels. Since specific gravity is a strong indicator of the product present, speed of sound likewise is useful for distinguishing one product from another. Speed of sound also varies with temperature and pressure. Any system designed to identify products based on speed of sound must include compensation for these factors.

Zacharias and Ord (18) show a modified transit-time flowmeter which, in addition to the usual flow output, also registers the speed of sound of fluid for product identification purposes. The device was successful in tests in distinguishing between fuel oil, kerosene, and gasoline. Commercial devices (19) based on this principle, which can be used to automatically batch products based on speed of sound, have been developed.

Noise-Sensitive Flowswitch

This is primarily an acoustic, rather than an ultrasonic, technique. Flow through a pipe generates noise due to turbulence. By sensing when this noise exceeds a threshold, the existence of a flow is indicated. The noise level is a sufficient guide to generate a flow/no-flow signal. Lynnworth (3,4) notes that little success has been achieved in making more quantitative measurements of flow from noise parameters.

MECHANICAL CONCERNS

Closed-pipe ultrasound systems can be divided into clamp-on and wetted transducer types, each of which has inherent advantages. Clamp-on models can be quickly set up and taken down. Often their setup only entails the application of coupling jelly to the transducer face, and the devices are portable. They can be used to verify the proper operation of other meters in a system. Clamp-on transducers never contact the flow. This allows them to measure highly corrosive or otherwise hostile flows without difficulty. High-temperature flows can be measured using momentary-contact transducers (4). Wetted transducers have as their principle advantage better acoustic coupling to the flow of interest. The transducers are in direct contact with the flow, or they operate through carefully designed windows with good acoustic properties. Clamp-on devices, in contrast, must propagate the acoustic wave through the pipe wall, whose acoustic properties are, in general, uncontrolled. Some pipe materials do not lend themselves to the use of clamp on transducers. Cast iron, concrete, and lined pipes are all particularly troublesome because of their potentially high attenuation. Lined pipes often have thin air layers trapped between the air and the lining, rendering them relatively impenetrable to ultrasound. Pipes suffering from a thick buildup of corrosion or scale may also be unsuitable. Wetted transducers are essential in such installations.

Clamp-On Transducers

Clamp-on systems employ one or more wedge-mounted transducers pressed into contact with the pipe (Fig. 12). Wedges are constructed from a variety of materials, including acrylic, Perspex, and steel. They provide a means of acoustic impedance matching and a known angle of contact. Depending on the transducer and wedge material used, longitudinal or shear waves may be coupled to the pipe wall. Any shear waves will be mode-converted to longitudinal waves at the pipe–fluid interface, however.

Simple Doppler systems employ a single hand-held transducer that is pressed into contact with the pipe. Alignment with the pipe axis is achieved either visually or with the aid of grooves on the transducer head. Dual transducer Doppler and speckle-tracking systems require that the transmit and receive beam patterns intersect for proper operation. A jig may be provided to assist the alignment process. Less complicated systems uses pipe clamps or straps to hold the transducers in place and require manual alignment.

Transit-time devices usually employ a rack of some type to assist in locating the transducers. The rack maintains the axial alignment of the transducers while allowing one or both to slide along the pipe axis. This facilitates locating the signal reflected from the far wall. The rack is clamped to the pipe with roller chain or pipe clamps. One transducer remains fixed while the second is positioned so that a good reflection is obtained, at which point it is fixed in place.

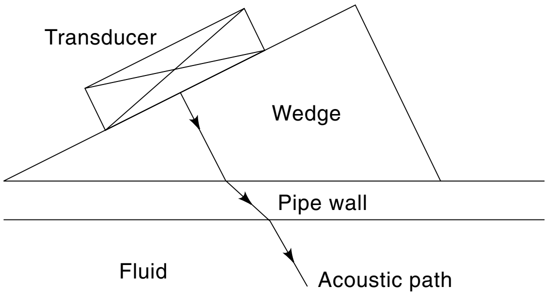

Figure 12. An acoustic wedge may be used to couple a transducer to a pipe. Refraction of the acoustic path into the pipe may be significant if materials are not well-matched.

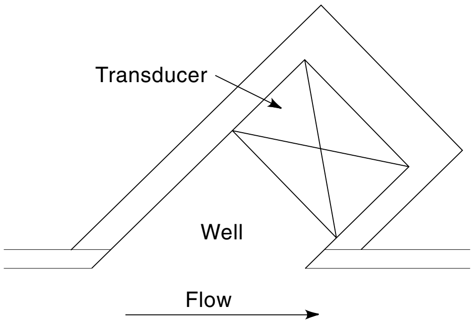

Figure 13. A wetted transducer places the element in direct contact with the flow. Alternatively, the well space may be filled with epoxy to buffer the transducer from the flow.

Wetted Transducers

Manufacturers supply both field-installable transducers and preassembled spool pieces. In either case, the transducer is allowed to make direct contact with the flow (Fig. 13). Transducers separated from the flow by acoustic windows designed specifically for the purpose are also covered, since most of the details are similar.

A spool piece is a section of pipe with ports drilled out at appropriate locations for transducers. This eliminates the need for the user to align the transducers. Prefabricated spool pieces also allow for designs with complex acoustic paths to be easily incorporated into the flow. Spool pieces are available in a wide range of materials; carbon steel, stainless steel, and polyvinyl chloride (PVC) are common. Some manufacturers will also supply spool pieces in custom materials upon request. The simplest models provide a threaded connection to the pipe for the transducer. In this configuration, the flow must be shut down in order to change and/or inspect the transducers. So-called “hot-tap” designs employ a valve between the transducer and the flow. The valve is designed to provide an unobstructed acoustic path in normal operation. When it is necessary to remove the transducer, the valve can be closed. This allows removal of the transducer without interrupting flow. Some types also provide small secondary ports that can be used to flush deposits out of the transducer well, should it become clogged.

Field-installable transducers are supplied with fittings that may be welded to the pipe. These allow a meter to be fitted permanently to a pipe without requiring a section to be removed for a spool piece. They are also used in instances where the pipe diameter exceeds the range of spool pieces available. These kits are supplied with detailed instructions on proper installation and transducer alignment, which is critical to the proper functioning of the meter.

The above types place the transducer face in direct contact with the flow. While this provides the best acoustic coupling possible, there are situations where it may not be desirable to do so. The flow may contain corrosive chemicals, or it may have a tendency to deposit residues in the well. One solution to these problems is to use an acoustic window between the transducer and main flow. An epoxy plug can be formed into the well, providing a smooth face to flow and protecting the transducer. The transducer is acoustically connected to the epoxy window with a coupling fluid or high pressure. When using a coupling fluid it is critical to ensure that it does not dry out or decompose under operating conditions. A small reservoir is often employed to ensure an adequate couplant level. Solid materials such as rubber or plastic may be used to make the acoustic connection, eliminating such difficulties.

Another method for isolating the transducer from the flow is to use a thin membrane seal to isolate the transducer well from the main flow. The membrane should be thin compared to the ultrasound wavelength to minimize attenuation. Coupling between the membrane and the transducer is normally achieved with a fluid couplant.

Under conditions of highly attenuating flow, transit-time meters can encounter difficulties due to an acoustic “short” around the pipe. The transmitted pulse can be conducted by the pipe wall from the transmitter to the receiver and interfere with the measurement. While signal-processing techniques can alleviate the problem, another solution is to acoustically isolate one transducer from the other with a split-cell design. A coupling sealed by an acoustically lossy gasket is set between the transmitter and receiver. This effectively reduces the pipe-conduced signal to a level that no longer interferes with the measurement.

A typical commercial Doppler system (11) that incorporates a wetted insertion transducer. The transducer is inserted into the flow through a single hole in the pipe wall. The probe can be installed through a valve to allow removal without interrupting flow. Two transducer elements are located in the tip of the probe and aligned such that the beam is parallel to the flow. The beam interrogates the flow upstream from the transducer to minimize the effects of the flow disturbance created by the probe. The system operates in a CW mode, with one element transmitting and the other receiving. This system has the advantage of interrogating along the axis of flow, which maximizes the Doppler shift and increases sensitivity.

For very slow flows or narrow pipes, axial flow cells are employed. This arrangement allows interrogation of the flow over a much greater length than a single diagonal path. The longer path increases Δt and allows slower flows to be measured for a given time resolution than would otherwise be possible. In large-diameter pipes, the transducers are inserted into the pipe to a given radius. In narrow pipes, the transducers may be set into T connections at the ends of a straight run (see Fig. 4).

Where increased accuracy is required, a spool piece of square cross section may be constructed. Using a sheet beam or multiple narrow beams, the entire cross section may interrogated with equal weighting. This reduces sensitivity to flow profile disturbances.

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