Flowmeters

DIFFERENTIAL PRESSURE - ORIFICE

The most commonly used flowmeter is the orifice meter. The orifice meter consists of two parts. As shown in Figure 1, they are the measurement orifice plate, which is installed in the process line, and the differential pressure transmitter, which measures the pressure developed across the orifice plate. There has been extensive research to determine the operating characteristics of orifice meters.

The physical phenomenon of the orifice meter is described by the Continuity equation and the Bernoulli equation. The continuity states that the mass entering a control volume is the same as the mass leaving the control volume. (Control volumes are convenient methods for studying fluid problems). In a numerical form, the Continuity equation is written:

$$m_1 = m_2$$

$$A_1V_1/v_1 = A_2V_2/v_2$$

To help make this point, imagine the flow of water through a pipe. For this example, we will assume that the liquid is incompressible, that is its volume (v) is constant. This is a legitimate assumption because liquids are virtually incompressible at normally encountered pressures and temperatures. If v is constant, the continuity equation simplifies to:

$$A_1V_1 = A_2V_2$$

If the liquid flows through an orifice, the area of the pipe will be reduced in the orifice and the velocity will increase as the fluid passes through the orifice.

The Bernoulli equation relates the increase in velocity to a change in static pressure. In more general terms, Bernoulli's equation relates the energy at one point in the control volume to the energy in a second point in the control volume. Bernoulli's equation written on a per unit weight basis can be represented as:

$$\frac{V_1^2}{2g} + Lz_1 + \frac{P_1}{\rho} + u_1 =$$

$$\frac{V_2^2}{2g} + Lz_2 + \frac{P_2}{\rho} + u_2 + q + ws$$

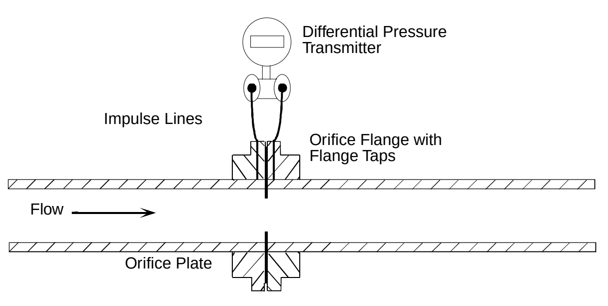


FIGURE 1 Orifice Plate and Differential Pressure Transmitter

where $\frac{V^2}{2g}$ = kinematic energy

Lz = potential energy due to gravity

P = potential energy due to static

ρ = density of fluid

u = internal energy in the fluid

q = change in heat energy of the fluid

ws = shaft work done by the fluid

For virtually all flow applications, this equation can be simplified. The first simplification is to state that there is no heat transfer in the control volume, so the factor q is 0.0. The next simplification is that there is no shaft work, so ws is 0.0.

ORIFICE EQUATION FOR LIQUIDS

Since liquids are incompressible under normal operating conditions, the equations governing orifices can be further simplified for them. The first simplification is made in the continuity equation, specified volume, v, is constant and can be eliminated from the equation yielding:

$$V_1A_1 = V_2A_2 \text{ or } V_1 = A_2V_2/A_1$$

Bernoulli's equation can be simplified for liquids if these conditions are assumed; the pipe is horizontal and the internal energy is the same in the sections on temperature and fluid properties (i.e. the temperature is the same). Based on these assumptions, Bernoulli's equation becomes:

$$\frac{P_1}{\rho} + \frac{V_1^2}{2g} = \frac{P_2}{\rho} + \frac{V_2^2}{2g}$$

If we substitute V_1 from the continuity equation, we can rewrite Bernoulli's equation as:

$$\frac{V_2^2}{2g}[1-(A_2/A_1)^2] = \frac{1}{\rho}(P_1 - P_2)$$

or

$$\rho V_2^2 = \frac{1}{[1 - (A_2/A_1)^2]}[2g(P_1 - P_2)]$$

These are the basic orifice equations. Since it is common to use these measure volumetric flow or mass flow, the square root is usually taken on both sides of the equation to solve for V_2.

$$(\rho)^{1/2}V_2 = \frac{1}{[1 - (A_2/A_1)^2]^{1/2}}[2g(P_1 - P_2)]^{1/2}$$

Since Q is equal to A_2V_2, we multiply both sides of the equation by A_2 and divide both sides by $(\rho)^{1/2}$ yielding:

$$Q = A_2V_2 = \frac{A_2}{[1 - (A_2/A_1)^2]^{1/2}} \frac{[2g(P_1 - P_2)]^{1/2}}{(\rho)^{1/2}}$$

Also, since the mass flow rate W, is equal to the volumetric flowrate times the density, W can be expressed as:

$$W = Q\rho = \frac{A_2}{[1 - (A_2/A_1)^2]^{1/2}} [2g\rho (P_1 - P_2)]^{1/2}$$

The term $1/[1 - (A_2/A_1)^2]^{1/2}$ is called the Velocity of Approach factor. Contained within this term is the Beta Ratio. The Beta Ratio is the ration of the area of the orifice to the area of the pipe, A_2A_1. The Beta Ratio is typically depicted by the Greek letter β.

The velocity of approach factor can sometimes be combined with other coefficients. These equations are the theoretical flow equations and are based on the fluid area at the downstream pressure tap. The area of the fluid is not precisely known, and therefore, the bore of the orifice is used for the area. This introduces an error into the calculation. To correct for this error, a flow coefficient is used to produce what is referred to as the working model of the equation.

To obtain Q actual, we multiply Q theoretical by C, which is the discharge coefficient. By doing this, the equation becomes:

$$Q_{act} = \frac{CA_2}{[1 - (A_2/A_1)^2]^{1/2}} \frac{[2g(P_1 - P_2)]^{1/2}}{(\rho)^{1/2}}$$

Often the velocity of approach factor is combined with C to yield another discharge coefficient, K.

$$Q_{act} = \frac{KA_2 [2g(P_1 - P_2)]^{1/2}}{(\rho)^{1/2}}$$

The common way to get the discharge coefficient is to refer to the standard tables and graphs that plot K versus the Beta ratio. The second method for determining the discharge coefficient is to actually measure it. An assembly that consists of the orifice plate and the inlet and outlet sections of the pipe are wet calibrated to determine the discharge coefficient. This assembly is commonly referred to as a meter run. This approach is usually taken with small pipe sizes and low flow ranges, where installation effects can cause significant errors.

ORIFICE EQUATIONS FOR GASES AND STEAM

To use the orifice equations for gases and steam, an additional factor must be added to compensate for the fact that gases and steam are compressible. The factor is called the expansion factor and denoted by Y. The expansion factor is determined by taking the ratio of actual flow of a gas or steam through an orifice to the flow that is predicated by the liquid orifice equation. The expansion factor can then be added to the liquid equation to make it suitable for gases and steam. The equation then becomes:

$$Q_{act} = \frac{YKA_2 [2g(P_1 - P_2)]^{1/2}}{(\rho)^{1/2}}$$

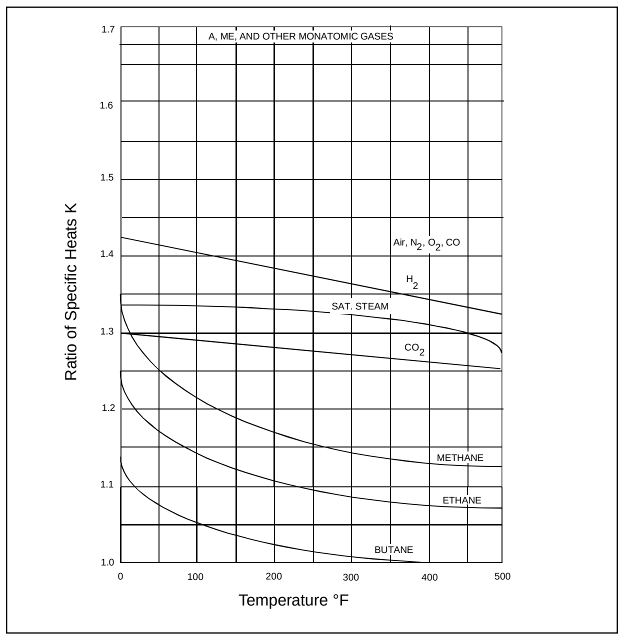


FIGURE 3 Ratio of Specific Heats

It is necessary to use the expansion factor when the density of a gas is substantially less downstream than it is upstream of the orifice. The expansion factor is determined by the ratio of the differential pressure across the orifice over the ratio of specific heats times the upstream static pressure. Figures 3 and 4 show the ratio of specific heats for selected gases and their expansion factors.

Because the expansion factor is affected by the differential pressure across the orifice plate, it will vary throughout the operating range of the meter. To minimize the effect of the variation in Y, it is best to keep the maximum differential pressure less than 2% of the upstream static pressure, P_1.

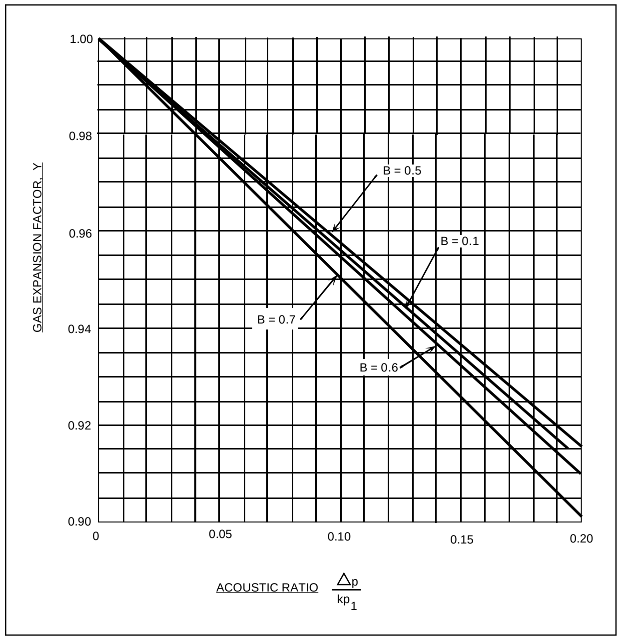


Figure 4 Expansion Factors

APPLICATION OF ORIFICE EQUATIONS

In its simplest form, the orifice equation for liquids can be reduced to:

$$Q_{act} = \frac{K' [P_1 - P_2]^{1/2}}{[\rho]^{1/2}}$$

where $K' = KA_2[2g]^{1/2}$

This form is commonly encountered when metering a liquid. If the liquid has a constant density, then the density can be combined with K' and the flowrate is only dependent on the differential pressure produced across the orifice.

For gases and steam, density is usually calculated at the operating conditions and will be used to calculate flowrate. In many applications, the expansion factor will be assumed to be unity, so it will have no effect on the equation. If a value other than 1.0 is used for the expansion factor, it can be combined with K' to produce a new coefficient K', which is equal to YK'.

TYPES OF ORIFICE PLATES

The most common types of orifice plates are the square-edged concentric bore plates, eccentric bore plates, segmental plates and integral orifice assemblies.

The most common type of plate is the square-edged concentric bore orifice plate. As its name implies, this plate has the opening centered on the plate. This is the plate with the most readily available flow coefficients and is suitable for the majority of applications.

The eccentric bore plate also has a circular hole in it. For this type of plate, the hole is located near the top for liquids near the bottom of the pipe for gases. The purpose for the eccentric bore is to allow entrained gas to pass through

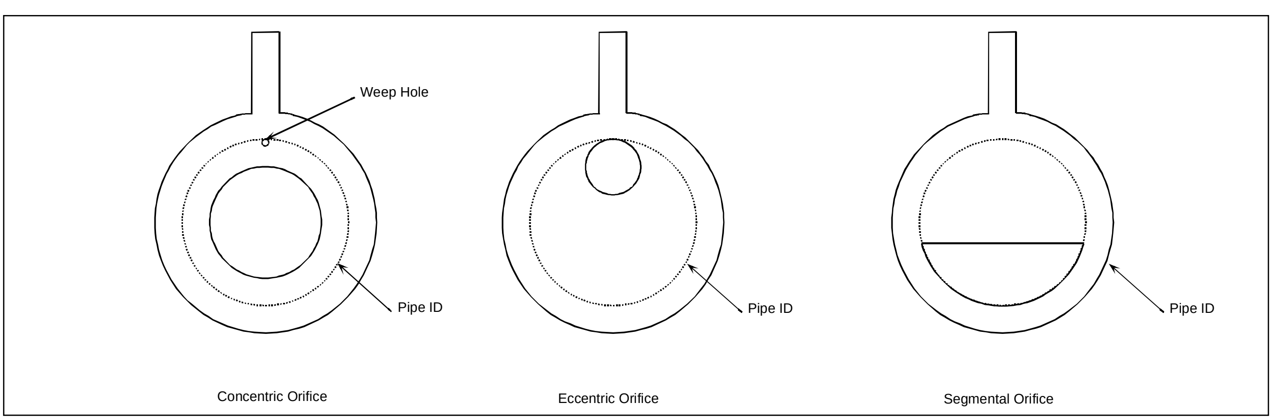


FIGURE 5 Common Orifice Plate Types

the opening when a liquid is being measured and to allow condensed vapors to pass through when a steam or gas is being metered. Typically, a concentric orifice plate with a vent or weep hole will be used for these applications. A vent hole is a small hole located along the top of the plate that allows entrained gases to pass through, while a weep hole is a hole along the bottom of the plate that allows condensed vapor to pass through.

The segmental orifice plate has an opening that is semi circular in shape and is used for liquids with suspended solids or a high concentration of entrained gas. Figure 5 shows the most common types of orifice plates.

The integral orifice is a special type of orifice. That is mounted directly to the differential pressure transmitter. The integral orifice is commonly used on smaller size lines and is often supplied with a calibrated meter run to improve the installed accuracy. Figure 6 shows an integral orifice assembly.

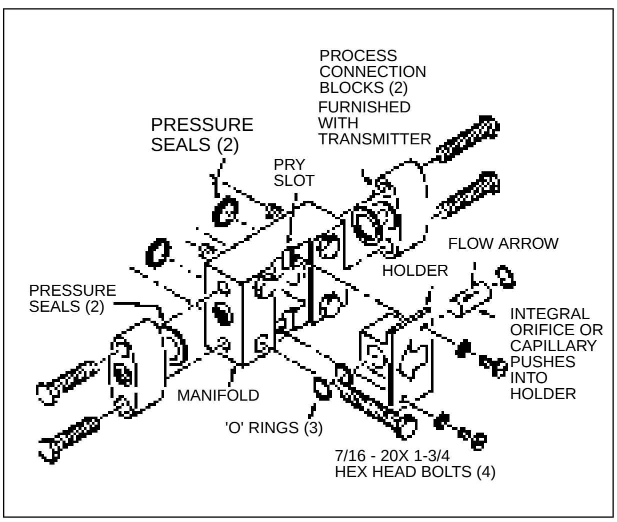


FIGURE 6 Integral Orifice Assembly

WEIRS AND FLUMES

WEIRS

Weirs are apertures in the top of a dam across a channel through which flows the liquid to be measured (Figure 7). The aperture may be rectangular (Figure 8), trapazoidal (Figure 9), or a V-notch (Figure 10). The special case of a trapazoidal weir with wide slopes of 1:4 (Figure 9) is known as a Cippoletti weir, this form leads to a simplified flow equation. V-notch weirs have an angle of 30° to 90°, depending on the required flow capacity.

As shown in Figure 7, the head, H, is measured as the difference in the level of the pool at an adequate distance upstream from the weir compared to the horizontal crest of the rectangular or trapazoidal weir or the bottom of the V in the V-notch weir. The head is usually between 1" and 12".

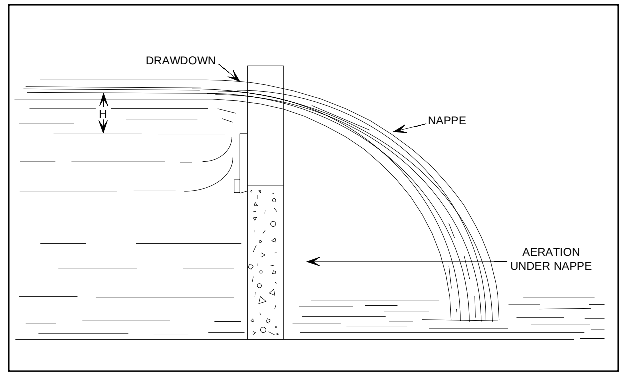


FIGURE 7 Flow Over a Weir

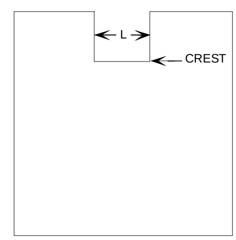


FIGURE 8 Rectangular Weir

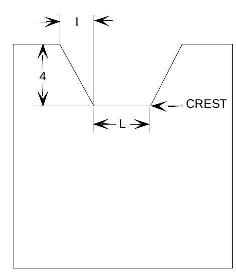


FIGURE 9 Cippoletti (Trapezoidal) Weir

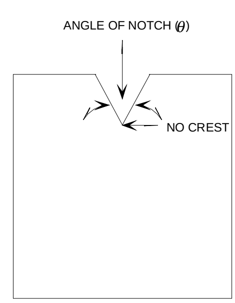


FIGURE 10 V-Notch Weir

The formulas for these weirs are as follows:

Rectangular weir

$$Q = 1494.61*(L-0.2H)H^{1.5}$$

Cippoletti (trapazoida) weir

$$Q = 1511.21*L*H^{1.5}$$

V-notch weir

$$Q = 1113.1*\tan(/2)*H^{2.5}$$

Q in GPM; L & H in Ft.

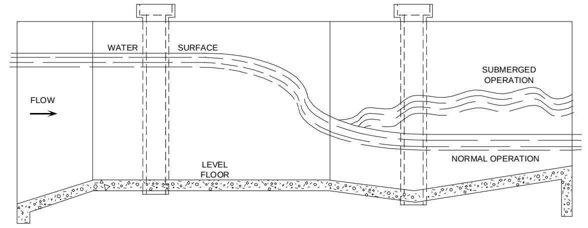
V-notch weirs are used for lower flows while rectangular and Cippoletti weirs are used for higher flows. For example, a 30° angle V-notch weir will generate a head, H, of 1.23" H_2O at 1 GPM and 12.03 H_2O at 300 GPM; and a 90° angle V-notch weir will generate a head, H, of 1.38" H_2O at 5 GPM and 12.05 H_2O at 1125 GPM. A Cippoletti weir with a crest length of 12" will generate a head, H, of 1.07" H_2O at 40 GPM and 12.05 H_2O at 1520 GPM.

In order to achieve the $\pm$2% to 4% accuracy that these devices are capable of delivering, there are some installation requirements that must be met. For example, the width and depth of the channel immediately ahead of the weir should be sufficient so that the wall effect of the bottom and sides of the channel has negligible effect on the pattern of flow through the notch. It is important that the flow should break clear form the sharp edge of the notch with an air pocket maintained immediately beyond and below the weir plate. In additon, the channel downstream from the weir must be sufficiently wide and deep so there is an ample clearence between flow through the notch to downstream liquid level so that the air pocket is maintained at maximum flow (Figure 7). The upstream edge of the weir should be sharp and straight. It is usual practice to bevel the downstream edge of the weir at 45° to about 1/32 inch edge. For rectangular and Cippoletti weirs, the crest must be carefully leveled.

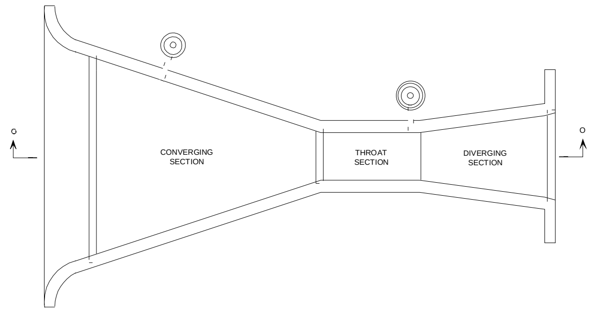
FLUMES

A flume is a device to measure open channel flows. Unlike the weir, the flow in a flume is not dammed. Thus the head loss of a flume is about one quarter of an equivalent capacity weir. Head loss is the amount of pressure lost in making the flow measurement and is usually expressed as a percentage of the pressure generated by the flow primary. Head loss varies with the type and design of flow primary used to generate the pressure. The most popular flume design is a Parshall flume, which is a special shape venturi flume. The relatively high velocities in the system tend to flush away deposits of silt and other solids that accumulate and alter the measurement. The design has no sharp edges, pockets, or crevices and has few critical dimensions. Unlike weirs, Parshall Flumes do not require a large upstream stilling basin. In fact, the head is measured in the converging inlet section of the flume (Figure 11).

The accuracy of a Parshall flume is 3 to 5% with minimal maintenance and good repeatability. Downstream level has no effect on the measurement as long as the level at the downstream end of the throat does not exceed 70% of the level measured at the input converging section (Figure 11).



Parshall Flume (SECTION 0 - 0)



Parshall Flume (Plan)

FIGURE 11

For flumes with a throat less than 1 ft. wide, a ratio of 60% is preferred. This is the mode of operation that provides the best accuracy. It also only requires a single level measurement at the input converging section of the flume to provide a measurement of the flowrate.

Where operating conditions (available head, maximum flowrate, throat size, etc.) result in a throat level that exceeds the desired level, so-called submerged operation results. Measurement can be obtained with a downstream throat level as high as 95% of the upstream level. However, this requires a correction factor based on upstream and downstream levels in the flow computation, and accuracy suffers. The simplified equations for a Parshall flume based on normal operation are as follows:

For L=0.25 ft

$$Q= 1781.86* L*H^{1.547}$$

For L=0.5 ft

$$Q= 1849.18*L*H^{1.58}$$

For L=0.75 ft

$$Q= 1840.21*L*H^{1.53}$$

For L=1 to 8 ft

$$Q= 1795.32*L*H\wedge(1.522*(L)^{.026})$$

Q in GPM; L & H in Ft

Throat Size	Min Flow	Min Head	Max Flow	Max Head
3"	13.5 Gpm	1.25" H_2O	494 Gpm	12.83" H_2O
6"	22.4 Gpm	1.14" H_2O	1750 Gpm	17.97" H_2O
9"	40.4 Gpm	1.19" H_2O	3950 Gpm	23.86" H_2O
12"	157 Gpm	2.42" H_2O	7225 Gpm	29.96" H_2O
24"	296.2 Gpm	2.26" H_2O	14855 Gpm	31.03" H_2O

As you can see, the above equations are beyond the capability of most pressure transmitter. However, if the transmitter had a characterized output function, one could solve for the head generated over the flow range of interest by using the formulas above. The XTC can measure the level and the equations would be solved in a secondary device, such as a controller.

PRESSURE TAPS

Pressure taps are located upstream and downstream of the orifice plate. They provide the measuring points for the differential pressure transmitter. Common types of taps include corner taps, flange taps, full flow (or pipe) taps, radius tapes, and contracta taps.

Corner taps are located within the orifice flanges and sense the pressure on the upstream and downstream faces of the orifice plate.

Flange taps are also located in the orifice plates and sense the pressure 1 inch upstream and 1 inch downstream of the orifice plate. Both corner and flange taps have the benefit of being integral to the flanges. As such, they don't neccessitate any additional penetrations to the pipe.

Full flow taps are located 2.5 diameters upstream of the orifice plate and 8 diameters downstream of the orifice plate.

Radius taps are located 1 diameter upstream and 0.5 diameters downstream of the orifice plate.

Vena contracta taps are located 1 diameter upstream of the orifice and at the point downstream where there is the lowest static pressure, the vena contracta. The point downstream where the pressure is the lowest is dependent on the type of orifice plate and the beta ratio. Figure 12 shows the location of the various taps, while Table 1 shows the values for these locations.

The discharge coefficient is dependent on the type of orifice and the tap location.

When dealing with flowmeters, this constant is most often referred to as the K factor. The K factor is typically given in units of pulses/gallons. The constancy of the K factor is what determines the accuracy of the flowmeter.

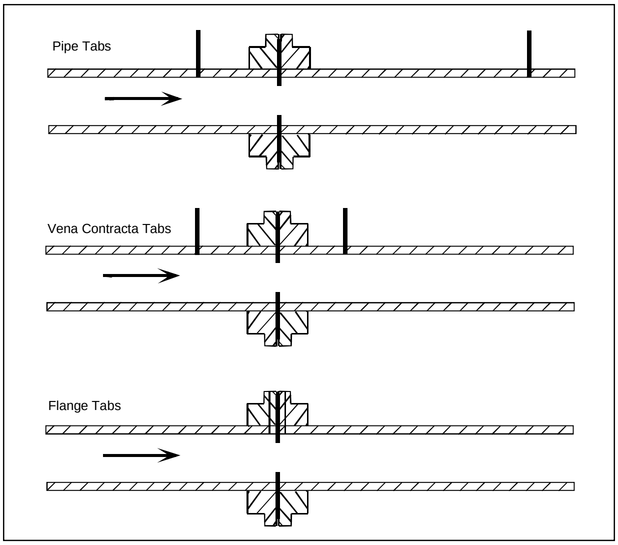


FIGURE 12 Tap Locations

TABLE 1 Location of Various Pressure Taps

Tap Type	Upstream	Downstream	Application
Flange	1"	1"	2" pipes or larger
Vena Cont	1 D	Vena Cont.	Steam Application
Full Flow	2 1/2 D	8 D	
Radius	1 D	0.5 D	Similar to Vena Contracta
Corner	0 D	0 D	pipes less than 2"

PITOT TUBES

The pitot tube was invented in 1732 to measure the flowing velocities of fluids. Pitot tubes detect the flowing velocity either at one point (standard), at several inlet points into an averaging probe (mutliple-ported), or at many points across the cross section of a pipe or duct (area averaging). Their advantages are low cost, low permanent head loss and the ability to insert the probe-type sensors (wet or hot tapped) into existing or operating pipes. Their disadvantages are low accuracy, low rangeability, and limitation to clean gas or liquid service, unless purged.

SIMPLE PITOT TUBE

In its simplest form, the pitot tube consists of a small open-ended tube that is parallel to the line of the flow (Figure 13).

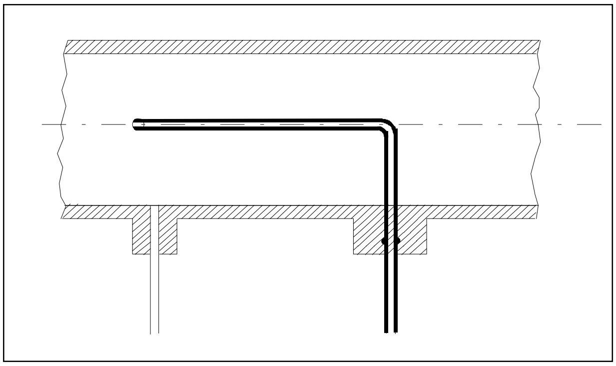


FIGURE 13 Simple Pitot Tube

The basic equation for the pitot tube is as follows:

$V_p = (P_t - P)^{1/2} * C/\rho$

V_p = approach velocity at the probe location, ft/sec

P_t = Total Pressure measured by the probe, lb/ft^2

P = Static Pressure in the line, lbf/ft^2

C = is adimensional constant,

ρ = fluid density, lbm/ft^3

Thus the velocity is directly proprotinal to the square root of the pressure difference. In order to use this simple pitot tube to measure the total flow in the pipe, a careful traverse at several points across the pipe to determine the true average velocity is required. If the velocity measured by the pitot tube is not the average velocity, a substantial error in flow indication will result. This error cannot be easily eliminated, because even if the pitot tube insertion is careully set to measure the average velcoity under one set of conditions, it will still be incorrect as soon as flow velocity changes.

MULTIPLE OPENING PITOT TUBES (ANNUBARS)

One approach to overcoming the inherent limitatin of the single port pitot tube (that of being a point velocity sensor) was to measure the velocities at several points and average these readings. It is argued that by averaging the velocities at four or more points, changes in the velocity will be detected, and therefore, the reading of a multiple opening pitot tube will be more accurate than the single tube (Figure 14). The manufacturers of the averaging pitot usually claim that the flow coefficient will be within 2% for Reynolds numbers from 50,000 to 1,000,000. This is probably so, but critics of this technology claim it might not be attributable to averaging action, but rather to the fact that in this highly turbulent region the velocity profile is flat and changes very little.They argue that it offers little improvement over the single port pitot tube because it is ineffective at Reynolds numbers below 50,000, making it unsuitable for some industrial flows.

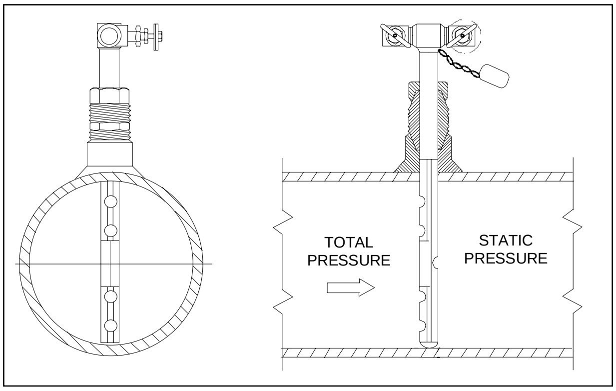


FIGURE 14 Multiple Port Pitot Tube (Annubar)

AREA-AVERAGING PILOT STATIONS

For the measurement of large volumes of low pressure gas flows, such as the detection of combustion air to boilers or air flow to dyers, area averaging pitot stations have been designed. These units are available with circular or rectangular cross sections (Figure 15) and can be mounted in large pipes or ducts, including the suction or discharge of fans. These stations are designed so that one total pressure port and one static port is located in each unit area of the duct cross section, and each is connected to its own manifold. The manifolds act as averaging chambers and may be purged to prevent individual ports from plugging.

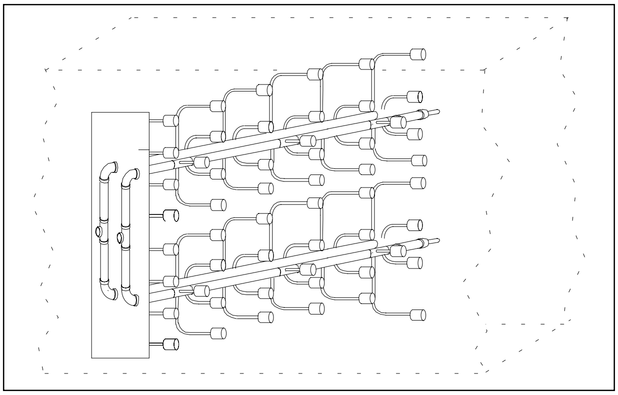


FIGURE 15 Area Averaging Pitot assembly

VENTURI TUBES, FLOW TUBES, AND FLOW NOZZLES

Venturi tubes, flow tubes, and flow nozzles, like all differential pressure flow producers, are based upon Bernoulli's theory. They operate on the principal of a high pressure in the low velocity, large diameter inlet section compared to a low pressure in a high velocity, smaller diameter throat section. General performance and calculations are similar to those for orifice plates except for the fact that they operate over a wider dynamic range and are more efficient differential pressure producers and have far less permanent head loss than orifice plates. The meter coefficient (C_d) for these devices is between 0.98 and 0.99 compared to orifice plates that average about 0.62. Thus, almost 60% (98/62) more flow can pass through these elements for the same differential pressure. The working equation for these devices varies by device and manufacturer, but it has the following form:

$$Q = K*d*C_d*(h)^{1/2}/(1- \rho^4)^{1/2}*(\rho)^{1/2}$$

- Q = flow
- K = A dimensional constant
- d = Throat diameter
- C_d = Discharge coefficient varies with type and manufacturer
- h = Differential pressure
- β = Ratio throat diameter to inlet diameter --d/D
- ρ = Density of fluid

THE ORIGINAL CLASSIC VENTURI TUBE

The venturi as designed by Clemens Herschel in 1987 and described in the ASME handbook entitled Fluid Meters is shown in Figure 16. It consists of a cylindrical inlet section equal to the pipe diameter; a converging conical section in which the cross sectional area decreases causing the velocity to increase and the pressure head to decrease; a cylindrical throat section where the velocity is constant so the decrease pressure head can be measured; and a diverging recovery cone where the velocity decreased almost all of the original pressure head is recovered. The unrecovered pressure head is commonly called head loss.

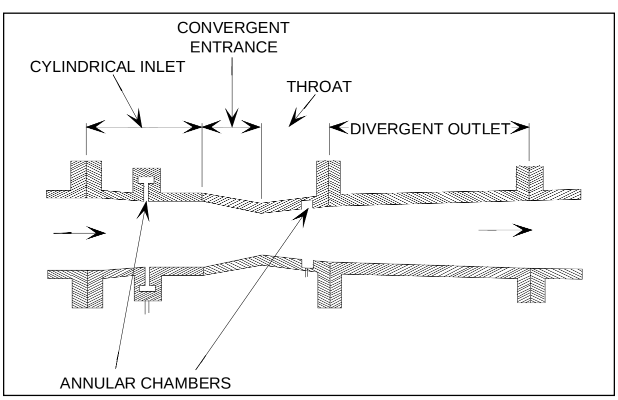


FIGURE 16 Classic Herschel venturi

In the original venturi, pressure is sensed as pure static pressure via annular chambers in the inlet and throat. Sensing the pressure where it is parallel to the pipe wall and perpendicular to the pressure tap is known as a static pressure tap, because the flow is not changing direction where the pressure is being sensed. This maximizes the accuracy of the flow measurement, because the exact area of the flowing fluid is known at the point of pressure measurement. The design of these original annular chambers limited the use of the venturi to clean, noncorrosive liquids or gases because it is impossible to clean out or flush out the pressure taps if they become clogged with dirt or debris. The flow coefficient of the original venturi was 0.984 with an uncertainty of 0.75% of rate.

THE SHORT FORM VENTURI TUBE

In an effort to reduce costs and laying length, manufacturers developed a second generation or short form venturi (Figure 17). There were two major differences in this design. The internal annular chambers were replaced by a single static pressure tap, or in some designs, an external pressure averaging chamber, and the recovery cone angle was increased from 7° to 21°. The flow coefficient of the short form venturi was 0.985 with an incertainty of 1.5% of rate.

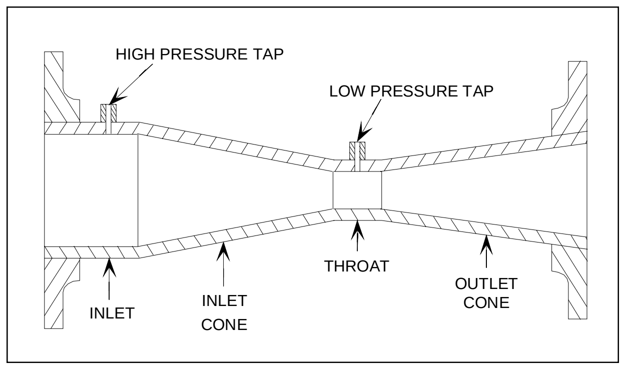


FIGURE 17 Short form venturi

FLOW TUBES

There are many proprietary designs of head type flow primaries that have been developed in the last 25 years. They are all considerably more compact than the classical venturi with its long recovery cone, although the short form venturi is almost as compact as some of these units. The flow coefficient of these tubes ranges from 0.980 for an all static tap, "near true venturi" design to 0.750 for an all corner tap "flow tube" design. A corner tap senses pressure in a section the velocity is changing direction and is not parallel to the pipe wall nor perpendicular to the pressure tap. Thus, the accuracy of the flow measurement is affected because the exact area of the flowing fluid is not known at the point of pressure measurement. In addition, accuracy can also vary with flowrate. Some of the representative designs are shown in Figure 18. They vary in internal contour used, type of pressure tap, differential pressure generated, and head loss for a given flow. All have a laying length less than 4 diameters long, the shortest being the all corner tap designs (which are 2.5 diameters long). All of these designs generate higher pressures and have lower head loss than the classic venturi (Figure 19).

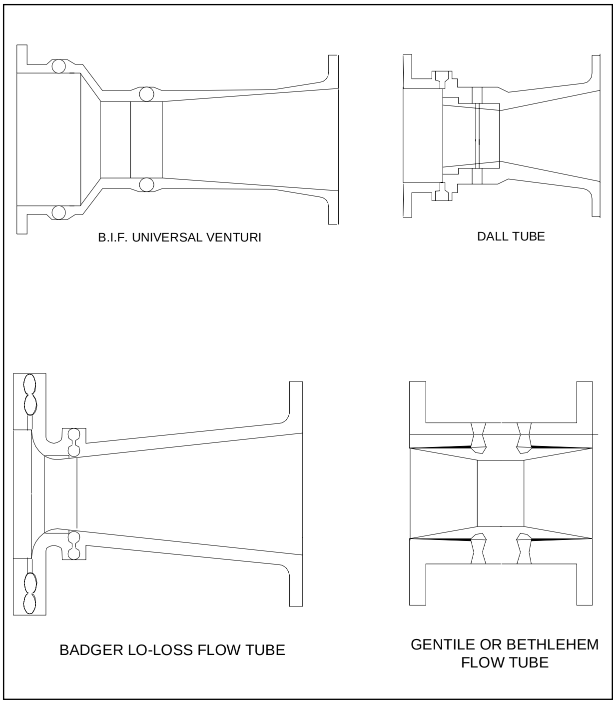


FIGURE 18 Different flow tube designs

The accuracy claimed for these devices ranges from 0.5% of rate for the all static tap designed to 1% to 2% of rate for the all corner tap design for Reynolds numbers above 100,000. The static tap designs will be accurate over a wide dynamic range of flow 50:1 to 100:1, while the corner tap designs are more limited 10:1 to 20:1 before losing accuracy.

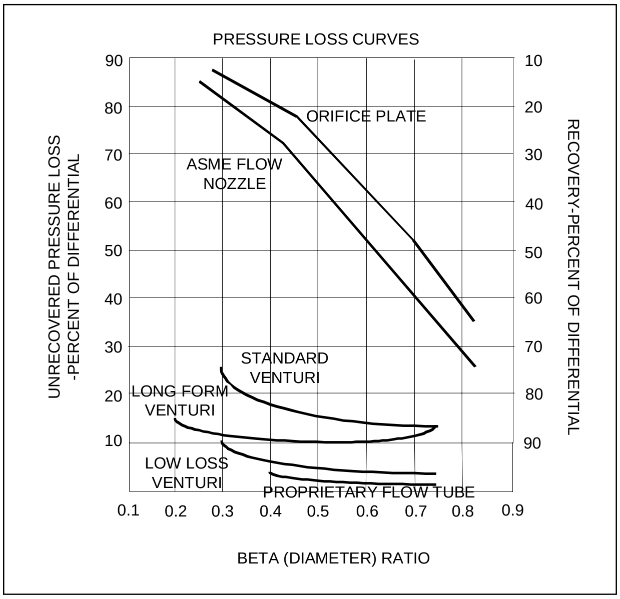


FIGURE 19 Head Loss Comparison

EXAMPLES OF FLOW CALCULATIONS

The manufacturer of the flow primary will usually specify the DP generated by the device for a given flow. The equation relating flow to DP for any square law primary is as follows:

$$(Q_{known})^2/(Q_{unknown})^2 = DP_{known}/DP_{unknown}$$

Let's look at an example--

Suppose a 4" venturi is rated to generate 100" H_2O at 345 GPM. What would the DP be at 400 GPM?

$$DP_{unknown} = DP_{known} * (Q_{unknown})^2/(Q_{known})^2$$
$$= 100''*(400)^2/(345)^2$$
$$=134.43''\ H_2O$$

Suppose for the same venturi we measure 73" H_2O with a gauge. What is the flowrate?

$$Q_{unknown} = Q_{known}*(DP_{unknown}/DP_{known})^{1/2}$$
$$= 345*(73/100)^{1/2}$$
$$= 294.77 \text{ GPM}$$

REYNOLDS NUMBER

The Reynolds number (R_d) is the ratio of the inertia forces of a flowing medium to the shear or frictional forces, and is used to describe the operating range of many flowmeters. It may be calculated using the following formulas:

For liquid flow:

$R_d = 50.6*Qp/D*$

$R_d = 3157*Q/D$ For Water @ 60°F

Q = GPM

ρ = density in lb/ft^3

D = Inside diameter in inches

μ = Viscosity in centipoise

For gas flow:

$R_d = 6.32*Q*p/D*$

Q = flow rate in scfh, (std cu. ft. per hr)

ρ = density at standard conditions in lb/ft^3

D = Inside diameter in inches

μ = Viscosity in centipoise

OSCILLATORY FLOWMETERS

Oscillatory Flowmeters utilize specially designed geometric shapes to create an environment where self induced, sustained oscillations will occur. Oscillating flowmeters are inherently digital devices, that is, the basic measurement they read is a frequency. In a properly executed flowmeter, the frequency of its oscillations is proportional to volumetric flowrate. There are several categories of oscillatory flowmeters, each with a unique shape.

For a flowmeter to be useful, there must be an accurate and repeatable relationship between its method of measurement and the flow of liquid through it.

VOLUMETRIC FLOWRATE VS. FREQUENCY

For any point in the operating region of the flowmeter, the frequency of oscillation will be related to the volumetric flowrate by the following equation:

$$F = KQ$$

where F is the frequency of oscillation

K is the calibration factor of the meter

Q is the volumetric flowrate

K FACTOR

It has been found that the K factor of oscillatory meters vary with Reynolds number. Because of this, it is convenient to plot the K factor versus the Reynolds number. If the meter were perfect, it would have a constant K factor at the Reynolds numbers, but this is not the case. All oscillatory meters exhibit a K factor curve that look similar to Figure 20.

How well the actual meter performs is a function of the design of the meter as well as the influence of the fluid flowing through it. There is a region on the curve where the K factor is essentially constant. This is the normal operating region for oscillating flowmeters. In this region, the accuracy is good enough to be stated as a percent of instantaneous flowrate.

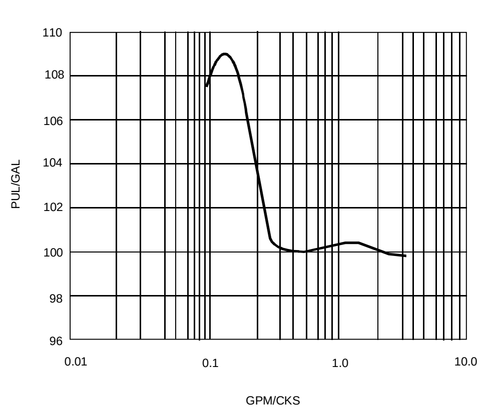


FIGURE 20 K Factor vs. Reynolds Number

COANDA FLOWMETERS

Coanda flowmeters are based on a phenomenon first observed in 1910 by Henri Coanda. Later in 1932, Coanda did further research and quantitized the phenomenon. Coanda discovered that as a free jet emerges from a nozzle or a conduit, it will tend to follow a nearby surface and will, in fact, attach to it.

The attachment to a surface is a result of a low pressure region that develops between the free stream and the wall. As the free stream moves past the wall, some of the fluid in that region will be entrained by the main stream. This causes the pressure in the region to decrease. As a result, the pressure in that region will begin to decrease. Because of this pressure differential, the free stream begins to deflect towards the wall. As more fluid is carried along with the main stream, the jets divert more and more to the wall unit it attaches to it.

The geometric shape of the Coanda flowmeter produces a continuous, self-induced oscillation at a frequency that is linearly proportional to flowrate. As fluid passes through the meter, it will attach itself to one of the side walls as a result of the Coanda effect. A small portion of the flow is diverted through the feedback passage and travels around to the control port. This feedback flow disrupts the attachment of the main jet to the side wall. The main jet is now free and will attach itself to the other side wall due to the Coanda effect. The feedback action will repeat itself, and in this manner the meter body produces a sustained oscillation. As the main fluid stream oscillates between the two side walls, the flow in the feedback passages cycles between zero and maximum. The cycling of the flow in the feedback passages is detected by a sensor located in one of the feedback passages, while the sensor signal is conditioned by a signal conditioner. Figure 21 shows the cross section of a Coanda flowmeter.

Momentum Exchange Flowmeters

Momentum Exchange flowmeters are based on the fluid phenomenon of momentum exchange. The momentum exchange flowmeter is similar to the Coanda flowmeter, but differs in the mechanism used to produce oscillations.

The geometric design of the momentum exchange meter body produces a continuous, self-induced oscillation at a frequency that is linearly proportional to volumetric flowrate.

The fluid oscillations are developed by the fluidic phenomenon of Momentum Exchange (MX). The geometric shape of the meter body creates a main flow of fluid, which passes through the nozzle, and is directed toward one side of the meter body or the other. The force of the jet of fluid will create a flow pulse in a feedback passage. This flow pulse will travel through the feedback passage and exert a force on the main jet. The momentum of the feedback fluid will deflect the main flow in such a manner that it will exert a force on the fluid in the other feedback passage, while the feedback action is repeated and results in a sustained oscillation. The sensor located in the feedback passage detects the fluid pulses, and the sensor signal is conditioned by a signal conditioner. Figure 22 shows the cross-section of a momentum exchange flowmeter.

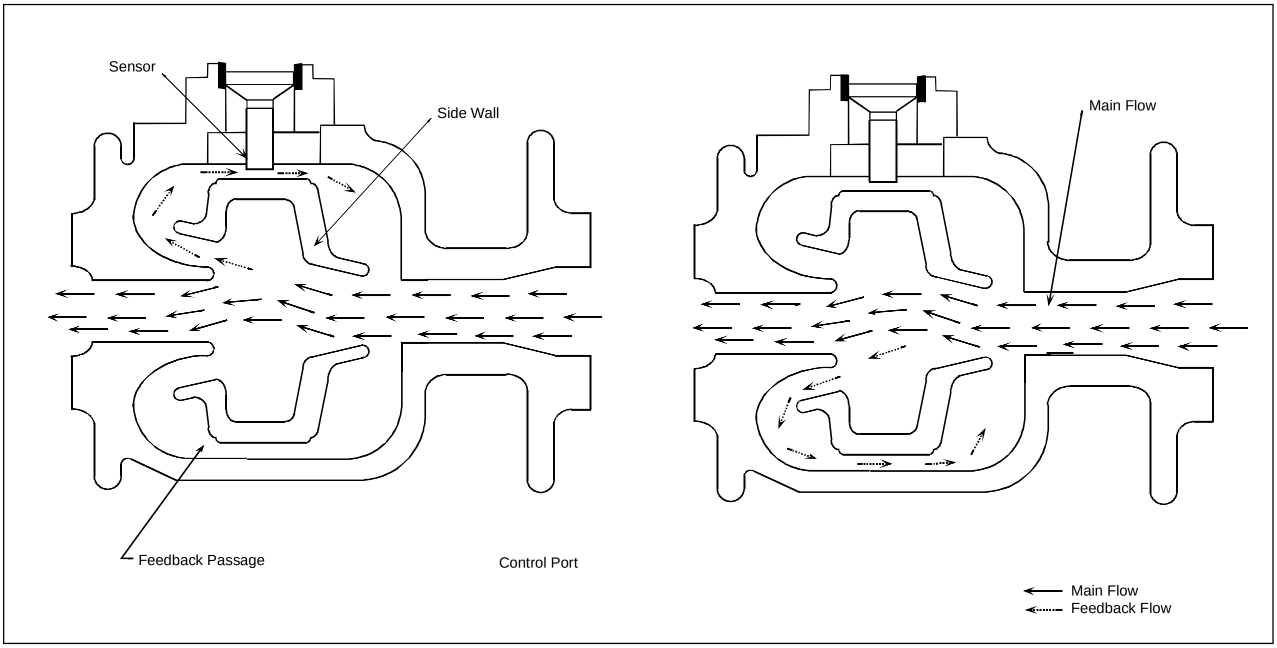


FIGURE 21 Cross-Section of a Coanda Flowmeter

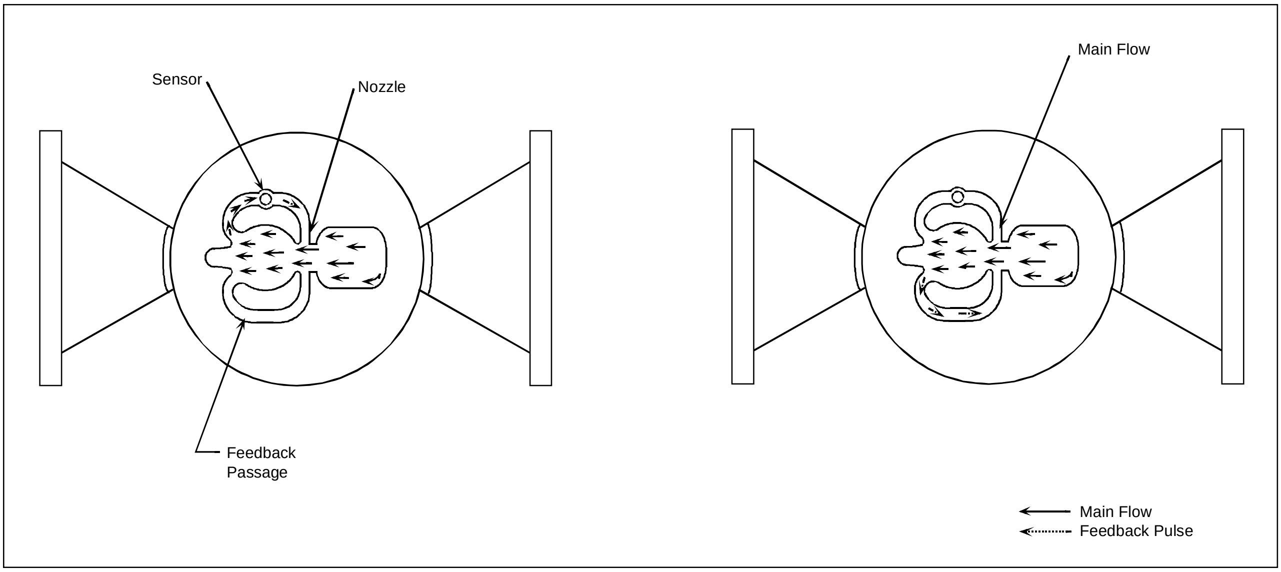


FIGURE 22 Cross-section of a Momentum Exchange Flowmeter

MAGNETIC FLOWMETER

Magnetic flowmeters are one of the most versatile flowmeters available today. They can measure the flowrate of any conductive liquid and provide no obstructions to the flow path. Magnetic flowmeters are available in a wide variety of materials that are corrosion resistant. Their corrosion resistance and obstructionless path make them ideal solutions for harsh liquids containing solids, such as pulps and slurries.

PRINCIPLE OF OPERATION

Magnetic flowmeters are based on Faraday's Law of Electromagnetic Induction. Faraday's law states that when a conductor is moved through a magnetic field, a voltage will be produced that is proportional to the velocity of the conductor, the length of the conductor, and the strength of the magnetic field. Moreover, this voltage will be produced in a plane that is perpendicular to both the velocity vector and the magnetic field.

Faraday's law can be applied to a flowmeter. When used in a magnetic flowmeter, the velocity of the conductor (V) is the velocity of the fluid flowing through the flowtube. The length of the conductor (D) is the distance between the electrodes, (B) is the strength of the magnetic field generated by the coils, and (E) is the voltage produced between the electrodes. Figure 23 shows a schematic diagram of a magnetic flowmeter. Faraday's law, as it is applied to a magnetic flowmeter, reduces to:

$$E = k_1BDV$$

where E is the voltage between the electrodes

k_1 is a proportionality constant

B is the strength of the magnetic field

D is the distance between electrodes

V is the velocity of the fluid

It is desirable to express flowrate in volumetric units, so the measured velocity (V) must be converted. The conversion is based on this relationship:

$$Q = V \times A$$

where Q is volumetric flowrate

V is the velocity of the fluid

A is the area of the flowtube

(A) can be expressed in terms of (D),

$$A = PI*D^2/4$$

By substituting Q/A for V we get

$$E = k_2BQ/D$$

To produce standardized flowmeter performance, the value of E and Q are measured during the calibration at the factory and each meter is assigned its own k_2 (referred to as GK in our magnetic flowmeter). k_2 will be fairly consistent for any line size, but will vary slightly from meter to meter.

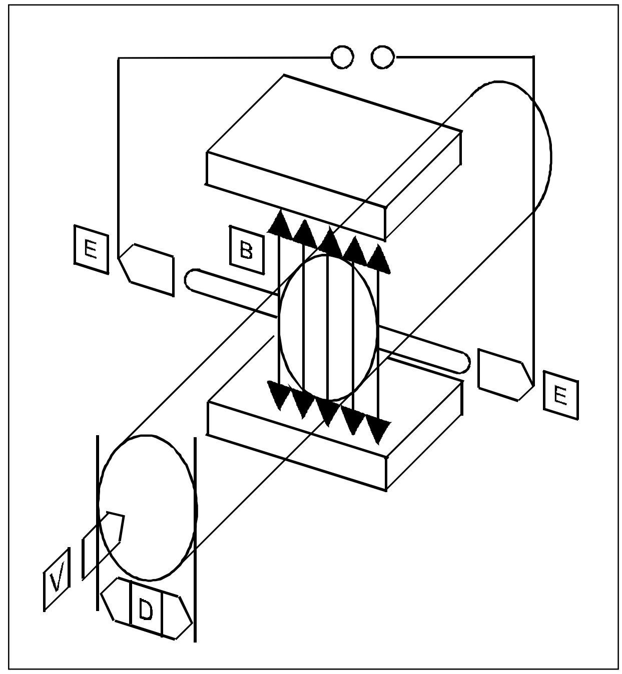


FIGURE 23 Schematic Diagram of a Magnetic Flowmeter

MAGNETIC FLOWMETER CONSTRUCTION

There are two basic components to a magnetic flowmeter; the primary and the secondary. The primary is the actual flowtube, which includes the pipe section with the coils and the electrodes. This is the portion of the meter subjected to the process conditions. The secondary is the transmitter. The transmitter can be integrally mounted on the primary or it can be remotely mounted away from the primary and the process.

FLOWTUBE

As mentioned before, the flowtube is the part of the magnetic flowmeter that is actually installed in the pipe. It contains the coils and the electrodes and its main function is to produce the voltage that is proportional to flowrate. Current is passed through the coils to produce the magnetic field. The flowtube must be made of nonconductive materials so as not to distort the magnetic fields.

The liner and electrode portions of the flowtube come into direct contact with the process fluid. Figure 24 shows the cross-section of a flowtube. Liners and electrodes are available in a variety of materials. The materials should be selected based on the application to provide the proper protection. Liners are usually selected based on the corrosion resistance, temperature, and pressure limits.

TRANSMITTER

Signal conditioning, data processing, and transmission are the principle operations of the transmitter. The transmitter provides the current to drive the coils in the flowtube and reads the voltage across the electrodes, then processes the

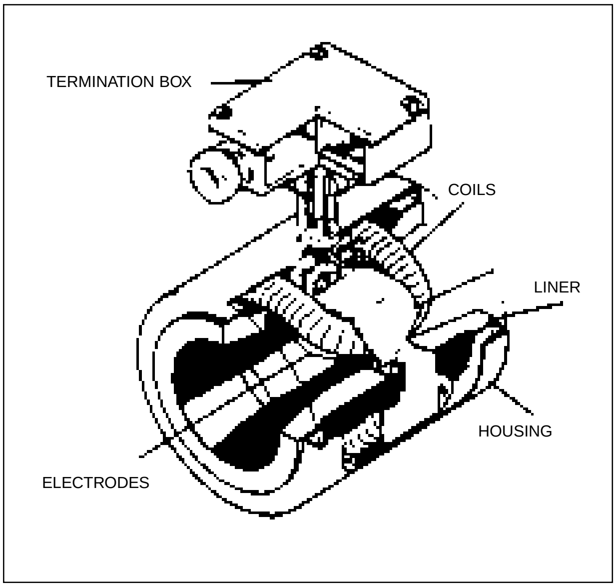


FIGURE 24 Cross-Section of Flowtube

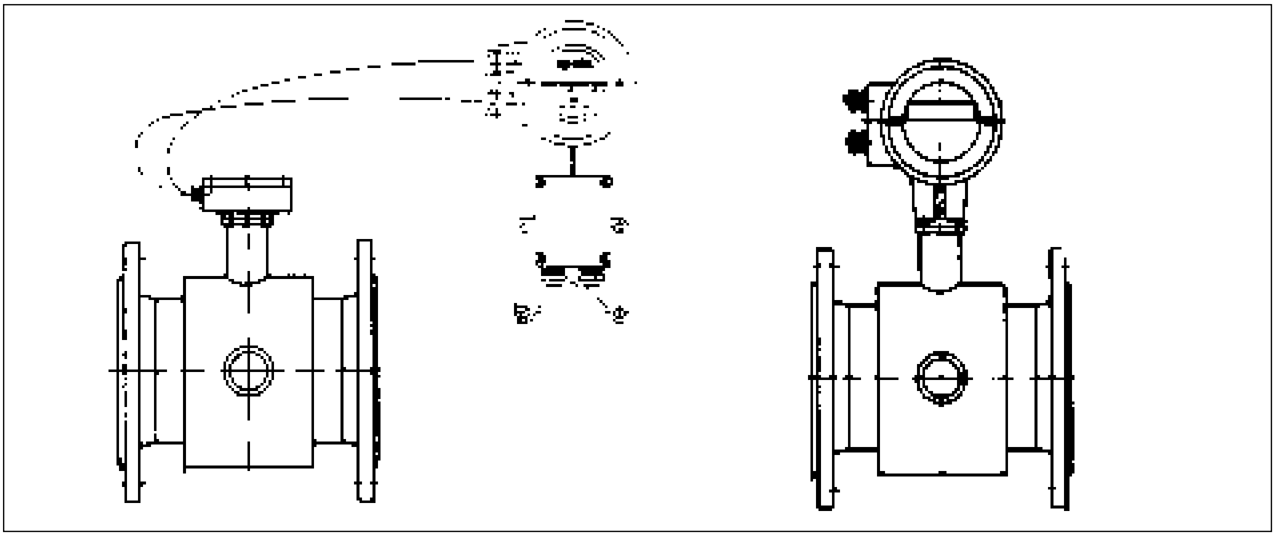


FIGURE 25 Transmitter Mounting Options

electrode voltage and calculates the volumetric flowrate. Transmitters provide both a current and frequency output.

The transmitter can be mounted integral to the flowtube or remotely. The integral mount option makes installation easier, because only one device must be installed. However, if the installation is in a difficult location, it is often desirable to mount the transmitter remote from the flowtube. A remote mount transmitter is more easily accessed. When the transmitter is remotely mounted, special signal cables must be used between the flowtube and the transmitter. Figure 25 shows the transmitter mounting options.

AC VS. DC MAGNETIC FLOWMETERS

The first magmeters to be introduced were what are called AC magnetic flowmeters. The current driving the coils was AC line current. While this worked well enough to allow magmeters to be used, there were several disadvantages to this approach. DC magmeters were introduced in the 70's, and they provide several improvements to their AC predecessors. AC magmeters are still requied in some applications.

OPERATION OF DC MAGNETIC FLOWMETERS

DC magnetic flowmeters power or excite the coils with pulsed DC current. When the current in the coil is turned on, it generates a magnetic field, which in turn, induces a voltage across the electrodes. The voltage on the electrodes is equal to the flow signal, plus the noise that is present. When the current is turned off, the voltage on the electrodes is equal to the noise only. Since the noise is measured with the second reading, it can be subtracted from the flow signal, next total is added to the noise reading to set the flow signal.

Because the noise is eliminated with every reading cycle, DC magnetic flowmeters inherently have a stable zero, making zero adjustments necessary. DC magnetic flowmeters eliminate zero shifts not only from noise, but also from electrode coating, and noise on the signal cable. DC magnetic flowmeter power and signal cables can be run in the same conduit. Figure 26 depicts the signal generated by a DC magmeter.

GROUNDING

Accurate flow measurement depends on proper grounding of the flowtube. With magnetic flowmeters, the fluid being measured acts as the electrical conductor. Consequently, the ground connection must ensure that measurements are not affected by any additional potential. The grounding conductor used must not transmit any interference voltages. The grounding wires supplied must be conductively connected to the primary head, the pipe flanges, and if applicable, the grounding rings.

GROUNDING RINGS

Grounding rings are required if the pipe is made of plastic or if it is internally coated. The purpose of the grounding ring is to make conductive contact with the fluid. There are several types of grounding rings available. They are:

Type 1 - General purpose

Type 2 - For flowtubes with PTFE liners. A grounding ring is recommended to protect the liner during transportation and installation.

Type 3 - In the case of abrasive fluid, this grounding is required to prevent damage to the liner.

Figure 27 shows the different types of grounding rings. When grounding rings are used, the installation dimension will increase.

APPLICATION CONSIDERATIONS

While magnetic flowmeters are one of the easiest flowmeters to use, there are still application considerations that must be considered.

AC or DC TYPE FLOWMETER

As discussed earlier, there are significant benefits to the DC style magnetic flowmeter over the AC style. However, there are several applications that require an AC magnetic flowmeter. The most frequently encountered applications that require AC magnetic flowmeters are:

- pulp stock over 4-1/2% consistency
- magnetic or magnetite applications
- fluids with nonconductive solids
- mining slurry
- low conductivity fluids
  < 5 umhos/cm general or
  < 20 umhos/cm water

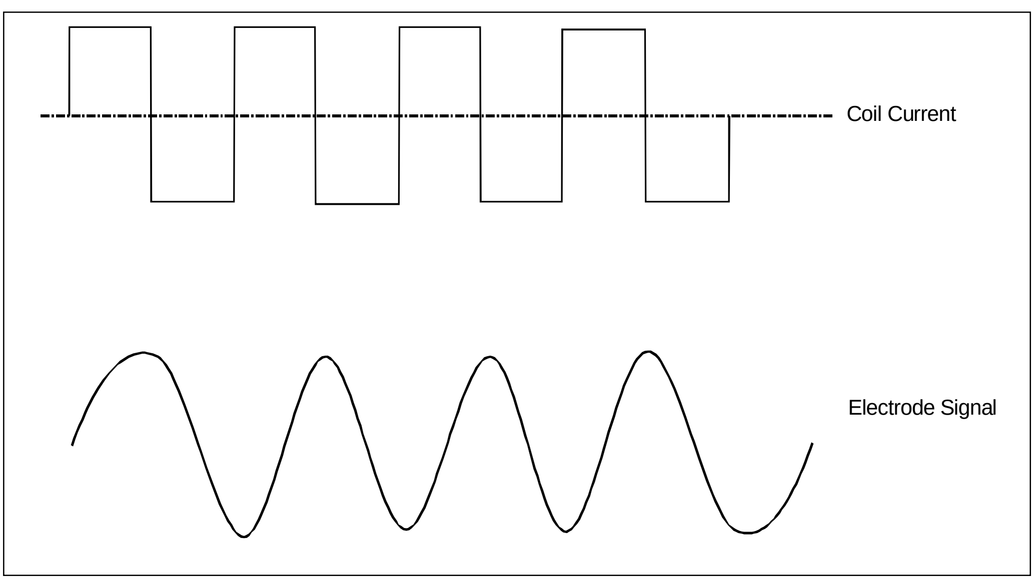


FIGURE 26 DC Magmeter Voltage Signal

CONDUCTIVITY

For magnetic flowmeters to work accurately, it is important that the fluid being measured has a minimum conductivity. Conductivity is inversely proportional to resistance, so a high conductivity is equivalent to a low resistance. Conductivity is typically expressed in microMHOS (*umhos)* or microsiemen (μS). There is a 1 to 1 relationship between *u*mhos and μS.

CORROSION

For any application, it is important that the materials of construction of the instrument are compatible with the process fluid. Ultimately, it is the responsibility of the user to specify the proper materials of construction.

LINERS

The choice of liner material is dependent upon several application related parameters. The most important parameters include corrosion resistance, abrasion resistance, maximum temperature, maximum pressure, and maximum vacuum. Table 2 shows the comparative performance of different liner materials.

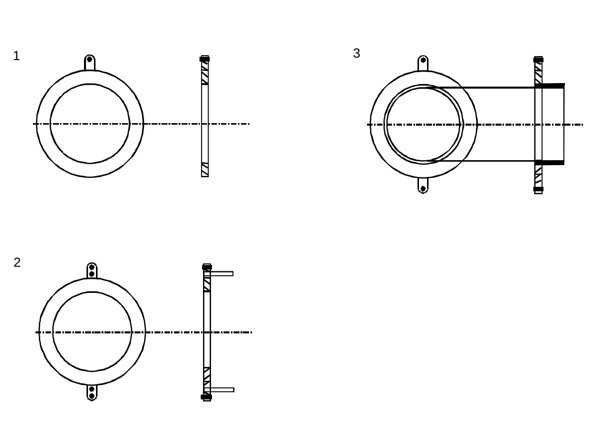


FIGURE 27 Types of Grounding Rings

TABLE 2 Relative Performance Characteristics of Liner Materials

LINER	Corrosion Resistance	Abrasion Resistance	Temp. Limit	Pressure Limit	Vacuum Limit
Al_2O_3	Highest	Highest	High	Low	Highest
PTFE	High	Low	Highest	Low	High
PFA	High	Medium	Highest	Low	Highest
Neoprene	Medium	Medium	Low	Medium	Lowest
H. Rubber	Low	Medium	Medium	High	Medium
Polyureth.	Lowest	High	Low	High	Low

Reference - *Flowmeters*