Beyond orifices for DP flowrate measurements
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While the orifice is the most common flowmeter restriction associated with differential pressure (DP) measurements, several others have found a solid place in process applications. Various designs of DP flowmeters provide for an optimum adaptation to the operating conditions and requirements of the user. An important consideration is the pressure drop, which as a rule of thumb should be as small as possible. Flowmeter technologies such as venturi tubes, nozzles, wedges, and flow tubes are characterized by very small pressure drops which leads to reduced energy loss and pumping requirements.

All DP primary elements restrict the flow in some way. According to Bernoulli’s law of conservation of energy, a restriction in a pipe results in an increase in the fluid velocity. The ensuing conversion to kinetic energy reduces the static pressure. This pressure drop is the measured differential pressure, which is proportional to the square root of the flow rate. The differential pressure phenomenon is a universal metering principle for flowmetering. This article reviews the attributes of flowmeter DP elements other than orifices.

Flowmeters based on differential pressure represent a popular choice in the processing industries, constituting a large plurality of the installations. Differential pressure meters are used for liquid, gas, and steam metering in both normal and extreme high temperatures and pressures. The characteristics of DP flow elements have been optimized by extensive research activities over decades and the results are published as standard. Generally they are easy to select for a specific application. They have no moving parts and can be fabricated in a wide selection of materials. Their purchase price is relatively low, even for large pipe sizes. Accuracy is moderate, ranging from 1 to 5 percent, but compensation techniques can improve these values to better than 1 percent.

Disadvantages revolve around rangeability, installation costs, density, and flow profiles. The square-root relationship limits the range of flowrates that can be realistically measured in a particular application; the typical rangeability is 4:1 or slightly higher. Installation requires a DP transmitter, manifold, valving, and impulse lines. The impulse lines leading to the DP transmitter can become plugged unless remote seals and filled capillaries transfer the pressures to the transmitter. The measured value varies with fluid density for both volumetric and mass flow. Additionally, flow elements tend to be sensitive to flow profiles within the pipe, requiring long upstream pipe runs or flow-straightening devices.

**Venturi tubes**

The classic venturi tube is a robust flow element, useful for applications requiring low loss of line pressure. A venturi tube is essentially a section of pipe with a converging conical entrance (about 20 degrees), a straight cylindrical throat section, and a diverging conical exit with a smooth, gradually increasing (about 7 degrees) diameter. Unlike the orifice, the interior surfaces always remain in contact with the fluid. Additionally, since dirt will not build up as it passes through the contoured sections (as it does in the front of an orifice), this differential producer can be used in dirty flow applications. For the same differential pressure the classic venturi can pass about 60 percent more flow than an orifice plate. Years of test data have documented and validated the flow coefficients for various sizes and fluids.

*Figure 1. The outlet cone of the classic venturi tube gradually diverges, permitting recovery of nearly all the initial pressure loss.*

Four or more high pressure taps in an annular chamber leading to the straight throat section average the lower pressure reading. Initially designed for large line size (>6 inches) water and wastewater applications, the venturi today ranges in line size from 2 to 48 inches and installation possibilities include flanged, welded or
threaded-end fittings. Manufacturers generally machine the smaller sizes from solid rods, while they fabricate the larger sizes from rolled plate. The lengths of the elements typically run five pipe diameters.

Since most of the pressure recovers, the venturi tube is a good choice for large flows where the velocity is higher and Reynolds number is in the turbulent flow regime. And while it has a relatively long length, the venturi tube requires minimal upstream flow profiling because its interior shape helps to condition the flow. Rangeability, while better than orifice plates, is less than 6:1, with typical accuracies of ± 1 to 2 percent of full scale.

Variations of the classic venturi tube are available. Shorter versions increase the angle of the outlet cone with some sacrifice in pressure recovery. Eccentric inlet and outlet cones can handle mixed phases or build-up of heavy materials. Forms with a rectangular cross-section often serve in ductwork for gaseous flows.

**Flow nozzles**

Like the orifice and venturi tube, these are standard DP elements with a strong history of generic testing and documentation. Because of its rigidity, flow nozzles are dimensionally more stable at higher temperatures and velocities than an orifice plate. They typically measure high velocity flows that might otherwise damage an orifice plate from cavitation or erosion. Applications include high velocity steam or fluids with entrained solids. Nozzles are not recommended for slurries or dirty fluids that might foul pressure taps. In contrast to an orifice plate, flow nozzles have no sharp edges that are susceptible to wear over time that could lead to performance degradation. So they maintain long-term accuracy with less wear and reduced possibility of distortion. Throat Reynolds number should be above 10,000, although data is available down to about 6000.

The initial cost of a flow nozzle is substantially higher that that of an orifice plate, but lower than that of a venturi; however the permanent pressure loss is significantly higher than that of a venturi. A flow nozzle will pass about 60 percent more flow than an orifice plate of the same diameter and differential pressure. Because of the nozzle’s streamlined interior, unrecoverable pressure loss is slightly less than that of an orifice, but can still range to 40 percent of the differential pressure and higher.

Nozzle standards include:
- NOZ-NI ISA 1932 Nozzle, not common in the U.S.
- NOZ-LR Long Radius Nozzle

The long-radius (ASME) flow nozzle that predominates in the U.S. comes in two design variations—one with a low-beta-ratio and the other with a high-beta-ratio. The converging section is a quarter ellipse followed by a cylindrical throat section. ASME has developed the nozzle geometries based on the beta ratio desired for the application:
* High-beta nozzles (throat/inlet diameter ratios between 0.45 and 0.80)
* Low-beta nozzles (ratios between 0.20 and 0.50)

The difference in geometry is a flattening of the elliptically shaped inlet in the high-beta-ratio version.

Users may either weld the nozzles into the pipe line or mount them with a holding ring between flanges. Where inspections are required, the flange mounting provides accessibility. In the U.S. the DP taps are commonly found one pipe diameter upstream and one-half pipe diameter downstream from the inlet. Flow nozzles may be installed

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*Figure 2. Low and high beta ratio long-radius nozzles, common in the U.S., both have elliptically shaped inlets.*
in any position. Vertical downward flows better suit wet steam or gases and liquids with suspended solids. Upstream and downstream piping requirements for flow conditioning are similar to those for orifices. Manufacturers can make nozzles from any machinable material, such as aluminum, fiberglass, stainless steel, or chrome-alloy steel. The bevel on the discharge side of the nozzle is a critical point of manufacture. The throat should be perfectly round with no taper. The standard surface finish is 16 RMS (rougauge measurement system). The standard nozzle coefficient is 0.9962, which users can adjust for actual beta ratio and throat Reynolds number.

A special variation known as a venturi nozzle combines the 1932 ISA nozzle inlet profile with the divergent cone of a venturi tube. Taps in the throat transmit the lower DP pressure. This nozzle can serve as a secondary flowrate standard when experiencing "choked" (sonic velocity) flow. It’s also commonly used to test steam turbines.

**Wedge elements**

The wedge element consists of a V-shaped restriction welded into the top of the meter body. In profile the wedge looks like a segmental orifice plate to the incoming fluid in that particulate matter or entrained gases easily pass through the meter. This basic meter has been on the market for over 40 years, demonstrating its ability to handle tough, dirty fluids. The slanted faces of the wedge provide self-scouring action and minimize damage from impact with secondary phases. Its fixed-body design provides a constant discharge coefficient over a wide range, 8:1, which is relatively high for a DP element. Accuracies are possible to ± 0.5 percent of full scale.

As with orifice elements, wedgemeters are characterized by an H/D ratio (analogous to the orifice beta ratio), where H is the height of the restricted opening, and D is the unrestricted inside diameter of the wedge element. The ability of the wedge to produce varying ranges of differential pressure depends on the H/D ratio selected.

Elements come with ratios in fixed steps (0.2, 0.3, 0.4, etc.) that allow a wide range of element sizing for a given pipe size. The meter coefficient is established at the time of factory calibration (in water).

Wedge meter technology extends the meter’s ability to handle flows with Reynolds numbers as low as 500, which is very helpful in metering slurries and liquids with high viscosities. It also allows the meter to measure flows bi-directionally with the same degree of accuracy.

Wedge elements can be supplied with remote seals having large-diameter diaphragms. These afford more sensitive response to DP changes while eliminating plugging of impulse lines. These wafer-type seal connections are raised off the meter body and may be preferable for the more aggressive and erosive applications. A second design permits use of isolating seals that can seat with diaphragms flush to the meter body. This seal arrangement keeps process fluid contained within the wedge element, with no dead zones under the seals where sludge and waste can build up. If the element is sized to have enough fluid velocity, a natural washing action will occur over the seal diaphragms and restriction, keeping the meter clean and sustaining maximum performance.

Like the nozzle, the wedgemeter does not rely on a restriction with sharp edges or machined bores. As a result, it will perform for long periods of service without the expense of maintenance and repairs. Solids and other debris easily pass under the V-shaped wedge and the inherent ruggedness of the restriction resists damage to its measuring edge, sustaining the initial calibrated accuracy.

As an example of the wedgemeter’s ability to maintain calibration in tough applications, ABB examined two stainless steel meters after 12 years of service—one 3-inch and one 4-inch with wafer-type seal connections. The meters measured steam-cracked tar, a byproduct of ethylene production. The cracked tar is kept at elevated temperature to prevent solidification of the abrasive coke fines and other particles in the process stream. The meters endured temperatures in excess of 355°F and pressures up to 310 psi. Fluid viscosities of 22 Cp produced Reynolds numbers of 1870 and 2850 at maximum flow rates. With over 5 million pounds a month of the abrasive tar being produced, repeatable and reliable measurement was a prime concern.

Calibration before and after the 12 years of service demonstrated that neither meter exhibited a major shift in meter coefficient. The 3-inch meter showed a deviation of 0.24% from its original testing while the 4-inch meter resulted in a 1.3% shift (based on averaged meter factor). Given typical calibration uncertainties, it’s safe to say that...
the meter factors remained virtually constant over 12 years of operation. Wedgemeters can be manufactured in virtually any alloy for service temperatures up to 720F and pressures over 6000 psi.

Flow tubes

The ASME defines flow tubes as any DP element whose design differs from the classic venturi (a definition that includes short-form venturi tubes, nozzles and wedges). In practice, flow tubes come in several proprietary shapes, but all tend to be more compact than the classic and short-form venturi tubes. Laying lengths tend to run from two to four pipe diameters. Being proprietary, flow tubes vary in configuration, tap locations, differential pressure, and pressure loss for a given flow.

While exhaustive generic test data is available for orifices, venturis, and nozzles, the user must depend on the manufacturer of flow tubes for sizing and calibration. The ASME recommends calibration with a piping section that replicates actual use over the full range of expected flows, which may be difficult and expensive for the larger sizes.

Three types of flow tubes are available, depending on pressure tap locations.

- Type 1 has static pressure taps at both the inlet and outlet
- Type 2 has a corner tap in the inlet and a static tap in the throat
- Type 3 has a corner tap at both the inlet and outlet.

Figure 4. This Type 1 flow tube has an inlet cone that converges in two steps, and comes close to the behavior of the venturi tube.

Static pressure taps, like those of a venturi tube, sense pressure where the fluid velocity doesn’t change direction and parallels the pipe wall. Otherwise the taps are called corner taps. Laying lengths tend to decrease with type number. Flow coefficients range from 0.9797 for Type 1 to 0.75 for Type 3.

Type 1 flow tubes more closely approach the characteristics of the classic venturi. The inlet cone converges in two angles that condition the fluid as it enters the throat. Flow coefficients are relatively stable for a variety of flow conditions. For large pipe sizes, the shorter Type 3 flow tubes may be useful, but may also require more upstream flow conditioning for good performance. The Type 3 meter coefficients may change with variations in Reynolds number, line size, and beta ratio.

Figure 5. Dall Type 3 flow tube from ABB creates a higher differential pressure than a comparable venturi tube, and has a greater pressure recovery as a percentage of the DP.

Flow tube sizes range from 4 to 48 inch. Their justification becomes easier for the larger pipe sizes, where their installed cost may be less than that of the venturi. But accuracy depends on the manufacturer’s calibration data. And extrapolation of meter flow coefficients for large sizes from tests on smaller sizes may be problematic.

Flow tubes can be fabricated from a variety of materials. In some cases they’re available as inserts of fiberglass-reinforced plastic or metal.

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