DIFFERENTIAL METERS OTHER THAN ORIFICE: ALTERNATIVE OPTIONS AVAILABLE FOR DIFFERENTIAL MEASUREMENT

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Flow is one of the four major physical measurements in processes. Flow meters may be classified in four categories: differential pressure, velocity, mass and positive displacement or volumetric. Each category has advantages and disadvantages; however, the focus of this paper will be the differential pressure flow meters.

Differential pressure (dP) flow meters include flow elements such as the orifice plate, venturi, flow nozzle, wedge meter, cone meter and proprietary devices. The elbow flow meter, pitot and annubar are also differential type flow meters, but have a different operating principle than the others and are outside of the scope of this paper. These meters may be referred to as flow elements (FE) or primary flow elements. These flow elements are called primary because an additional or secondary device must be attached to indicate the measured differential pressure. This secondary device may be an electronic transmitter, manometer, standpipe or gage.

dP flow elements are often called "head" type, obstruction or inferential meters. The flow rate is calculated or inferred from the measured difference in pressure or head. The basic principle of operation is that an obstruction is placed in the flow stream reducing the flow area, thereby creating an increase in velocity and a decrease in the flowing pressure.

The theories of dP flow meters were proposed in the 17^{th} century. The basic concepts were established by the works of Bendetto Castilli (1578-1643) and Evangelista Torricelli (1608-1647). In 1738, Daniel Bernoulli (1700 – 1782) published his textbook on hydrodynamics in which he stated a relationship in frictionless flow between pressure, velocity and elevation. Leonhard Euler (1707-1783) offered a complete derivation of the Bernoulli Equation in 1755. The first testing of conical contraction and expansion was done by Giovanni Venturi (1746-1822). His study was published in 1797. In 1898, Clemens Herschel (1842-1930) invented the classical venturi.

All dP meters are based on Bernoulli's theorem which is an application of the law of conservation of energy. If no work is done to or by the system and the heat transfer to or from the system is negligible, then the energy of the fluid is the sum of the pressure head (static energy), the velocity head (kinetic energy) and elevation head (potential energy). This relationship can be expressed as:

$$E = \frac{p}{\rho} + \frac{v^2}{2} + zg \qquad \text{(Eq. 1)}$$

Where at a particular point in the fluid:

E is the Total Energy of the fluid
p is the pressure
ρ is the density
v is the fluid velocity
z is the elevation or height
g is the local acceleration due to gravity

If energy is conserved, then E should be equal at any point in the system. For dP flow elements, these points are typically upstream of the flow element and at or near the point of the reduction of the area, downstream, as shown in Figure 1 for the Orifice and Figure 2 for the venturi. These are the points where the pressure or differential pressure is measured.

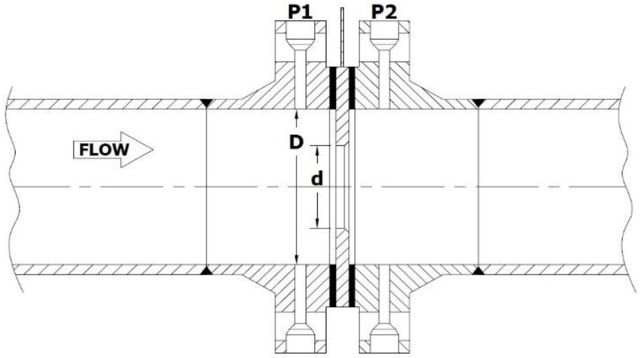

Figure 1: Thin, square-edged, concentric bore orifice

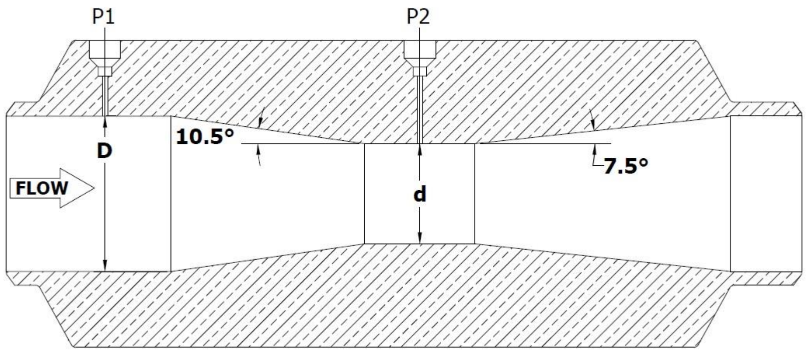

Figure 2: Venturi

Designating the upstream area as Point 1 and the downstream area as Point 2,

$E_1 = E_2$ (Eq. 2)

$$\left(\frac{p}{\rho} + \frac{v^2}{2} + zg\right)_1 = \left(\frac{p}{\rho} + \frac{v^2}{2} + zg\right)_2 \quad \text{or} \quad \frac{p_1}{\rho_1} + \frac{v_1^2}{2} + z_1 g = \frac{p_2}{\rho_2} + \frac{v_2^2}{2} + z_1 g \qquad \text{(Eq.3)}$$

In addition to the aforementioned assumptions of no work or heat transfer, the fluid is assumed to be incompressible and without friction losses. If the flow is incompressible, then the density is the same at Points 1 and 2 or $\rho_1 = \rho_2$.
The Law of Conservation of Mass, also known as the Continuity Equation, states that the rate of mass flow is equal at Points 1 and 2. This is expressed by Equation 4.

$\dot{m}_1 = \dot{m}_2$ (Eq.4), where $\dot{m}$ is the mass flow rate

And $\dot{m} = \rho A v$ (Eq. 5), where A is the cross sectional area.

$(\rho A v)_1 = (\rho A v)_2 \quad or \quad \rho_1 A_1 v_1 = \rho_2 A_2 v_2$ (Eq.6)

The area upstream, Point 1, is typically calculated from the pipe or inlet diameter, and noted as upper case D while for orifice, venturi and flow nozzles the reduced area is calculated from the area at Point 2 and is noted as lower case, d. The circular cross- sectional area is calculated at each point.

$A_1 = \frac{\pi}{4} D^2$ (Eq 7a) $\qquad A_2 = \frac{\pi}{4} d^2$ (Eq 7b)

Substituting (Eq 7a) and (Eq 7b) into (Eq. 6) and solving for v_1 yields

$v_1 = \frac{d^2}{D^2} v_2$ (Eq. 8)

If we can assume that the flow is horizontal, Points 1 and 2 are at the same elevation and $z_1 = z_2$. With the elevation term eliminated, and (Eq.8) substituted for v_1, (Eq.3) can be solved for v_2 yielding

$$v_2 = \sqrt{\frac{2\,(p_1 - p_2)}{\rho\left(1 - (\frac{d}{D})^4\right)}} \qquad \text{(Eq.9)}$$

Solving (Eq. 5) for v_2 and substituting (Eq. 7b),

$$v_2 = \frac{4\dot{m}}{\rho \pi d^2} \qquad \text{(Eq. 10)}$$

Combining (Eq. 9) and (Eq.10) and solving for $\dot{m}$ yields,

$$\dot{m} = \sqrt{\frac{2\,(p_1 - p_2)\,\rho}{\left(1 - (\frac{d}{D})^4\right)}}\;\frac{\pi}{4}\,d^2 \qquad \text{(Eq.11)}$$

(Eq. 11) is the basic mass flow equation for dP meters.

The following assumptions are made when utilizing the Bernoulli Equation: the flow is frictionless, incompressible, steady and has a fully developed velocity profile.

Several flow measurement codes and standards are available. These references provide design, manufacture and installation requirements that must be followed to achieve the published uncertainty. American Gas Association (AGA) Report No. 3 Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids-Concentric, Square-edged Orifice Meters seems to be the most widely used reference for thin, square edge, concentric bored Orifice Plates in the Oil and Gas Industry. Other references – such as American Society of Mechanical Engineers (ASME) MFC-3M Measurement of Fluid Flow in Pipes Using Orifice, Nozzle and Venturi, ASME Performance Test Code (PTC) 19.5 Flow Measurement and the International Organization for Standardization (ISO) 5167 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – provide guidelines for the orifice, flow nozzles and venturis. In 2016, ISO added Part 5: Cone Meters to ISO 5167. Some meters are considered proprietary and these guidelines must be provided by the manufacturer.

These standards have added terms to (Eq. 11) to compensate for some of these assumptions. The coefficient of discharge (C) corrects for the frictionless flow and other pressure losses. The coefficient of discharge is the ratio of the theoretical flow rate to the actual flow rate. Values of C range from about 0.6 for an orifice to very close to 1 for flow nozzles and venturis. The standards provide equations for calculating the theoretical coefficient of discharge as well as the expected uncertainty of the equation and limits of use. These limits are typically given in terms of beta ratio (β), D and Reynolds number. The actual flow rate is determined by flow calibration. Data from many flow calibrations have been analyzed to determine the theoretical equations.

A gas expansion factor (Y) compensates for the change in density between Points 1 and 2 for compressible flows. The standards provide the equations for Y and the limitations for their use. The equation used to determine Y depends on which meter is used and the location of the differential pressure taps. Different equations are provided for abrupt inlet meters such as the orifice and contoured inlet meters like the venturi and flow nozzle.

Another factor, N, a constant, includes the constants shown, i.e. $\sqrt{2}\,\frac{\pi}{4}$, and unit conversions are typically included.

The ratio of the bore area to the pipe area diameter is commonly encountered and is called the beta (β) ratio. For circular cross-sections, this reduces to the ratio of the diameters.

$$\beta = \frac{d}{D} \qquad \text{(Eq.12)}$$

The fluid’s velocity profile is important to achieve an accurate flow measurement. In 1883, a British Engineer, Osborne Reynolds (1842-1912), proposed a relationship of the inertial forces to the viscous forces. The Reynolds Number (Re) is utilized to determine if the flow profile is laminar (Re<2000) or turbulent (Re>4000.)

A fully developed velocity profile is achieved by installing straight lengths of pipe upstream of the flow element. The standards provide recommended lengths for various disturbances such as 90˚ bends, valves, reductions and expansions. A flow conditioner may be used to reduce the amount of required straight length.

The thin, square edge concentric bored orifice is the most commonly used dP flow element. Advantages of the orifice include low uncertainty, and it is easy to install or replace if the flow rate changes. Disadvantages include high unrecoverable pressure loss, wear and buildup on the orifice, deflection and long straight lengths required before and after the orifice.

Other styles of orifice include Circular Inlet or Quadrant Edge, Eccentric Bore, and Segmental Bore which are designed for specific applications. The Quadrant edge plate is used in low Reynolds number, high viscosity applications. The aperture of the Eccentric bore orifices is tangent to the top or bottom of the pipe diameter for liquids with entrained gases or gases that contain liquids, respectively. Segmental bore orifices also have apertures tangent with the bottom of the pipe internal diameter. Both Segmental and Eccentric bore orifices can be used for fluids with suspended solids or slurries. The location of the bore allows the fluid and solids to pass, preventing buildup at the upstream face of the orifice.

There are variations of the flow nozzle including the Long Radius Flow Nozzle (LRFN) with wall taps, LRFN with throat taps and the ISA 1932 flow nozzle. The LRFN has an elliptical inlet and cylindrical throat section. For both types the high pressure is sensed at a distance of 1 pipe diameter, D, upstream of the nozzle. The low pressure is sensed in the throat for the throat tap flow nozzle and a distance of D/2 downstream of nozzle inlet for wall tap flow nozzles. The ISA 1932 Flow Nozzle has a curved inlet and the differential pressure taps are more closely spaced than the LRFN with wall taps. The measured differential pressure is less than for an orifice plate at the same line size, β, and flow rate; therefore, the permanent pressure loss is less than for an orifice plate. The required length of straight pipe upstream of the flow nozzle is about the same as for the orifice plate.

Venturis consist of an inlet cylinder, conical convergent, cylindrical throat and conical divergent. The venturi requires less upstream straight length than the flow nozzles and orifice plates because of the gradual reduction in area. The conical divergent which is typically either 7° or 15° enhances pressure recovery; therefore, the permanent pressure loss for the venturi is considerably less than for an orifice or flow nozzle.

Except for the segmental bore and eccentric bore orifice plates, all of the meters described provide a reduction of the flow area that is concentric to the pipe. That is the reduction of flow area has the same centerline as the pipe. One of the disadvantages of this type of meter is that material in the fluid may accumulate at the face of the meter and disrupt the flow profile and increase the measurement uncertainty. Cone meters and wedge meters are designed to prevent this damming effect.

Cone meters (see Figure 3), as the name implies, have a cone placed in the pipe centerline and the fluid flows between the pipe internal diameter and the cone. The cone gradually increases in diameter from upstream to downstream.

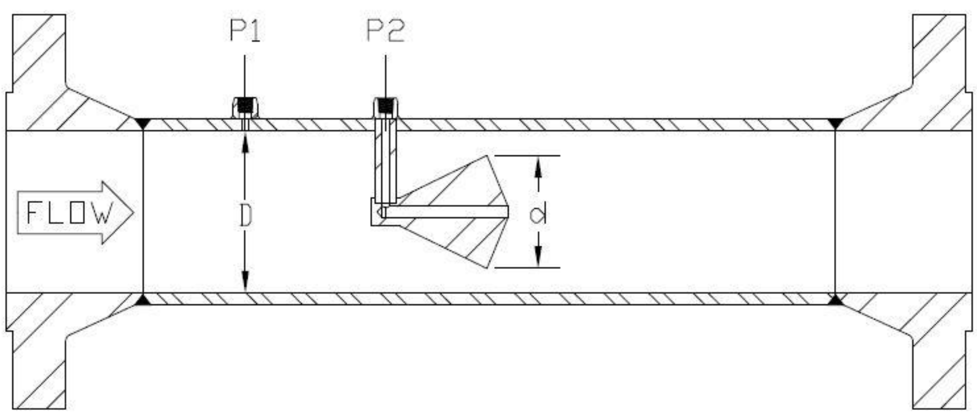

Figure 3: Cone meter

The area between the cone and the pipe is open around most of the circumference allowing free flow without accumulation. Similar to the other meters, the high pressure is sensed upstream of the cone in the pipe. The low pressure is sensed at the downstream of the cone and through its center. A part of the structure holds the cone in place and is part of the conduit sensing the downstream pressure. The permanent pressure loss is less than that of the orifice plate. The β ratio is calculated as the ratio of the open area of the annulus to pipe area.

$$\beta = \frac{\sqrt{D^2 - d^2}}{D^2} \qquad \text{(Eq 13)}$$

The wedge meter (Figure 4) does not have a circular cross section at the area reduction. This flow meter has a sloped inlet and outlet that make a "V" or wedge shape in the flow area.

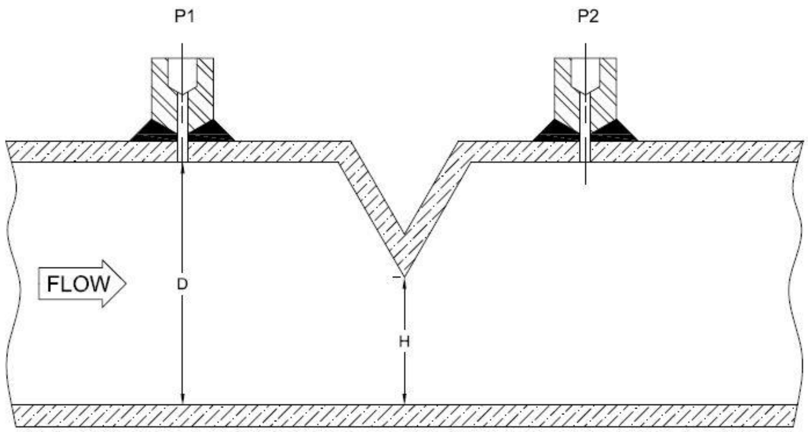

Figure 4: Wedge meter

Similar to the segmental bore orifice, the wedge has an open segment at the bottom of the flow area. The equation for the beta ratio is rather complex and is not presented. Instead of 'd', which is a diameter, the height, H, of the opening is shown. The high pressure is sensed upstream of the reduction while the low pressure is sensed just past the reduction.

For all of the dP flow meters described, as the fluid passes through the meter, a portion of the measured differential is recovered. The unrecovered pressure is the pressure loss, and is typically referred to as the permanent pressure loss or ppl. The ppl varies with each meter.

Some of the factors that should be considered when selecting a dP flow element are:

Uncertainty – calibrated or uncalibrated
Flow Profile: Laminar or Turbulent (Reynolds number)
Upstream straight length requirements
Flow conditions: high temperature, high velocity
Fluid properties – does the fluid contain solids, is the fluid two phase (gas and liquid)
Differential pressure – flow element structural integrity (deflection)
Permanent pressure loss
Costs: Installation and operating

In conclusion, this paper is intended to be a general introduction to the various dP flow meters. For detailed guidelines and explanations, the references or a meter manufacturer should be consulted. Although the thin, square-edge, concentric bore orifice is the most widely used dP meter, other dP meters are available and should be considered.