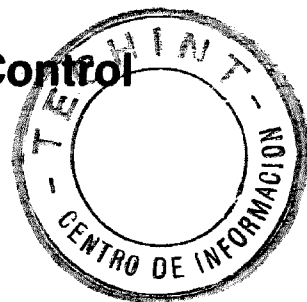


Manual on Installation of Refinery Instruments and Control Systems

Part I—Process Instrumentation and Control Section 1—Flow

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SECTION 1—FLOW

1.1 Scope

This section presents recommended practices for installing differential pressure instruments and area flowmeters. These meters are commonly used to indicate, record, transmit, and control fluid flow.

Flow measurement falls into two broad classifications: refinery process flow measurement and custody transfer. This section is primarily concerned with process flow measurement. Liquid custody transfer is normally done with positive displacement meters or turbine meters, usually combined with meter proving equipment. Custody transfer flow measurement [1, 2, and 3] is covered in Chapters 4, 5, and 6 of the *API Manual of Petroleum Measurement Standards*.¹

1.2 General

1.2.1 DIFFERENTIAL PRESSURE INSTRUMENTS

The differential-head type of instrument measures flow inferentially from the differential pressure caused by flow through a primary element. This differential pressure is sensed by diaphragms, bellows, or manometers. Transmitters of the force or motion type are either pneumatic or electronic. Electronic transmitters use strain gages, capacitance detectors, or other solid state detectors to provide output with minimal sensing element displacement.

Primary elements are generally one of the types described in 1.2.1.1 through 1.2.1.6.

1.2.1.1 Orifice

Orifices are usually thin concentric plates, but they may be eccentric, segmental, quadrant edge, or some other special form, depending upon their application.

1.2.1.2 Flow Nozzle

Flow nozzles are used in installations where higher velocity and moderately better pressure recovery are required than are obtainable with an orifice plate.

1.2.1.3 Venturi Tube

Venturi tubes are used in installations where high capacity and good pressure recovery are required or where the measured stream contains some solids.

1.2.1.4 Flow Tube

Flow tubes are used in installations where low pressure loss is a major consideration or where piping configurations are restrictive.

1.2.1.5 Pitot Tube

Generally, pitot tubes are used in installations where no appreciable pressure drop can be tolerated on high-volume flows, such as on cooling water. The accuracy of the measurement depends upon the determination of the average velocity from the velocity profile. An averaging pitot tube is also available.

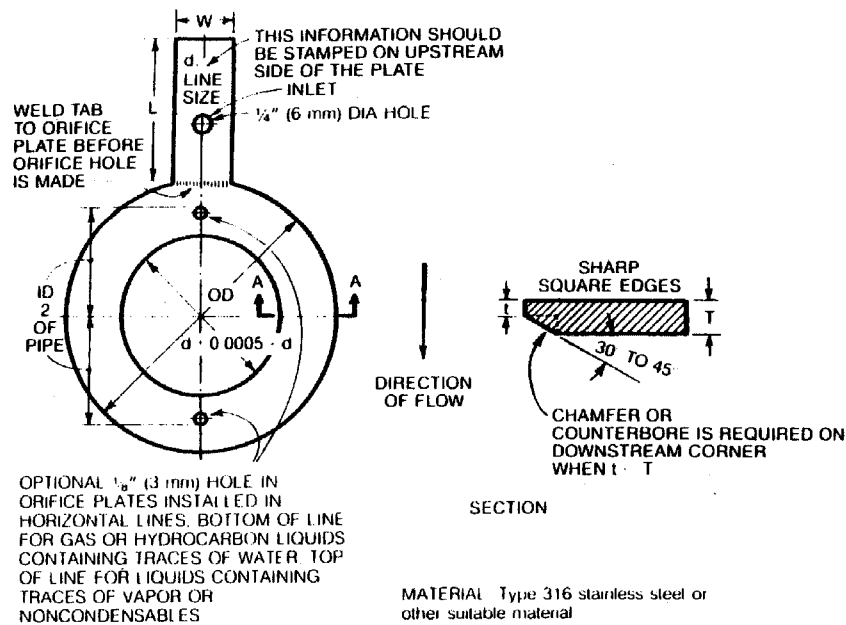
1.2.1.6 Elbow Taps

Elbow taps are used in installations where the velocity is sufficient and where high accuracy is not required [4]. Although they are less accurate than other differential pressure instruments, elbow taps possess good repeatability. A water velocity of 17 feet per second (5 meters per second) will produce a water differential of approximately 100 inches (2500 millimeters). Some test data are available [5, 6].

1.2.2 VARIABLE AREA FLOWMETERS

For refinery service, rotameters are the most commonly used meters in the area class.

¹Bracketed numbers indicate references to be found on pages 27 and 28.



Orifice Plate Outside Diameters to Fit ANSI Service Rated Flange Unions

Nominal Pipe Size	T	t	CLASS					TAB	
			300	600	900	1500	2500	L	W
2	1/8	1/32	4 3/8	4 3/8	5 5/8	5 5/8	5 3/4	4	3/4
3	1/8	1/32	5 7/8	5 7/8	6 5/8	6 7/8	7 3/4	4	3/4
4	1/8	1/16	7 1/8	7 5/8	8 1/8	8 1/4	9 1/4	6	1
6	1/8	3/32	9 7/8	10 1/2	11 3/8	11 1/8	12 1/2	6	1
8	1/8	1/8	12 1/8	12 5/8	14 1/8	13 7/8	15 1/4	6	1
10	1/4	3/16	14 1/4	15 3/4	17 1/8	17 1/8	18 3/4	6	1
12	1/4	7/32	16 5/8	18	19 5/8	20 1/2	21 5/8	6	1
14	1/4	7/32	19 1/8	19 3/8	20 1/2	22 3/4		6	1
16	3/8	9/32	21 1/4	22 1/4	22 5/8	25 1/4		6	1
18	3/8	9/32	23 1/2	24 1/8	25 1/8	27 3/4		6	1
20	3/8	3/8	25 3/4	26 7/8	27 1/2	29 3/4		7	1
24	3/8	3/8	30 1/2	31 1/8	33	35 1/2		7	1

NOTES:

1. All measurements in inches.
2. The outside diameter (OD) of the orifice plate is that required to fit inside the bolts of standard ANSI flanges. The outside diameter is equal to the diameter of bolt circle minus the nominal diameter of bolt, within a manufacturing tolerance of +0 inches, -1/32 inch (+0 millimeters, -8 millimeters).
3. For orifice plate outside diameters in flange sizes and ratings not listed above, refer to gasket OD dimensions given under Figure 3, Table 1, Appendix E in ANSI B 16.5—1981, *Steel Pipe Flanges and Flanged Fittings*, available from the American Society of Mechanical Engineers, 345 East 47th Street, New York, New York 10017.
4. The upstream face of the orifice plate shall be as flat as can be obtained

commercially; any plate departing from flatness along any diameter more than 0.010 per inch (.25 millimeters) of diam height, $(D-d)/2$, shall be unacceptable. Surface roughness shall not exceed 50 microinches in a band at least 0.25 diameter wide around the orifice bore.

5. All seating surfaces for spiral-wound gaskets should be clean and free of rust, burrs, nicks, and so forth. Any surface not meeting the following tolerances should be relapped:

- (a) Roughness: Should not exceed 80 root mean square with 63 root mean square or better as optimum.
- (b) Flatness: Out-of-plane tolerances must not exceed 0.0025 inch (0.06 millimeter). The cumulative out-of-flatness for two mating surfaces shall not exceed 0.0040 inch (0.1 millimeter).

Figure 1-1—Concentric Orifice Plate

1.2.3 FORCE OR TARGET FLOWMETERS

Force or target flowmeters measure flow inferentially by measuring the force developed at a disk-shaped target suspended in the flow path.

1.2.4 TURBINE FLOWMETERS

Turbine meters measure flow from the rotation produced by the flow past a turbine or propeller.

1.2.5 ELECTROMAGNETIC FLOWMETERS

If a fluid has some degree of electrical conductivity, an electromagnetic flowmeter can measure its average flow velocity inferentially from the voltage generated by the fluid as it moves through a magnetic field.

1.2.6 POSITIVE DISPLACEMENT METERS

This meter measures flow by isolating, counting, and totaling segments of known volume as they are displaced through its body [1].

1.2.7 VORTEX SHEDDING FLOWMETERS

Vortex meters are oscillatory flowmeters that utilize the vortex train generated by an obstruction placed in a fluid stream. They measure flow by counting the vortices.

1.2.8 SONIC FLOWMETERS

There are two main classes of sonic flowmeters. Contrapropagating meters measure the difference in the transit times of sounds transmitted upstream and downstream. Doppler or reflection meters measure the frequency shift of sound reflected back from particles or bubbles in the flow stream.

1.3 Differential Primary Elements

1.3.1 THIN-PLATE ORIFICES

1.3.1.1 Concentric Orifice Plates

The sharp-edge, concentric orifice plate is the most frequently used primary element because of its low cost, adaptability, and the availability of accurate coefficients.

For most services, orifice plates are made of corrosion-resistant materials, usually Type 304 or 316 stainless steel. Other materials are used for special services.

The upstream face of the orifice plate should be as flat as can be obtained commercially. It must be smooth, and its finish should be at least equivalent to that given in Figure 1-1.

The thickness of the orifice plate at the orifice edge should not exceed (minimum requirements governing in all cases):

$D/50$	(one-fiftieth of pipe diameter)
$d/8$	(one-eighth of orifice diameter)
$(D - d)/8$	(one-fourth of dam height)

In some cases, including large pipe diameter and high pressure and temperature, the thickness of the orifice plate will be greater than is permitted by the limitations for the thickness of the orifice edge. In such a case, the downstream edge shall be counterbored or beveled at an angle of 45 degrees or less to the required thickness at the orifice edge. The word "upstream" or "inlet" should be stamped on the orifice tab on the square-edge side of the plate. Dimensions for orifice plates are shown in Figure 1-1.

Bores must be round and concentric. Practical tolerances for orifice diameters, as given in ANSI/API 2530 [7], are shown in Table 1-1.

The upstream edge of an orifice should be square and sharp. It is usually considered sharp if the reflection of a beam of light from its edge cannot be seen without magnification. The edge radius should not exceed 0.0004 times the bore diameter. It should be maintained in this condition at all times. For two-way flow, both edges must be square. Orifice plate details and schedule of thicknesses are shown in Figure 1-1. Detailed tolerances are discussed in ANSI/API 2530 and American Society of Mechanical Engineers publications [8, 9].

In wet-gas or wet-steam services, where the volume of condensate is small, a weep hole flush with the bottom of the orifice run may be used to prevent a buildup of condensate in horizontal lines. The weep hole serves as a drain to prevent freeze-up during shutdown periods. A weep hole flush with the top of the pipe can also be used to pass small quantities of gas in liquid streams. If the diameter of the hole is less than one-tenth of the orifice bore diameter, the maximum flow through the drain hole is less than 1 percent of the total flow.

Table 1-1—Practical Tolerances for Orifice Diameters
(Dimensions in Inches)

Orifice size, d	Tolerance plus or minus (per inch of diameter)
0.250	0.0003
0.375	0.0004
0.500	0.0005
0.625	0.0005
0.750	0.0005
0.875	0.0005
1.000	0.0005
Over 1.000	0.0005

Because more test information is available for thin-plate orifices than for other primary devices, it is possible to design orifice installations to acceptable accuracies. Sometimes the layout of equipment precludes the use of the most accurate design. A lower order of accuracy is often acceptable in installations used only for control purposes than in installations used for accounting, material balance, or custody transfer.

1.3.1.2 d/D (β) Ratio

Orifice diameters should be selected so that the ratio of orifice diameter to actual internal pipe diameter, d/D , does not exceed the limits as shown on ANSI/API 2530, as follows:

1. With meters using flange taps, β shall be between 0.15 and 0.70.
2. With meters using pipe taps, β shall be between 0.20 and 0.67.

With either type of pressure taps, diameter ratios as low as 0.10 may be used while ratios as high as 0.75 may be used with flange taps and as high as 0.70 may be used with pipe taps. The flow constants, F_b , for these extreme values of β are subject to higher tolerances, and it is recommended that the use of these extreme ratios be avoided (see ANSI/API 2530).

When using small bores, care should be exercised to prevent plugging by pipe scale or other foreign material.

1.3.1.3 Other Orifice Plates

Eccentric or segmental orifices may be used in horizontal runs for special services where concentric orifices cannot be used. In some installations, the fluid stream possesses a large quantity of undissolved gas or a gas containing condensables, which may be carried along the pipe. This type of plate can produce full venting or full drainage, whichever is required, if the orifice opening is properly located.

Segmental orifices are recommended for slurry services because of their insensitivity to changes in the liquid-solid ratio and their relatively satisfactory accuracy (approximately 2.2 percent for plate calculations) [10].

The eccentric orifice usually is placed with its edge tangent to a circle having a diameter 0.98 of that of the pipe. The point of tangency is at the top, vertical centerline for liquids containing some vapor, and at the bottom, vertical centerline for vapors containing some liquids. Coefficients are also available for differential pressure taps at 90 or 180 degrees from the point of tangency. Eccentric and segmental orifice plates are shown in Figure 1-2. Segmental orifices are usually constructed with a circle diameter (D) between 0.97 and 0.98

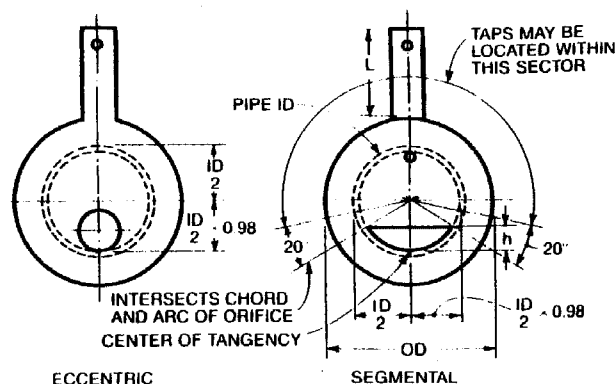


Figure 1-2—Eccentric and Segmental Orifice Plates

percent of the inside pipe diameter (ID). They are generally used in services that require that the orifice be placed at the bottom of the line. For best accuracy, the tap location should be 180 degrees from the center of tangency. However, to avoid gas bubbles in the taps, the location may be anywhere within the sector shown in Figure 1-2.

The quadrant-edge, or quarter-circle, orifice is a device in which the upstream edge is rounded to form a quarter circle. The thickness of the plate near the orifice is equal to the radius of the quarter circle.

The quadrant-edge orifice is used for the flow measurement of viscous streams because of its relatively constant coefficient over a wide range of low Reynolds numbers. It is especially valuable where the viscosity is high and variable. In contrast, the square-edge orifice coefficients show increasing dependence on orifice Reynolds number,² R_d , below 100,000. Square-edge orifice coefficient correction factors are available for R_d down to approximately 25,000.

The quadrant-edge orifice may be used when the line Reynolds numbers (R_D) range from 100,000 down to 3000 to 5000, depending upon the β ratio. It has a standard deviation of ± 1 percent for β from 0.3 to 0.6 and ± 1.25 percent for β from 0.25 to 0.3. It is recommended for measurement of flows when the Reynolds number, based on pipe diameter, is less than 10,000. When R_D is below the 3000 to 5000 range, the coefficient curve shows a hump, which is proportionally higher for longer upstream runs. The hump may be suppressed, even at values of R_D below 1000, by taking the flow straight out of a vessel nozzle through a meter run of only a few pipe diameters ahead of the orifice. The hump may also be suppressed by using a screen, such as a multiplate flow straightener, a few diameters upstream [11-14].

² In some data, R_D (the Reynolds number for the pipe) is given; in other data, R_d (the Reynolds number for the restriction) is given. The difference between these two numbers is shown in the following equation:

$$R_D = \beta R_d$$

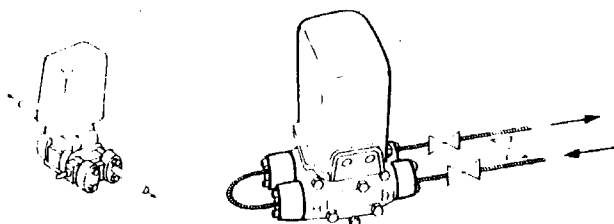
Readings for flows exceeding the maximum Reynolds number limits may be very inaccurate. High-quality machining of quadrant orifice plates is important because the dimensions, shape, and smoothness of the edges can affect the accuracy of its readings.

A very small orifice plate or capillary that is an integral part of a diaphragm pressure transmitter is sometimes used for the measurement of very small flows. Flows as low as 0.04 cubic centimeters per minute of water equivalent or 0.027 standard cubic feet per minute of air may be measured using this method (see Figure 1-3).

1.3.1.4 Sizing Orifices

It is common to size the orifice for a 100-inch (2500-millimeter) water column (dry calibration) at maximum flow. This permits either an increase or a decrease in maximum flow, without changing the orifice bore, by an adjustment of the differential transmitter range. Smaller differentials, 50 inches (1250 millimeters) or 20 inches (500 millimeters), are now commonly used to save energy. For gas or steam flow, a good rule of thumb is that the meter range, in inches of water, should not exceed the flowing pressure, in pounds per square inch absolute.

The procedures for computing orifice sizes and flow through orifices are given in various publications [4, 7, 9, 15, 16]. Special slide rules are especially valuable for checking longhand or computer computations and for preliminary



NOTES

1. Upstream strainers or filters are optional, but highly desirable.
2. For continuous services, provide block and bypass valves to allow meter calibration.
3. Provide breakout unions where piping cannot be spread to remove meter body.

Figure 1-3—Integral Orifice Flowmeter—Liquid and Gas

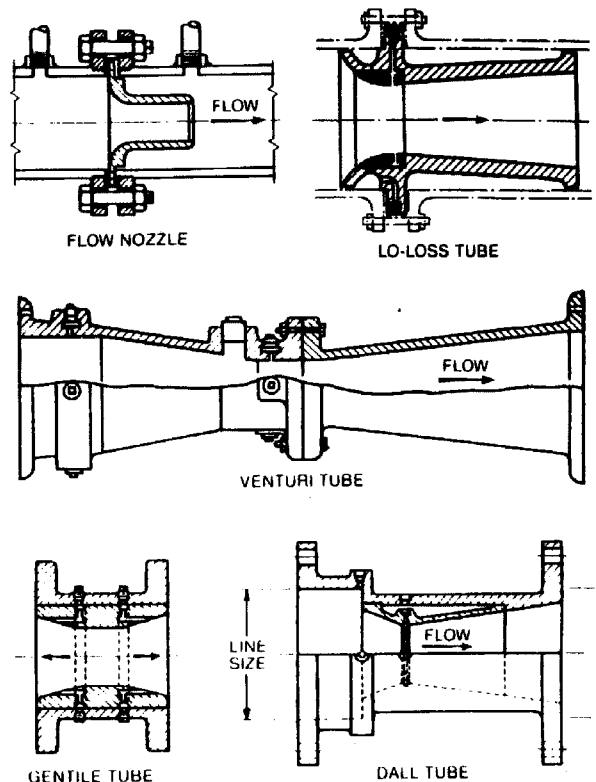


Figure 1-4—Flow Nozzle, Venturi Tube, and Flow Tubes

orifice sizing. Programs to size orifices are also available for various programmable calculators. Orifice calculations can be purchased from the manufacturers of orifice plates or flowmeters. Occasionally, only approximate physical properties of the flowing fluid are known before startup; in such cases, a flow slide rule may be used to determine orifice size. Computations can be made later using actual flow conditions, or corrections can be applied to preliminary computations made with the approximate values.

1.3.2 FLOW NOZZLES

Flow nozzles are used less frequently than orifice plates. Their principal advantages are better pressure recovery and approximately 65 percent higher flow capacity for a given diameter than can be obtained under the same conditions with orifice plates. Flow nozzles may be used in light slurry service; however, accuracy is poor below certain Reynolds numbers [1, 5, 6]. Meter run requirements, flange ratings, and tap requirements are generally the same as for orifice installations. However, because the d/D ratio for the same flow and line size is smaller, a shorter meter run may be used where the run length is based on the minimum run for the actual d/D ratio.

A typical flow nozzle is shown in Figure 1-4. There are

several forms of flow nozzles, one of the most common being the American Society of Mechanical Engineers' long-radius form [4, 9]. Properly installed and calibrated, flow nozzles are nearly equal in accuracy to sharp-edge orifices. Calculation procedures and coefficients for flow nozzles have been published [4, 7, 8].

1.3.3 VENTURI TUBES AND FLOW TUBES

1.3.3.1 General

Venturi tubes and flow tubes are frequently used in refinery operations. Permanent head loss for these devices is lower than for other constricting primary elements. Venturi and flow tubes should be considered for all applications where minimizing head loss is an important factor. These primary devices are more costly than orifice or flow nozzle installations, and the long-form venturi is the most expensive. The venturi tube and flow tubes are shown in Figure 1-4.

1.3.3.2 Venturi Tubes

Venturi tubes (see Figure 1-4) give a much lower permanent head loss than orifices or flow nozzles. For a long-form venturi tube, the approximate head loss will be between 10 and 14 percent of the measured differential, dependent upon the d/D ratio. Minimum runs are usually shorter for these tubes than for orifice plates or flow nozzles. As a rule, the manufacturer of the venturi tube can supply the minimum length meter run data.

Although coefficients are available for the calculation of flow through venturi tubes [4, 8, 9], the manufacturer may specify the flow for a given differential. Venturi tubes usually give an accuracy nearly equal to that of a thin-plate orifice. Venturi tube flow coefficients are relatively stable over a wider range of Reynolds numbers than are the coefficients of sharp-edge orifices.

When properly purged, venturi tubes are suitable for metering streams that contain solids. An increase in the solid-liquid ratio will cause a higher reading.

1.3.3.3 Dall Tubes

The Dall tube [17] is available as a fabricated line insert, approximately 2 diameters long. The static pressure tap is in a line-size section followed by a sharp shoulder and a steep, conical entrance to a short, cylindrical section, which has an annular slot, followed by a 15-degree conical diffuser, terminating with a shoulder (see Figure 1-4).

Upon examination, the Dall tube gives the impression that a fluid flowing through it would be subject to a very high permanent head loss. Actually, the Dall tube head loss is only about 2½ to 6 percent of the measured differential as compared to 10 to 14 percent for the same flow in a long-form venturi. The coefficient may vary for line Reynolds numbers

below 500,000. Rounding of the sharp edges will cause slight variations in the coefficients.

Unless it is purged, the Dall tube should not be used for slurries or fluids that contain suspended solids because the annular throat slot is subject to plugging. Dall tubes require longer minimum meter runs than venturi tubes.

1.3.3.4 Gentile Tubes

The Gentile tube has impact- and suction-type piezometer openings to increase the measured differential. The Gentile tube is short and gives a good differential with a relatively small amount of constriction (approximately 1½ diameters) (see Figure 1-4). Its coefficients are the same for flow in either direction, and it is less expensive than a venturi tube. However, Gentile tubes are very susceptible to line roughness. Until sufficient data has been accumulated on the effect of manufacturing tolerances and upstream piping configurations on its accuracy, a Gentile tube should be calibrated for any application where accuracy is important [18].

1.3.3.5 Lo-Loss Tubes

The Lo-Loss tube [19] is another type of differential producer designed for very high-pressure recovery. Its installation requires much less length than the venturi tube, but its use should be restricted to relatively clean services (see Figure 1-4).

1.3.4 PITOT TUBES AND PITOT VENTURIS

Pitot tubes and pitot venturis are used where the pressure drop or power loss through other devices cannot be tolerated and where accuracy is not of prime concern (see Figure 1-5). Frequently, these devices are used to measure high air and water flow rates. Pitot venturis are useful in applications where an ordinary pitot tube does not give satisfactory differential. However, they require a larger tap size. Pitot venturis should not be used in a liquid service of greater than 9 feet per second if dissolved gases are present. Higher velocities cause cavitation, and gas bubbles collect in the meter connecting lines. A traverse is required for good measurement unless there is sufficient straight upstream run to obtain a uniform velocity profile, except in cases where an averaging type of pitot tube is used.

Proper design will permit the installation or removal of pitot tubes and pitot venturis from lines that are in service. Care should be exercised when considering their use in hot oil or other hazardous service except in fixed installations designed to be leakproof. As the line size increases, the cost of pitot tubes and pitot venturis decreases in relation to other primary elements. A typical pitot tube installation is shown in Figure 1-6.

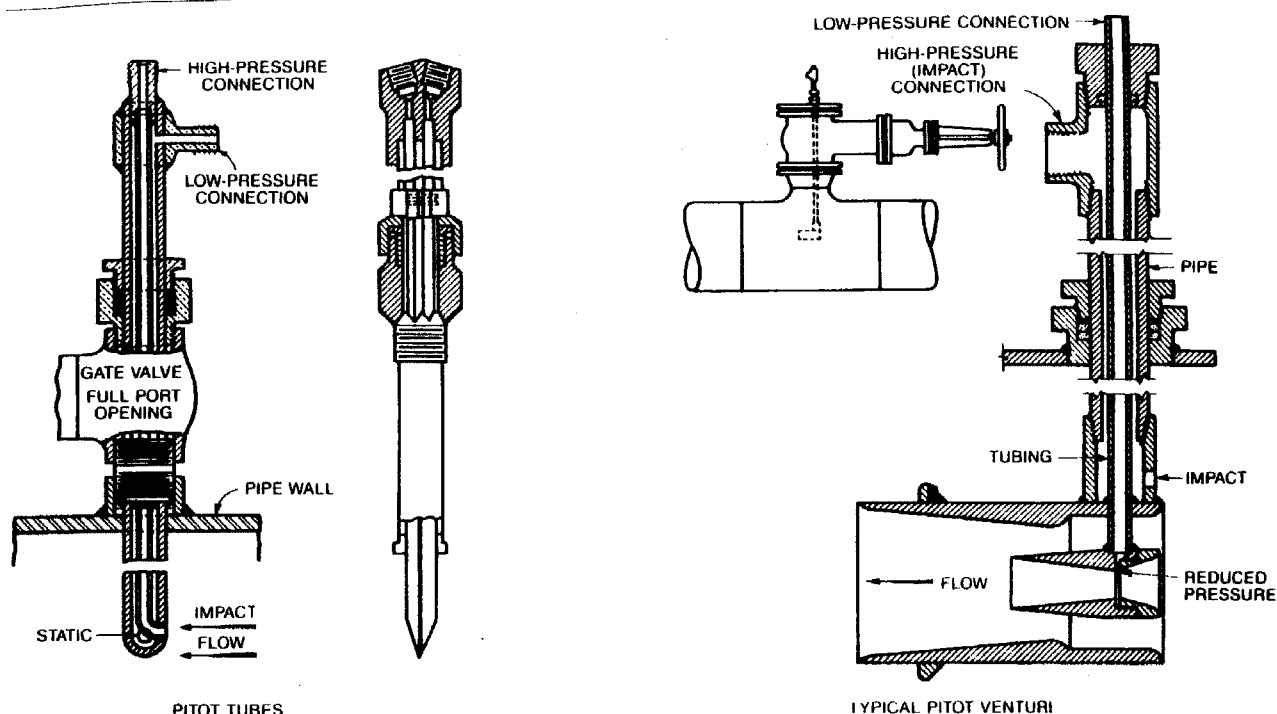


Figure 1-5—Pitot Tubes and Pitot Venturi

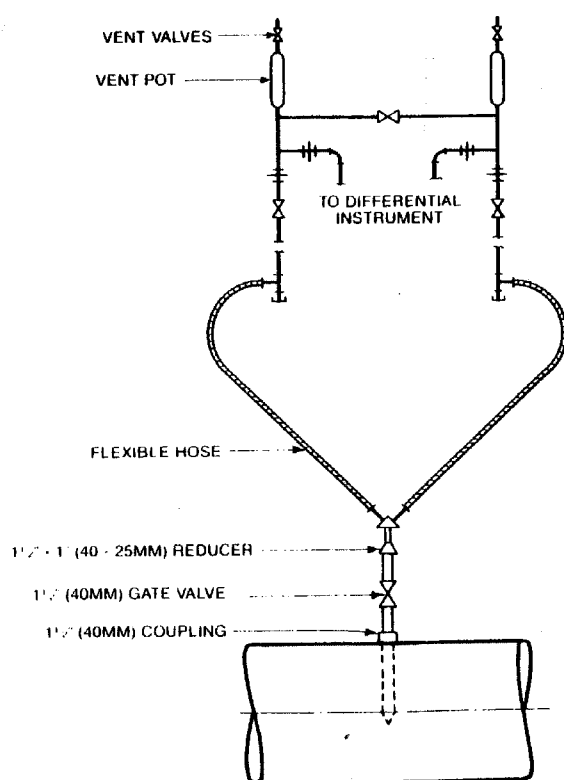


Figure 1-6—Pitot Tube Installation

1.3.5 METERING RUNS

1.3.5.1 Orifice Taps

Orifice taps may be of several types, as shown in Figure 1-7. Flange taps usually are preferred for refinery use. Vena contracta taps and pipe taps sometimes are used in refineries. However, vena contracta taps cannot be used with some sizes and pressure ratings of welding-neck flanges because one or both taps may fall in an undesirable location in the flange hub or weld. Also, when changing orifice bore, the downstream tap must be changed.

Radius or throat taps (those located 1 pipe inside diameter upstream and $\frac{1}{2}$ pipe inside diameter downstream) can be used for refinery service. The downstream tap for the radius or throat tap sometimes falls either fully or partially into the flange hub.

Corner taps [20] are used by some refiners, particularly on small lines where flange taps may be at the wrong location in the pressure profile. One type of corner tap orifice flange arrangement is shown in Figure 1-8.

Pipe taps or full-flow taps, located $2\frac{1}{2}$ diameters upstream and 8 diameters downstream, measure the permanent pressure loss. These can measure higher flow rates for a given meter differential than can flange, vena contracta, radius, or corner taps.

Orifice flanges with flange taps, as shown in Figure 1-8, are generally used. These flanges have a minimum thickness of $1\frac{1}{2}$ inches (40 millimeters). In the smaller sizes, they are