ASME MFC-3Ma–2007

Addenda to ASME MFC-3M–2004

Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi

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Addenda to the 2004 edition of ASME MFC-3M–2004 are issued in the form of replacement pages. Revisions, additions, and deletions are incorporated directly into the affected pages. It is advisable, however, that this page, the Addenda title and copyright pages, and all replaced pages be retained for reference.

SUMMARY OF CHANGES

This is the first Addenda to be published to ASME MFC-3M–2004.

Replace or insert the pages listed. Changes given below are identified on the pages by a margin note, **(a07)**, placed next to the affected area. The pages not listed are the reverse sides of the listed pages and contain no changes.

Page	Location	Change
7	1-5.3.1	Equations and nomenclature revised
9	1-6.4.1(e)	Metric values for D_{small} and D_{large} in subparas. (1) and (2) revised
11	Table 1A-1	In the fifth column, sixth and eighth entries are revised
14, 14.1	Fig. 1C-1	General Note added
20	2-4.1.5	Revised
21	2-4.2.1(b)(2)	Revised
22	Fig. 2-3	Note (1) revised
25	2-4.3.2.1	In Eq. (2-5), values for U.S. Customary units revised
	2-4.3.2.1(c)	(1) Penultimate paragraph added (2) Last paragraph revised
26, 26.1	2-5.1	First sentence revised
27	Table 2-3	Sixth column head revised
28	2-5.2(h)(1)(b)	Third line revised
29	2-5.2(i)	First line revised
	2-5.2(i)(2)	Second line editorially revised
33	2-5.3.2.4	Fifth line revised
34	2-5.3.3.1	Last line of first paragraph revised
48.1	Nonmandatory Appendix 2B	Added
49	3-1	Last sentence of the third paragraph revised

Page	Location	Change
Page	*Location*	*Change*
51–52.1	3-4.1.1	Last sentence added
53	3-4.1.7.2	Equation (3-8) revised in its entirety
55	3-4.2.5(b)	Last sentence of the last paragraph revised
	3-4.2.6.1	New subpara. (c) added and subsequent subparagraph redesignated as (d)
56	3-4.2.7.2	Equation (3-14) revised in its entirety
61	3-5.2(h)(2)(b)	Last line of second paragraph revised
	3-5.2(i)	First line revised
63, 64	3-5.4(c)	In the last paragraph, "10%" revised to read "6%"
71, 72	4-4.2.8	Second and third paragraphs revised
73	4-4.5.3(c)	Revised
75, 76	4-5.2(h)(1)(b)	Last sentence of the second paragraph revised
	4-5.2(i)	(1) Last sentence revised (2) In Examples (1) and (2), fifth line revised

cient can occur over a period of time and can lead to values outside the uncertainties given in this Standard.

(c) The primary device shall be manufactured from materials for which the coefficient of expansion is known.

1-5.2 Nature of the Fluid

(a) The fluid can be either compressible or incompressible.

(b) The fluid shall be such that it can be considered as being physically and thermally homogeneous and single-phase. Colloidal solutions with a high degree of dispersion can be considered to behave as single-phase fluids.

(c) For measurement, it is necessary to know the density and viscosity of the fluid at the working conditions. In the case of a compressible fluid it is also necessary to know the isentropic exponent of the fluid at the working conditions.

1-5.3 Flow Conditions

(a07) **1-5.3.1 Pulsating Flow.** This Standard does not provide for the measurement of pulsating flow (see ISO 3313 for reference). The flow is considered sufficiently steady for this Standard to apply when

(SI Units)

$$\frac{\Delta p'_{rm}}{\overline{\Delta p}} \le 0.10 \qquad (1\text{-}10)$$

(U.S. Customary Units)

$$\frac{h'_w}{\overline{h_w}} \le 0.10$$

where
$\overline{\Delta p}\ (\overline{h_w})$ = time-mean value of the differential pressure
$\Delta p'_{rm}\ (h'_w)$ = root-mean-square value of $\Delta p'\ (h'_w)$, the fluctuating component of the pressure

$\Delta p'_{rm}\ (h'_w)$ can be measured accurately only by using a differential pressure sensor with sufficiently fast response (see ISO 3313 for reference). Furthermore, the whole secondary system should conform to the design recommendations specified in ASME MFC-8M.

1-5.3.2 Phase Change of Metered Fluid. The uncertainties specified in this Standard are valid only when there is no change of phase through the primary device. Increasing the bore or throat of the primary element will reduce the differential pressure and may prevent a change of phase. For liquids, the pressure in the throat section must not fall below the vapor pressure of the liquid (otherwise, cavitation will result). For gases, it is only necessary to calculate the temperature at the throat if the gas is in the vicinity of its dew point. The temperature in the throat can be calculated assuming an isentropic expansion from the upstream conditions (the

upstream temperature may need to be calculated in accordance with the Eq. (1-8) such that the fluid is in the single-phase region.

1-5.3.3 Pressure Ratio. If the line fluid is a gas, the pressure ratio (throat pressure to upstream pressure ratio, P_2/P_1) shall be between 0.80 and 1.00. If the fluid is a liquid, there is no limit to the pressure ratio, provided there is no phase change in the process fluid, and the primary element does not deform or deflect excessively. For detailed information, refer to Parts 2, 3, or 4 of this Standard as appropriate for specific primary devices.

1-6 INSTALLATION REQUIREMENTS

1-6.1 General

(a) The method of measurement applies only to fluids flowing through a pipeline of circular cross section.

(b) The pipe shall run full at the measurement section.

(c) The primary device shall be fitted between two straight sections of cylindrical pipe of constant diameter and of specified minimum lengths in which there is no obstruction or branch connection other than those specified in Parts 2, 3, or 4 of this Standard as appropriate for specific primary devices.

The pipe is considered to be straight when the deviation from a straight line does not exceed 0.4% over its length. Flanges in the straight sections of pipe upstream and downstream of the primary device shall be at 90 deg ($\pm \frac{1}{2}$ deg) to the pipe itself. The minimum straight lengths of pipe conforming to the above requirement necessary for a particular installation vary with the type and specification of the primary device and the nature of the pipe fittings involved.

(d) The pipe bore shall be circular over the entire minimum length of straight pipe required. The cross section can be considered circular if it appears so by visual inspection. The circularity of the outside of the pipe can be used as a guide, except in the immediate vicinity (2D) of the primary device where special requirements shall apply according to the type of primary device used.

Seamed pipe can be used, provided the internal weld bead is parallel to the pipe axis throughout the entire length of the pipe required to satisfy the installation requirements for the primary device being used. The seam must not be situated within 30 deg of any pressure tap used in conjunction with the primary device; no weld bead shall have a height greater than the permitted step in diameter according to the requirements of the primary device used. If spirally wound pipe is used then it must be honed or machined smooth.

(e) The interior of the pipe shall be clean at all times. Dirt that can readily detach from the pipe shall be removed. Any metallic pipe defects must be removed.

The acceptable value of pipe roughness depends on the primary device. In each case there are limits on the value of the arithmetic mean deviation of the roughness

profile, R_a [see paras. 2-4.3.1, 3-4.1.2(i), 3-4.1.6.1, 3-4.2.2(f), 3-4.2.6.1, and 3-4.3.4.1 or para. 4-5.4.2). The internal surface roughness of the pipe shall be measured at approximately the same axial locations as those used to determine and verify the pipe internal diameter. A minimum of four roughness measurements shall be made to define the pipe internal surface roughness. In measuring R_a, an averaging-type surface roughness instrument with a cut-off value of not less than 0.75 mm (0.03 in.) shall be used. The roughness can change with time as stated in para. 1-5.1(b), and this should be taken into account in establishing the frequency of cleaning the pipe or checking the value of R_a.

An approximate value of R_a can be obtained by assuming that R_a is equal to k/π, where k is the uniform equivalent roughness as given in a Moody diagram. The value of k is given directly by a pressure loss test of a sample length of pipe, using the Colebrook-White Equation given in para. 1-6.4.1(e) to calculate the value of k from the measured value of friction factor, λ. Approximate values of k for different materials can also be obtained from the various tables given in reference literature, and Table 1B-1 gives values of k for a variety of materials.

(f) The pipe can be provided with drain holes and/or vent holes to permit the removal of solid deposits and entrained fluids. There shall be no flow through either drain holes or vent holes, however, during the flow measurement process. In many custody transfer applications, drain holes or vent holes are explicitly prohibited.

Drain and vent holes should not be located at the primary device. When it is not possible to conform to this requirement, the diameter of the vent or drain hole shall be less than 8% of the pipe inside diameter. The centerline of a pressure tap and the centerline of a drain or vent hole shall be offset from each other by at least 30 deg azimuthally (i.e., in the plane perpendicular to the axis of the pipe) and they shall be located no closer than 0.5D from each other.

(g) Insulation of the meter may be required if the temperature difference between ambient conditions and the flowing fluid are significant given the desired measurement uncertainty. This is particularly important if the fluid being metered is near its critical point: small temperature changes result in major density changes. It can be important at low flow rates, where heat transfer effects can cause distorted temperature profiles, and a change in the mean temperature value from the upstream to the downstream side of the meter run, as well as stratification of temperature layers from top to bottom. A temperature difference between the upstream and the downstream sides of the meter run can also occur.

1-6.2 Minimum Upstream and Downstream Straight Lengths of Pipe

(a) The primary device shall be installed in the pipeline at a position such that the flow conditions immediately upstream of the primary device approximate

those of swirl-free, fully developed pipe flow. Conditions meeting this requirement are specified in para. 1-6.3.

(b) The required minimum upstream and downstream straight lengths required for installation between various fittings and the primary device depend on the primary device. For some commonly used fittings as specified in paras. 2-5, 3-5, and 4-5 of this Standard, the minimum straight lengths of pipe indicated can be used. Flow conditioners, such as those described in para. 1-6.4, however, often permit the use of shorter upstream pipe lengths. Such flow conditioners must be installed upstream of the primary device for fittings not covered by paras. 2-5, 3-5, and 4-5 of this Standard, or where sufficient straight lengths to achieve the desired level of uncertainty are not available.

1-6.3 General Requirement for Flow Conditions at the Primary Device

1-6.3.1 Requirement. If the specified conditions given in paras. 2-5, 3-5, and 4-5 of this Standard cannot be met, but the flow conditions immediately upstream of the primary device can be demonstrated to conform to swirl-free fully developed flow (as defined in paras. 1-6.3.2 and 1-6.3.3) over the entire Reynolds number range of the flow measurement application, the applicable sections of this Standard remain valid.

1-6.3.2 Swirl-Free Conditions. Swirl-free conditions can be taken to exist when the swirl angle at all points over the pipe cross-section is less than 2 deg.

1-6.3.3 Acceptable Flow Conditions. Acceptable velocity profile conditions can be presumed to exist when, at each point across the pipe cross-section, the ratio of the local axial velocity to the maximum axial velocity at the cross-section is within 5% of that which would be achieved in swirl-free flow at the same radial position at a cross-section located at the end of a very long (over 100D) straight length of similar pipe with fully developed flow.

1-6.4 Flow Conditioners

Some additional material regarding flow conditioners is given in Nonmandatory Appendix 1C.

1-6.4.1 Compliance Testing
(a) If a given flow conditioner passes the compliance tests outlined in paras. 1-6.4.1(b) to 1-6.4.1(f) for a particular primary device, the flow conditioner can be used with the same type of primary device with any value of diameter ratio up to 0.67 downstream of any fitting. If the distance between the flow conditioner and the primary device, and that between the upstream installation and the flow conditioner, are in accordance with para. 1-6.4.1(e), and the downstream straight length of pipe is in accordance with the requirements for the particular primary device, it is not necessary to increase the

uncertainty of the discharge coefficient to take account of the installation.

(b) Using a primary device of diameter ratio 0.67, the shift in discharge coefficient from that obtained in a long straight pipe shall be less than 0.23% when the flow conditioner is installed in each of the following situations:

　(1) in good flow conditions

　(2) downstream of a 50% closed gate valve (or a segmental orifice plate)

　(3) downstream of a device producing a high swirl (a maximum swirl angle across the pipe of 24 deg measured 18D downstream from the device, or at least 20 deg 30D downstream from it).

The length of straight pipe upstream of these fittings shall be sufficiently long so the primary device is not affected by any fittings further upstream.

These tests are required to establish that a flow conditioner does not have an adverse effect on good flow conditions, is effective on highly asymmetric flow, and is effective on highly swirling flow. The use of this test does not imply that flow measurement should be carried out downstream of control valves; rather, flow control should be performed downstream of the primary device.

(c) Using a primary device of diameter ratio 0.4, the shift in discharge coefficient from that obtained in a long straight pipe shall be less than 0.23% when the flow conditioner is installed downstream of the same fitting that generates a swirl as outlined in para. 1-6.4.1(b). This test is included in case there is still swirl downstream of the conditioner.

(d) To determine the acceptability of both the test facility and the primary devices with which the test is being conducted, the baseline discharge coefficient for a particular primary device, as determined in a long straight pipe by the test facility, shall lie within the uncertainty limits of the discharge coefficient (or discharge coefficient equation) for an uncalibrated primary device given by the applicable portions of this Standard. For these tests, the flow calibration facility must first verify that no swirl is present, then have sufficient straight pipe upstream of the primary device.

(a07) *(e)* If the flow conditioner is to be acceptable at any Reynolds number, then it is necessary to establish that it not only meets paras. 1-6.4.1(b) and (c) at one Reynolds number, but that it meets para. 1-6.4.1(b) at a second Reynolds number. If the two pipe Reynolds numbers are $R_{d\text{-low}}$ and $R_{d\text{-high}}$, then they shall meet the following criteria:

　(1) $10^4 \leq R_{d\text{-low}} \leq 10^6$　and　$R_{d\text{-high}} \geq 10^6$

　(2) $\lambda(R_{d\text{-low}}) - \lambda(R_{d\text{-high}}) \geq 0.0036$

where λ is the pipe friction factor that can be obtained graphically from the Moody diagram, or from the Colebrook-White equation

$$\frac{1}{\sqrt{\lambda}} = 1.74 - 2\log_{10}\left(\frac{2k}{D} + \frac{18.7}{R_D\sqrt{\lambda}}\right) \quad (1\text{-}10)$$

with k evaluated as πR_a.

If it is desired to use the flow conditioner only for $R_D > 3(10^6)$, it is sufficient to carry out the test in para. 1-6.4.1(e) at a single value of $R_D > 3(10^6)$.

If the flow conditioner is to be acceptable for any pipe size, then it is necessary to establish that it not only meets the requirements of paras. 1-6.4.1(b) and (c) at one pipe size, but that it meets the requirements of para. 1-6.4.1(b) at a second pipe size. If the two pipe diameters are D_{small} and D_{large}, then they shall meet the following criteria:

　(1) $D_{\text{small}} \leq 100$ mm (4 in.) (nominal)

　(2) $D_{\text{large}} \geq 200$ mm (8 in.) (nominal)

(f) The range of distances that are considered during the test between the flow conditioner and the primary device, and the range of distances between the upstream fitting and the flow conditioner, will determine the acceptable ranges of distances when the flow meter is used. The distances shall be expressed in terms of numbers of pipe diameters.

(g) If it is desired to carry out compliance testing for a flow conditioner for use with primary elements with $\beta > 0.67$, then it must be shown to meet the requirements of paras. 1-6.4.1(b) through (e). Then the test described in paras. 1-6.4.1(b), (d), and (e) shall be carried out at the maximum value of β over which the conditioner is to be used, β_{max}. The permitted shift in discharge coefficient is increased to $(0.63\beta_{\text{max}} - 0.192)\%$. In the case outlined in para. 1-6.4.1(e),

$$\lambda(R_{d\text{-low}}) - \lambda(R_{d\text{-high}}) \geq \frac{0.00241\beta_{\text{max}} - 0.000735}{\beta_{\text{max}}^{3.5}} \quad (1\text{-}11)$$

Provided that the conditioner meets all the compliance tests outlined above, it has then passed the compliance test for $\beta \leq \beta_{\text{max}}$. The acceptable ranges of distances between the flow conditioner and the primary device and between the upstream fitting and the flow conditioner are determined as given in para. 1-6.4.1(f).

1-6.4.2 Specific Test. If a compliance test has not been carried out to permit the use of a flow conditioner downstream of any upstream fitting, it may be necessary to carry out a flow test specifically for the installation in question. The test will be deemed satisfactory if it shows that the shift in discharge coefficient from that obtained in a long straight pipe is less than 0.23%. The permitted shift in discharge coefficient can be increased to $(0.63\ \beta_{\text{max}} - 0.192)\%$ for $0.67 < \beta \leq 0.75$ (for orifice plates and venturi tubes), $0.67 < \beta \leq 0.80$ (for flow nozzles), or $0.67 < \beta \leq 0.775$ (for venturi nozzles). In this situation it is not necessary to increase the uncertainty of the discharge coefficient to take account of the installation.

1-7 UNCERTAINTIES IN THE MEASUREMENT OF FLOW RATE

Broader and more detailed information for calculation of the uncertainty in flow measurement is given in ASME MFC-2M and ISO/TR 5168.

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1-7.1 Definition of Uncertainty

(a) For the purposes of this Standard the uncertainty is defined as a range of values within which the value of the measurement could reasonably be expected to lie providing a level of confidence of approximately 95%.

(b) The uncertainty in the measurement of the flow rate shall be calculated and given whenever a measurement is claimed to be in conformity with this Standard.

(c) The uncertainty can be expressed in absolute or relative terms and the result of the flow measurement can then be given in one of the following forms:

$$\text{flow rate} = q \pm \delta q$$
$$= q(1 \pm U_q')$$
$$= q \text{ within } (100 \; U_q')\%$$

where the uncertainty δq shall have the same dimensions as q while $U_q' = \delta q / q$ and is dimensionless.

(d) A distinction is made between the uncertainties associated with measurements made by the user and those associated with quantities specified in this Standard. Uncertainties associated with quantities specified in this Standard are on the discharge coefficient and the expansibility factor, $\varepsilon (Y)$ and occur because variations in geometry are allowed, and because the investigations on which the values are based were made with some uncertainty as well.

1-7.2 Practical Computation of the Uncertainty

(a) The basic equation of computation of the mass flow rate, q_m, is

(SI Units)

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \; \varepsilon \; \frac{\pi}{4} \; d^2 \sqrt{2\Delta p \rho_1} \qquad (1\text{-}12)$$

(U.S. Customary Units)

$$q_m = 0.09970190 C Y d^2 \sqrt{\frac{h_w \rho_1}{1 - \beta^4}}$$

The various quantities that appear on the right-hand side of this formula are not independent, so it is not correct to compute the uncertainty of q_m directly from the uncertainties of these quantities. C, for instance, is a function of d, D, V_1, ν_1, and ρ_1, while $\varepsilon (Y)$ is a function of d, D, $\Delta p (h_w)$, P, and κ.

(1) For most practical purposes, however, it is sufficient to assume that the uncertainties of C, $\varepsilon (Y)$, d, $\Delta p (h_w)$, and ρ_1 are independent of each other.

(2) A practical working formula for δq_m that takes into account the interdependence of C on d, and D (which enters into the calculation as a consequence of the dependence of C on β) can then be derived. Note that C may also be dependent on the Reynolds number. The deviations of C due to these influences, however, are of a second order and are included in the uncertainty on C.

Similarly, the deviations of $\varepsilon (Y)$ that are due to un-

certainties in the value of β, the pressure ratio, and the isentropic exponent are also of a second order and are included in the uncertainty on $\varepsilon (Y)$. The contribution to the uncertainty due to the covariance terms can be considered as negligible.

(3) The uncertainties that will be included in a practical working equation for δq_m are, therefore, those of the quantities C, $\varepsilon (Y)$, d, D, $\Delta p (h_w)$, and ρ_1.

The practical working equation for the uncertainty, δq_m, of the mass rate of flow is as follows:

(SI Units)

$$\frac{\delta q_m}{q_m} = \left[\left(\frac{\delta C}{C} \right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon} \right)^2 + \left(\frac{2\beta^4}{1 - \beta^4} \right)^2 \left(\frac{\delta D}{D} \right)^2 \right.$$
$$\left. + \left(\frac{2}{1 - \beta^4} \right)^2 \left(\frac{\delta d}{d} \right)^2 + \frac{1}{4} \left(\frac{\delta \Delta p}{\Delta p} \right)^2 + \frac{1}{4} \left(\frac{\delta \rho_1}{\rho_1} \right)^2 \right]^{\frac{1}{2}} \quad (1\text{-}13)$$

(U.S. Customary Units)

$$\frac{\delta q_m}{q_m} = \left[\left(\frac{\delta C}{C} \right)^2 + \left(\frac{\delta Y}{Y} \right)^2 + \left(\frac{2\beta^4}{1 - \beta^4} \right)^2 \left(\frac{\delta D}{D} \right)^2 \right.$$
$$\left. + \left(\frac{2}{1 - \beta^4} \right)^2 \left(\frac{\delta d}{d} \right)^2 + \frac{1}{4} \left(\frac{\delta h_w}{h_w} \right)^2 + \frac{1}{4} \left(\frac{\delta \rho_1}{\rho_1} \right)^2 \right]^{\frac{1}{2}}$$

In this equation, some of the uncertainties, such as those on the discharge coefficient and expansibility factor, are given in this Standard [see paras. 1-7.2(a)(3)(a) and (a)(3)(b)], while others must be determined by the user [see paras. 1-6.2(a)(3)(c) and (d)].

(a) In Eq. (1-13), the values of $\delta C / C$ and of $\delta \varepsilon / \varepsilon$ $(\delta Y / Y)$ shall be taken from the appropriate clauses of this Standard.

(b) When the straight pipe lengths are such that an additional uncertainty of 0.5% is considered, this additional uncertainty shall be added arithmetically in accordance with the requirements given in this Standard, and not root-mean-square as with the other uncertainties in Eq. (1-12). Other uncertainties shall be added arithmetically in the same way.

(c) In Eq. (1-13), the maximum values of $\delta D / D$ and $\delta d/d$ can be adopted or alternately, the smaller actual values can be calculated by the user. (The maximum value for $\delta D/D$ will not exceed 0.4% whereas the maximum value for $\delta d/d$ will not exceed 0.1%.)

(d) The values of $\delta \Delta p / \Delta p$ $(\delta h_w / h_w)$ and $\delta \rho_1 / \rho_1$ shall be determined by the user because this Standard does not specify the method of measurement of the quantities $\Delta p (h_w)$ and $\delta \rho_1$. The uncertainties in the measurement of both quantities may include components stated by manufacturers as a percentage of full scale. Calculation of percentage uncertainty below full scale must reflect this increased percentage uncertainty.

(e) In order to give an overall uncertainty of q_m providing a level of confidence of approximately 95%, the user-determined uncertainties must also be obtained to provide the same level of confidence.

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NONMANDATORY APPENDIX 1A
ITERATIVE COMPUTATIONS

An iterative computation procedure is required when a problem cannot be solved by direct calculation methods (see para. 1-4.3).

In the case for orifice plates, for instance, iterative computations are always required to calculate

   (a) the flow-rate q_m at given values of μ_1, ρ_1, D, $\Delta p\,(h_w)$, and d

   (b) the orifice diameter d and β at given values of μ_1, ρ_1, D, $\Delta p\,(h_w)$, and q_m

   (c) the differential pressure $\Delta p\,(h_w)$ at given values of μ_1, ρ_1, D, and q_m

   (d) the diameters D and d at given values of μ_1, ρ_1, β, $\Delta p\,(h_w)$, and q_m

The principle is to regroup all known values of the basic flow-rate equation:

(SI Units)

$$q_m = \frac{C}{\sqrt{1 - \beta^4}}\ \varepsilon\ \frac{\pi}{4}\ d^2\ \sqrt{2\Delta p \rho_1} \qquad (1A\text{-}1)$$

(U.S. Customary Units)

$$q_m = 0.09970190\, CYd^2 \sqrt{\frac{h_w \rho_1}{1 - \beta^4}}$$

and the unknown values in the other member. The known member is then the "invariant" of the problem.

A first guess, X_1, is introduced into the unknown member and results in a difference, δ_1, between the two members. Iterative computation enables a second guess, X_2, to be substituted to obtain δ_2. Then X_1, X_2, δ_1, and δ_2 are entered into a linear algorithm that computes $X_3 \ldots X_n$ and $\delta_3 \ldots \delta_n$ until $|\delta_n|$ is smaller than a given value, or until two successive values of X or of δ are seen to be "equal" for a given precision.

An example of a linear algorithm with rapid convergence is

$$X_n = X_{n-1} - \delta_{n-1}\ \frac{X_{n-1} - X_{n-2}}{\delta_{n-1} - \delta_{n-2}} \qquad (1A\text{-}2)$$

If the computations are carried out using a programmable calculator, the use of a linear algorithm reduces only slightly the resulting calculations by successive substitutions in the case of computations found in applications relative to this part of this Standard.

The values of d, D, and β to be introduced in the calculations are those prevailing under the working conditions.

For orifice plates, if the plate and the metering tube are made of different materials, it is possible that the variation in β due to the working temperature is significant. Examples of full schemes for iterative computations are given in Table 1A-1.

Table 1A-1   Methods for Iterative Computation   (a07)

Problem	$q =$	$d =$	$\Delta p =$	$D =$
At Given Values	$\mu_1, \rho_1, D, d, \Delta p$	$\mu_1, \rho_1, D, q_m, \Delta p$	μ_1, ρ_1, D, d, q_m	$\mu_1, \rho_1, d, q_m, \Delta p$
Please Find	q_m and q_v	d and β	Δp	D and d
Invariant	$A_1 = \dfrac{\varepsilon d^2 \sqrt{2\Delta p \rho_1}}{\mu_1 D \sqrt{1 - \beta^4}}$	$A_2 = \dfrac{\mu_1 R_D}{D\sqrt{2\Delta p \rho_1}}$	$A_3 = \dfrac{8(1 - \beta^4)}{\rho_1}\left(\dfrac{q_m}{C\pi d^2}\right)^2$	$A_4 = \dfrac{4\varepsilon \beta^2 q_m \sqrt{2\Delta p \rho_1}}{\pi \mu_1{}^2 \sqrt{1 - \beta^4}}$
Iteration Equation	$\dfrac{R_D}{C} = A_1$	$\dfrac{C\,\varepsilon \beta^2}{\sqrt{1 - \beta^4}} = A_2$	$\dfrac{\Delta p}{\varepsilon^{-2}} = A_3$	$\dfrac{R_D^2}{C} = A_4$
Variable in Linear Algorithm	$X_1 = R_D = CA_1$	$X_2 = \dfrac{\beta^2}{\sqrt{1 - \beta^4}} = \dfrac{A_2}{C}$	$X_3 = \Delta p = \varepsilon^{-2} A_3$	$X_4 = R_D = \sqrt{CA_4}$
Precision Criterion [Note (1)]	$\left\|\dfrac{A_1 - \dfrac{X_1}{C}}{A_1}\right\| < 1 \times 10^{-n}$	$\left\|\dfrac{A_2 - X_2 C\varepsilon}{A_2}\right\| < 1 \times 10^{-n}$	$\left\|\dfrac{A_3 - \dfrac{X_3}{\varepsilon^{-2}}}{A_3}\right\| < 1 \times 10^{-n}$	$\left\|\dfrac{A_4 - \dfrac{X_4{}^2}{C}}{A_4}\right\| < 1 \times 10^{-n}$
First Guess	$C = C_\infty$	$C = 0.606$ (Orifice plate) $C = 1$ (Other primaries) $\varepsilon = 1$	$\varepsilon = 1$	$C = C_\infty$ $D = D$ (if flange tap)
Second Guess	$q_m = \dfrac{\pi}{4}\mu_1 DX_1$ $q_v = \dfrac{q_m}{\rho_1}$	$d = D\left(\dfrac{X_2{}^2}{1 + X_2{}^2}\right)^{0.25}$ $\beta = \dfrac{d}{D}$	$\Delta p = X_3$ [Note (2)]	$D = \dfrac{4q_m}{\pi \mu_1 X_4}$ $d = \beta D$

NOTES:
(1) Where n is chosen by the user.
(2) If the fluid is considered incompressible, Δp is obtained in first loop.

NONMANDATORY APPENDIX 1B
EXAMPLES OF VALUES OF PIPE WALL UNIFORM EQUIVALENT ROUGHNESS, k

Table 1B-1   Values of k

Material	Condition	k	R_a	
			mm	in.
Brass, Copper, Aluminum, Plastics, Glass	Smooth, without sediment	< 0.03	< 0.01	< 0.0004
	New, stainless	< 0.03	< 0.01	< 0.0004
	New, seamless, cold drawn	< 0.03	< 0.01	< 0.0004
	New, seamless, hot drawn	0.05 to 0.10	0.015 to 0.030	0.0006 to 0.0012
	New, seamless, rolled	0.05 to 0.10	0.015 to 0.030	0.0006 to 0.0012
	New, welded longitudinally	0.05 to 0.10	0.015 to 0.030	0.0006 to 0.0012
	New, welded spirally	0.10	0.03	0.0012
	Slightly rusted	0.10 to 0.20	0.03 to 0.06	0.0012 to 0.0024
Steel	Rusty	0.20 to 0.30	0.06 to 0.10	0.0024 to 0.0039
	Encrusted	0.50 to 2	0.15 to 0.60	0.0059 to 0.0236
	Heavy encrustation	> 2	> 0.6	> 0.0236
	Bituminized, new	0.03 to 0.05	0.010 to 0.015	0.0004 to 0.0006
	Bituminized, normal	0.10 to 0.20	0.03 to 0.06	0.0012 to 0.0024
	Galvanized	0.13	0.04	0.0016
Cast Iron	New	0.25	0.08	0.0031
	Rusty	1.0 to 1.5	0.3 to 0.5	0.0118 to 0.0197
	Rust encrusted	> 1.5	> 0.5	> 0.0197
	Bituminized, new	0.03 to 0.05	0.010 to 0.015	0.0004 to 0.0006
Asbestos Cement	New	< 0.03	< 0.01	< 0.0004
	Typical, uncoated	0.05	0.015	0.0006

GENERAL NOTE: For this table, R_a has been calculated on the basis that $R_a \approx (k/\pi)$.

NONMANDATORY APPENDIX 1C
FLOW CONDITIONERS AND FLOW STRAIGHTENERS

1C-1   GENERAL

Flow conditioners can be classified as either true flow conditioners or flow straighteners. In this Standard, but beyond this Appendix, the term "flow conditioner" is used to describe both true flow conditioners and flow straighteners.

Inclusion in this Appendix does not imply that a flow conditioner or flow straightener has passed the compliance test in para. 1-6.4.1 with any particular primary device at any particular location.

The descriptions of flow straighteners and flow conditioners given here does not limit the use of other designs that have been tested and proved to provide sufficiently small shifts in discharge coefficient when compared with discharge coefficients obtained in a long straight pipe.

1C-2   FLOW STRAIGHTENERS

1C-2.1 General Description

A flow straightener is a device that removes or significantly reduces swirl, but may not simultaneously produce the flow conditions specified in para. 1-6.3.3. The tube bundle (see Fig. 1C-1), the Étoile (see Fig. 1C-2), and the AMCA (see Fig. 1C-3) are all examples of flow straighteners.

1C-2.2 Examples

1C-2.2.1   The Tube Bundle Flow Straightener. The tube bundle flow straightener consists of a bundle of parallel and tangential tubes fixed together and held rigidly in the pipe (see Fig. 1C-1). It is important to ensure that the various tubes are parallel to each other and to the pipe axis since, if this requirement is not met, the straightener itself might introduce swirl to the flow.

There shall be at least nineteen tubes. Their length shall be greater than or equal to $10d_t$, where d_t is shown on Fig. 1C-1. The tubes shall be joined together and the bundle shall rest against the pipe.

The pressure loss coefficient, K, for the tube bundle flow straightener depends on the number of the tubes and their wall thickness, but is approximately equal to 0.75, where K is given by the following equation:

$$K = \frac{\Delta p_c}{\frac{1}{2}\,\rho V^2} \qquad (1C-1)$$

where
Δp_c = pressure loss across the flow straightener or flow conditioner
V = mean axial velocity of the fluid in the pipe

A special case (the 19-tube bundle flow straightener) is described in para. 2-5.3.2 of this Standard.

1C-2.2.2   The Étoile Straightener. The Étoile straightener (see Fig. 1C-2) consists of eight radial vanes at equal angular spacing with a length equal to twice the diameter of the pipe (see Fig. 1C-4). The vanes shall be as thin as possible but shall provide adequate strength. The pressure loss coefficient, K, for the Étoile straightener is approximately equal to 0.25.

1C-2.2.3   The AMCA Straightener. The AMCA straightener consists of a honeycomb with square meshes, the dimensions of which are shown in Figure 1C-3. The vanes shall be as thin as possible but shall provide adequate strength. The pressure loss coefficient, K, for the AMCA straightener is approximately equal to 0.25.
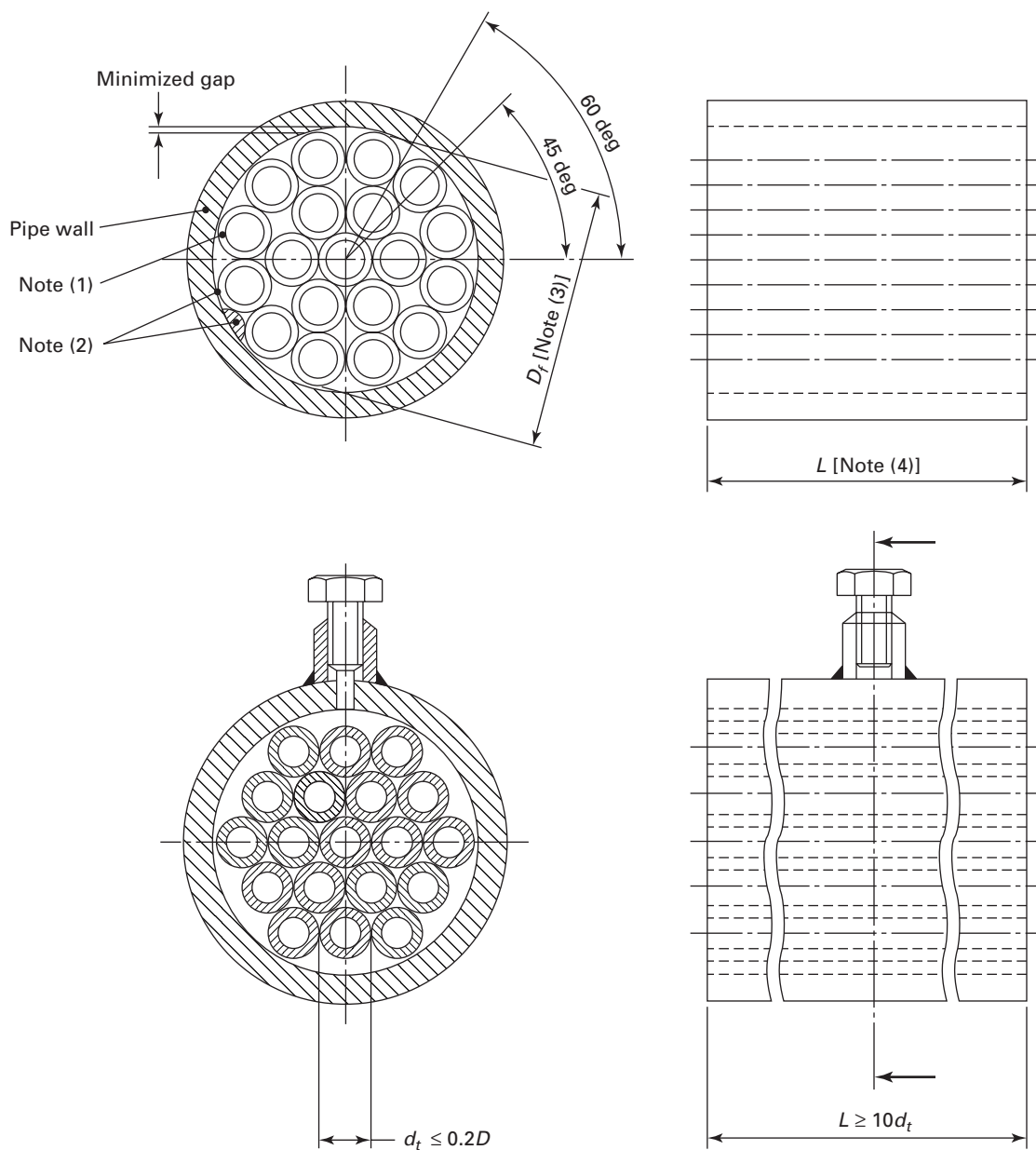
1C-3   FLOW CONDITIONERS

1C-3.1 General Description

A flow conditioner is a device that, in addition to meeting the requirements of removing or significantly reducing swirl, will redistribute the velocity profile to produce conditions close to those of para. 1-6.3.3.

Many flow conditioners either are or include a perforated plate. Several such devices are now described in technical literature, and they are in general easier to manufacture, install, and accommodate than the tube bundle flow straightener. They have the advantage that their thickness is typically around $D/8$ as compared to a length of at least $2D$ for the tube bundle. Moreover, since they can be drilled from the solid rather than fabricated, a more robust device is produced offering repeatable performance.

In these devices swirl is reduced and the profile simultaneously redistributed by a suitable arrangement of hole and plate depth. A number of different designs are available as indicated in Nonmandatory Appendix 2B. The geometry of the plate is critical in determining the performance, effectiveness, and pressure loss across the plate. The NEL (Spearman), Sprenkle, and Zanker flow conditioners are examples of flow conditioners.

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(a07)

GENERAL NOTE: References to the 19-tube flow straightener refer to the 1998 design as shown at the top of this figure. The hexagonal layout tube bundle shown at the bottom of this figure provides inconsistent performance and is not recommended.

NOTES:
(1) Tube wall thickness, $< 0.025D$.
(2) Centering spacer locations, typically four locations.
(3) D_f = flow straightener outside diameter, $0.95D \leq D_f \leq D$.
(4) Length, L, of the tubes, $2D \leq L \leq 3D$, as close to $2D$ as possible.

Fig. 1C-1   Tube Bundle Flow Straightener

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1C-3.2 Examples

1C-3.2.1 The NEL (Spearman) Flow Conditioner. The NEL (Spearman) flow conditioner is shown in Fig. 1C-4. The NEL (Spearman) flow conditioner is shown in Fig. 1C-4. The dimensions of the holes are a function of the pipe inside diameter, D. The pressure loss coefficient, K, for the NEL (Spearman) flow conditioner is approximately equal to 3.2.

1C-3.2.2 Sprenkle Conditioner. The Sprenkle conditioner consists of three perforated plates in series with a length equal to $D \pm 0.1D$ between successive plates.

14.1

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ISO 5167," *Flow Measurement and Instrumentation*, March 1997: 39–41.

Weiss, M., Studzinski, W., and Attia, J., "Performance Evaluation of Orifice Meter Standards for Selected T-Junction and Elbow Installations," Proceedings of 5th International Symposium on Fluid Flow Measurement, Washington, D.C., April 2002.

Zanker, K.J. and Goodson, D., "Qualification of a Flow Conditioning Device According to the New API 14.3 Procedure," *Flow Measurement and Instrumentation*, June 2000: 79–87.

2-3   PRINCIPLES OF THE METHOD OF MEASUREMENT AND COMPUTATION

The principle of the method of measurement is based on the installation of an orifice plate into a pipeline in which a fluid is running full. The presence of the orifice plate causes a static pressure difference to exist between the upstream section and downstream sides of the plate. The mass rate of flow can be determined by Eq. (2-1):

(SI Units)

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \ \varepsilon \ \frac{\pi}{4} \ d^2 \sqrt{2\Delta p \rho_1} \qquad (2\text{-}1)$$

(U.S. Customary Units)

$$q_m = 0.09970190 C Y d^2 \sqrt{\frac{h_w \rho_1}{1 - \beta^4}}$$

Δp (h_w) represents the differential pressure, as defined in Part 1 of this Standard. The diameters d and D mentioned in the equations are the values of the diameters at the working conditions. Measurements taken at any other conditions must be corrected for any possible expansion or contraction of the primary device and the pipe due to the temperature and pressure of the fluid during measurement.

The value of the volume rate of flow can be simply calculated since

$$q_v = \frac{q_m}{\rho} \qquad (2\text{-}2)$$

where
ρ = fluid density at the temperature and pressure for which the volume is stated

The uncertainty limits can be calculated using the procedure given in para. 1-7 of this Standard. Broader and more detailed information for calculation of the uncertainty in flow measurement is given in ASME MFC-2M and ISO/TR 5168.

Computation for flow rate is performed by utilizing Eq. (2-1). It is necessary to know the density and the viscosity of the fluid at the working conditions. In the case of a compressible fluid, it is necessary to know the isentropic exponent of the fluid at the working conditions.

2-4   ORIFICE PLATES

The various types of standard orifice plates are similar and therefore only a single description is needed. Each type of standard orifice meter is characterized by the arrangement of the pressure taps.

All types of orifice plate shall conform to the following description under working conditions. Limits of use are given in para. 2-4.3.1.

2-4.1 Description

The axial plane cross-section of a standard orifice plate is shown in Fig. 2-1. The letters given in the following refer to the corresponding references in Fig. 2-1.

2-4.1.1   General Shape
(a) The part of the plate inside the pipe shall be circular and concentric with the pipe centerline. The faces of the plate shall always be flat and parallel.

(b) Unless otherwise stated, the following requirements apply only to that part of the plate located within the pipe.

(c) Care shall be taken in the design of the orifice plate and its installation to ensure that plastic buckling and elastic deformation of the plate, due to the magnitude of the differential pressure or of any other stress, do not cause the slope of the straight line defined in para. 2-4.1.2(a) to exceed 1% under working conditions.
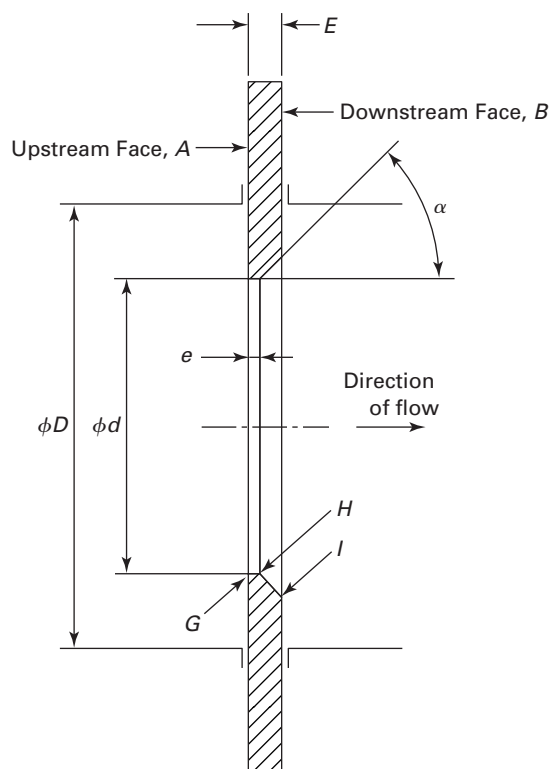

Fig. 2-1   Standard Orifice Plate

2-4.1.2 Upstream Face, *A*

(a) The upstream face, *A*, of the plate shall be flat when the plate is installed in the pipe with zero differential pressure across it. Provided it can be shown that the method of mounting does not distort the plate, this flatness can be measured with the plate removed from the pipe. Under these circumstances, the plate can be considered to be flat when the maximum gap between the plate and a straight edge of length *D* laid across any diameter of the plate (see Fig. 2-2) is less than [0.005(*D* − *d*)/2], i.e., the slope is less than 0.5%, when the orifice plate is examined prior to insertion into the pipeline. As can be seen from Fig. 2-2 the critical area is in the vicinity of the orifice bore. The uncertainty requirements for this dimension can be met using feeler gauges.

(b) The upstream face of the orifice plate shall have a roughness criterion $R_a < 10^{-4}d$ within a circle of diameter not less than *D* concentric with the orifice bore. If in the working conditions the plate does not fulfill the specified conditions, it shall be polished or cleaned to a diameter of at least *D*.

(c) Where possible, it is useful to provide a distinctive mark that is visible when the orifice plate is installed to show that the upstream face of the orifice plate is correctly installed relative to the direction of flow.
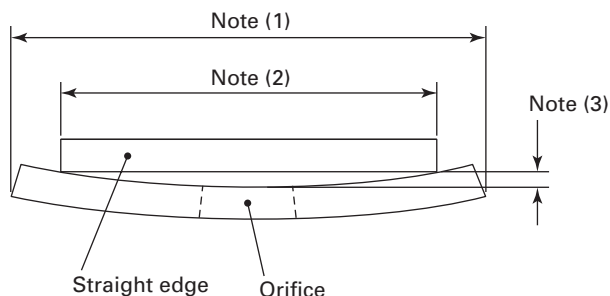
2-4.1.3 Downstream Face, *B*

(a) The downstream face, *B* shall be flat and parallel with the upstream face [see requirements of para. 2-4.1.4(d)].

(b) Although it may be convenient to manufacture the orifice plate with the same surface finish on each face, it is unnecessary to provide the same high quality finish for the downstream face as for the upstream face (see para. 2-4.1.8).

(c) The flatness and surface condition of the downstream face can be judged by visual inspection.

2-4.1.4 Thickness, *E* and *e*

(a) The thickness, *e*, of the orifice shall be between 0.005*D* and 0.02*D*.

NOTES:
(1) Orifice plate outside diameter.
(2) Pipe inside diameter.
(3) Departure from flatness.

Fig. 2-2   Orifice Plate Flatness Measurement

(b) The difference between the values of *e* measured at any point on the orifice shall not be greater than 0.001*D*.

(c) The thickness *E* of the plate shall be between *e* and 0.05*D*. When 50 mm ≤ *D* ≤ 64 mm (2 in. ≤ *D* ≤ 2.5 in.), however, a thickness *E* up to 3.2 mm (0.125 in.) is acceptable. It must also meet the requirements of para. 2-4.1.1(c).

(d) If *D* ≥ 200 mm (7.875 in.), the difference between the values of *E* measured at any point of the plate shall not be greater than 0.001*D*. If *D* < 200 mm (7.875 in.), the difference between the values of *E* measured at any point of the plate shall not be greater than 0.2 mm (0.008 in.).

2-4.1.5 Angle of Bevel, α (a07)

(a) If the thickness, *E,* of the plate exceeds the thickness, *e,* of the orifice, the plate shall be beveled on the downstream side. The beveled surface shall be smooth with no visible defects, such as grooves, pits, deposits, or ridges.

(b) The angle of bevel, α, shall be 45 deg ± 15 deg.

2-4.1.6 Edges, *G*, *H*, and *I*

(a) The upstream edge, *G* shall not have wire-edges, burrs, or any peculiarities visible to the naked eye.

(b) The upstream edge, *G* shall be sharp. It is considered so if the edge radius is not greater than 0.0004*d*.

If *d* ≥ 25 mm (1 in.), this requirement can generally be considered as satisfied by visual inspection by checking that the edge does not seem to reflect a beam of light when viewed with the naked eye. If *d* < 25 mm (1 in.), visual inspection is not sufficient. If there is any doubt as to whether this requirement is met, the edge radius shall be measured.

(c) The upstream edge shall be square. It is considered to be so when the angle between the orifice bore and the upstream face of the orifice plate is 90 deg ± 0.3 deg.

(d) The downstream edges, *H* and *I* are within the separated flow region. Consequently, the requirements for their quality are less stringent than those for edge, *G*. This being the case, small defects (e.g., a single nick not crossing the upstream edge) are acceptable.

2-4.1.7 Diameter of Orifice, *d*

(a) The diameter, *d* shall in all cases be greater than or equal to 12.5 mm (0.5 in.). The diameter ratio ($\beta = d/D$) shall be between 0.10 and 0.75. It should be noted, however, that the uncertainty statements given in this Standard favor diameter ratios between 0.20 and 0.60.

(b) The value, *d* of the diameter of the orifice shall be taken as the mean of the measurements of at least four diameters at approximately equal angles to each other. Care shall be taken that the edge and throat are not damaged when making these measurements.

The orifice plate temperature shall be recorded at the time the bore diameter measurements are made. These measurements shall be made under thermally stable conditions: during the measurement, the temperature should be constant within ± 0.5°C (± 1°F). For the purpose of flow calculation, the orifice bore diameter shall be corrected for the temperature difference between the

reference temperature of the bore measurement and the operating temperature under flowing conditions.

(c) The bore shall be cylindrical, concentric, and perpendicular to the upstream face.

No diameter shall differ by more than 0.05% from the value of the mean diameter. In all cases, the roughness of the orifice bore cylindrical section shall not be such that it affects the edge sharpness measurement.

The bore of the orifice plate shall be concentric with the axis of the adjacent pipe. Lack of concentricity is caused by the offset between the center of the bore and the center of the pipe. As stated in para. 2-5.3.3, this Part gives no information by which to predict the value of any additional uncertainty due to lack of concentricity.

2-4.1.8 Bidirectional Plates

(a) If the orifice plate is to be used for measuring reverse flows, the additional requirements of paras. 2-4.1.8(a)(1) through 2-4.1.8(a)(4) shall be fulfilled.

(1) The plate shall not be beveled.

(2) The two faces shall comply with the specifications for the upstream face given in para. 2-4.1.2.

(3) The thickness, E of the plate shall be equal to the thickness, e of the orifice specified in para. 2-4.1.4. Consequently, it may be necessary to limit the differential pressure to prevent plate distortion [see para. 2-4.1.1(c)].

(4) The two edges of the orifice shall comply with the specifications for the upstream edge specified in para. 2-4.1.6.

(b) For orifice plates with D and $D/2$ taps (see para. 2-4.2), two sets of upstream and downstream pressure taps shall be provided and used according to the direction of the flow.

2-4.1.9 Material and Manufacture.
The plate can be manufactured from any material and in any way, provided that it is and remains in accordance with the foregoing description during the flow measurements.

2-4.2 Pressure Taps

For each orifice plate, at least one upstream pressure tap and one downstream pressure tap shall be installed in one of the standard locations: D and $D/2$, flange, or corner taps.

A single orifice plate can be used with several sets of pressure taps suitable for different types of standard orifice meters. To avoid interference, multiple taps (either upstream or downstream) shall be offset by at least 30 deg. The location of the pressure taps characterizes the type of orifice meter.

2-4.2.1 Details of Pressure Taps for D and $D/2$ Tap Orifice Meters and Flange Tap Orifice Meters

(a) The spacing, l of a pressure tap is the distance between the centerline of the pressure tap and the plane of a specified face of the orifice plate (see Fig. 2-3). When installing the pressure taps, the thickness of the gaskets and/or sealing material shall be considered.

For orifice plates with D and $D/2$ taps, the spacing, l_1 of the upstream pressure tap is equal to

$$l_1 = D \pm 0.1D$$

The spacing, l_2 of the downstream pressure tap is equal to

(1) $l_2 = 0.5D \pm 0.02D$ for $\beta \leq 0.6$

(2) $l_2 = 0.5D \pm 0.01D$ for $\beta > 0.6$

Both l_1 and l_2 dimensions are measured from the upstream face of the orifice plate.

(b) For orifice plates with flange taps (see Fig. 2-3), the spacing, l_1 of the upstream pressure tap is nominally 25.4 mm (1 in.) and is measured from the upstream face of the orifice plate.

The spacing (l_2') of the downstream pressure tap is nominally 25.4 mm (1.00 in.) and is measured from the downstream face of the orifice plate.

These upstream and downstream dimensions (l_1 and l_2') shall be within the following ranges:

(1) 25.4 mm ± 0.5 mm, for $\beta > 0.6$ and $D < 150$ mm (1.00 in. ± 0.02 in., for $\beta > 0.6$ and $D < 6$ in.)

(2) 25.4 mm ± 1 mm, for $\beta \leq 0.6$ or $\beta > 0.6$ and **(a07)** 1000 mm ≥ D ≥ 150 mm (1.00 in. ± 0.04 in., for $\beta \leq 0.6$ or $\beta > 0.6$ and 40 in. ≥ D ≥ 6 in.)

(c) The centerline of the tap shall intersect the pipe centerline at an angle of 90 deg ± 3 deg.

(d) The hole on the inside wall of the pipe shall be circular. The edges shall be flush with the internal surface of the pipe wall and as sharp as possible. To ensure the elimination of all burrs or wire edges at the inner edge, rounding is permitted, but shall have a radius less than one-tenth of the pressure tap diameter. No irregularity shall appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or on the pipe wall close to the pressure tap.

(e) Conformity of the pressure taps with the requirements specified in paras. 2-4.2.1(c) and (d) can be judged by visual inspection.

(f) The diameter of pressure taps shall be less than $0.13D$ and less than 13 mm (0.5 in.). No restriction is placed on the minimum diameter, which is determined by the need to prevent blockage and to give satisfactory dynamic performance. The upstream and downstream taps shall have the same diameter.
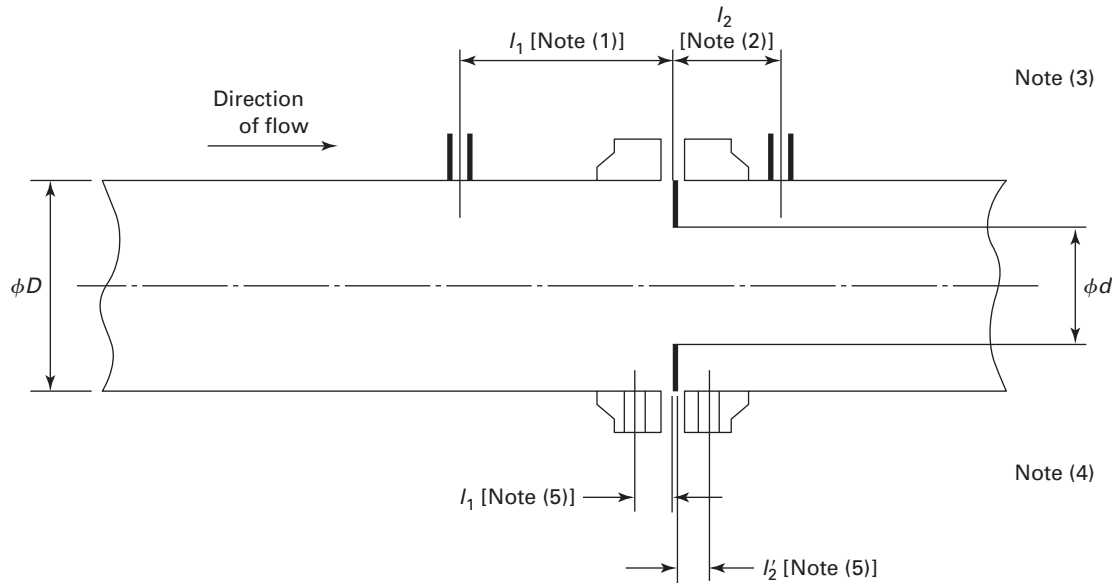
(g) The pressure taps shall be circular and cylindrical over a length of at least 2.5 times the internal diameter of the tap, measured from the inside wall of the pipe.

(h) The centerlines of the pressure taps can be located in any axial plane of the pipeline.

(i) The axes of the upstream and downstream taps shall be located in the same axial plane.

2-4.2.2 Orifice Plate With Corner Taps

(a) The spacing between the centerlines of the taps and the respective faces of the plate is equal to half the diameter or to half the width of the taps themselves, so that the tap holes break through the wall flush with the faces of the plate [see Fig. 2-4 and para. 2-4.2.2(e)].

NOTES:
(1) $l_1 = D \pm 0.1D$.
(2) $l_2 = 0.5D \pm 0.02D$ for $\beta \le 0.6$.
    $= 0.5D \pm 0.01D$ for $\beta > 0.6$.
(3) D and $D/2$ pressure tap arrangement.
(4) Flange tap arrangement.
(5) $l_1 = l'_2 = 25.4$ mm ± 0.5 mm (1.00 in. ± 0.02 in.) for $\beta > 0.6$ and $D < 150$ mm (6 in.)
    $= 25.4$ mm ± 1 mm (1.00 in. ± 0.04 in.) for $\beta \le 0.6$
    $= 25.4$ mm ± 1 mm (1.00 in. ± 0.04 in.) for $\beta > 0.6$ and 150 mm $\le D \le 1000$ mm (6 in. $\le D \le 40$ in.)

(a07) **Fig. 2-3 Spacing of Pressure Taps for Orifice Plates With D and $D/2$ Pressure Taps or Flange Taps**

(b) The pressure taps can be either single taps or annular slots. Both types of taps can be located either in the pipe or its flanges or in carrier rings as shown in Fig. 2-4.

(c) The diameter of a single tap and the width of annular slots are specified below. The minimum diameter is determined in practice by the need to prevent blockage and to give satisfactory dynamic performance.

For clean fluids and gases

(1) $0.005D \le a \le 0.03D$ for $\beta \le 0.65$

(2) $0.01D \le a \le 0.02D$ for $\beta > 0.65$

If $D < 100$ mm (4 in.), a value of a up to 2 mm (0.08 in) is acceptable for any β.

For any value of β

(3) for clean fluids: 1 mm (0.04 in.) $\le a \le 10$ mm (0.40 in.)

(4) for gases, in the case of annular chambers: 1 mm (0.04 in.) $\le a \le 10$ mm (0.40 in.)

(5) for gases and for liquefied gases, in the case of single taps: 4 mm (0.16 in.) $\le a \le 10$ mm (0.40 in.)

(d) The annular slots shall break through the inside wall of the pipe over the entire perimeter, with no break in continuity. If this is not possible, each annular chamber shall connect with the inside of the pipe by at least four openings, the axes of which are at equal angles to one another and the individual opening area of which is least 12 mm^2 (0.019 in.^{2}).

(e) If individual pressure taps are used, the centerline of the taps shall meet the centerline of the pipe at an angle of 90 deg ± 3 deg.

If there are several discrete pressure taps in the same upstream or downstream plane, their centerlines shall form equal angles to each other. The diameters of individual pressure taps are specified in para. 2-4.2.2(c).

The pressure taps shall be circular and cylindrical over a length of at least 2.5 times the internal diameter of the taps measured from the inner wall of the pipeline. The upstream and downstream pressure taps shall have the same diameter.

(f) The internal diameter, b, of the carrier ring shall be greater than or equal to the diameter, D, of the pipe, to ensure that they do not protrude into the pipe, but shall be less than or equal to $1.04D$. Furthermore, the following condition shall be met:

$$\frac{b - D}{D} \times \frac{c}{D} \times 100 \le \frac{0.1}{0.1 + 2.3\beta^4} \quad (2\text{-}3)$$

The lengths, c and c', of the upstream and downstream rings shall not be greater than $0.5D$. The thickness, f, of the slot shall be greater than or equal to twice the width of the annular slot, a. The area of the cross section of the annular chamber, gh, shall be greater than

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$$C = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\beta}{R_D}\right)^{0.7}$$

$$+ (0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{R_D}\right)^{0.3} + (0.043 + 0.080e^{-10L_1}$$

$$- 0.123e^{-7L_1})(1 - 0.11A)\,\frac{\beta^4}{1 - \beta^4} - 0.031(M_2' - 0.8M_2'^{1.1})\beta^{1.3}$$

$$\text{(2-4)}$$

When $D < 71.12$ mm (2.8 in.), the following term shall be added to Eq. (2-4):

(SI Units)

$$+0.011(0.75 - \beta)\left(2.8 - \frac{D}{25.4}\right) \qquad \text{(2-5)}$$

(U.S. Customary Units)

(a07)
$$+0.011(0.75 - \beta)(2.8 - D)$$

where
$\beta = d/D$
  = diameter ratio
R_D = pipe Reynolds number
$L_1 = l_1/D$
  = quotient of the distance of the upstream tap from the upstream face of the plate and the pipe diameter
$L_2' = l_2'/D$
  = quotient of the distance of the downstream tap from the downstream face of the plate, and the pipe diameter (L_2' denotes the reference of the downstream spacing from the downstream face, while L_2 would denote the reference of the downstream spacing from the upstream face)

$$M_2' = \frac{2L_2'}{1 - \beta}$$

$$A = \left(\frac{19000\beta}{R_D}\right)^{0.8}$$

The values of L_1 and L_2' to be used in this equation, when the dimensions are in accordance with the requirements of paras. 2-4.2.1(a) and (b) or para. 2-4.2.2 are as follows:

(a) for Corner taps

$$L_1 = L_2' = 0$$

(b) for D and $D/2$ taps

$$L_1 = 1$$
$$L_2' = 0.47$$

(a07) *(c)* for Flange taps
  (1) for D, mm: $L_1 = L_2' = (25.4/D)$
  (2) for D, in.: $L_1 = L_2' = (1/D)$

Equation (2-4) is valid only for the tap arrangements defined in paras. 2-4.2.1 or 2-4.2.2. It is not permitted to enter into the equation pairs of values of L_1 and L_2' that do not match one of these three tap arrangements.

This equation, as well as the uncertainties given in 2-4.3.3, is only valid when the measurement meets all the limits of use specified in para. 2-4.3.1 and the general installation requirements specified in para. 2-5, and in Part 1 of this Standard.

Nonmandatory Appendix 2B provides a discharge coefficient equation that has been analyzed, evaluated, and accepted by the international technical community and is often employed in custody transfer flow measurement in the oil and gas markets. This discharge coefficient equation shown in Nonmandatory Appendix 2B utilizes a subset of the data used to determine the discharge coefficients given by Eqs. (2-4) and (2-5). It has been found that for $0.35 \leq \beta \leq 0.60$, 100 mm $\leq D \leq 600$ mm (4 in. $\leq D \leq 24$ in.), the discharge coefficient values calculated by Eqs. (2B-1) and (2B-2) have been found to vary from the discharge coefficient values given by Eqs. (2-4) and (2-5) by less than 0.10%. For further information, see Nonmandatory Appendix 2B.

Values of C given in Eq. (2-4) as functions of β, R_D, and D are given for convenience in Tables 2A-1 to 2A-11. These values are not intended for precise interpolation and extrapolation is not permitted.

2-4.3.2.2 Expansibility Factor, ε (Y). For the three types of tap arrangement, the empirical formula for computing the expansibility factor, ε (Y), is as follows:

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8)\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{1}{\kappa}}\right] \quad \text{(2-6)}$$

Equation (2-6) is applicable only within the range of the limits of use specified in para. 2-4.3.1 and only if $P_2/P_1 \geq 0.80$.

Test results for the determination of ε (Y) are only known for air, steam, and natural gas. There is no known objection, however, to using the same formula for other gases for which the isentropic exponent is known.

Values of the expansibility factor as a function of the isentropic exponent, the pressure ratio, and the diameter ratio are given for convenience in Table 2A-12. These values are not intended for precise interpolation and extrapolation is not permitted.

2-4.3.3 Uncertainties

2-4.3.3.1 Uncertainty of Discharge Coefficient, C. For all three tapping arrangements, when β, R_D, D, and R_a/D are assumed to be known without error, the relative uncertainty of the value of C is equal to
(a) $\pm$ (0.7 $- \beta$)% for $0.1 \leq \beta < 0.2$
(b) $\pm$ 0.5% for $0.2 \leq \beta \leq 0.6$
(c) $\pm$ (1.667β $-$ 0.5)% for $0.6 < \beta \leq 0.75$
Where $D < 71.12$ mm (2.8 in.), the following relative uncertainty shall be added to the above values:

(SI Units)

$$\pm\ 0.9(0.75 - \beta)\left(2.8 - \frac{D}{25.4}\right)\% \qquad \text{(2-7)}$$

(U.S. Customary Units)

$$\pm\ 0.9(0.75 - \beta)(2.8 - D)\%$$

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Where $\beta > 0.5$ and $R_D < 10\,000$, 0.5% shall be added to the above values.

2-4.3.3.2 Uncertainty of Expansibility Factor, ε (Y). When β, $\Delta p/p_1$, and κ are assumed to be known without error, the relative uncertainty, %, of the value of ε (Y) is equal to

(SI Units)

$$\pm\ 3.5\ \frac{\Delta p}{\kappa p_1}\ \%\qquad(2\text{-}8)$$

(U.S. Customary Units)

$$\pm\ 3.5\ \frac{0.03606 h_w}{\kappa p_1}\ \%$$

2-4.4 Pressure Loss, $\Delta\varpi$ (h)

(a) The pressure loss, $\Delta\varpi$ (h), for the orifice plates described in Part 2 is approximately related to the differential pressure Δp (h_w) by the following equation:

(SI Units)

$$\Delta\varpi = \frac{\sqrt{1 - \beta^4(1 - C^2)} - C\beta^2}{\sqrt{1 - \beta^4(1 - C^2)} + C\beta^2}\ \Delta p\qquad(2\text{-}9)$$

(U.S. Customary Units)

$$h = \frac{\sqrt{1 - \beta^4(1 - C^2)} - C\beta^2}{\sqrt{1 - \beta^4(1 - C^2)} + C\beta^2}\ (0.03606 h_w)$$

This pressure loss is the difference in static pressure between the pressure measured at the wall on the upstream side of the orifice plate at a section where the influence of the approach impact pressure adjacent to the plate is still negligible (approximately $1D$ upstream of the orifice plate) and that measured on the downstream side of the orifice plate where the static pressure recovery by expansion of the jet may be considered as just completed (approximately $6D$ downstream of the orifice plate).

(b) Another approximate value of $\Delta\varpi/\Delta p$ (h/h_w) is $1 - \beta^{1.9}$.

(c) The pressure loss coefficient, K, for the orifice plate is

$$K = \left[\frac{\sqrt{1 - \beta^4(1 - C^2)}}{C\beta^2} - 1\right]^2\qquad(2\text{-}10)$$

where K is defined by the following Eq. (2-11):

(SI Units)

$$K = \frac{\Delta\varpi}{\frac{1}{2}\rho_1 V_1^2}\qquad(2\text{-}11)$$

(U.S. Customary Units)

$$K = \frac{h}{\frac{1}{2}\rho_1 V_1^2}$$

2-5 INSTALLATION REQUIREMENTS

2-5.1 General

(a07)

General installation requirements for pressure differential devices are contained in section 6 of Part 1 of this Standard and shall be followed in conjunction with the additional installation requirements for orifice plates given in this section. The general requirements for flow conditions at the primary device are given in para. 1-6.3 of this Standard. The requirements for use of a flow conditioner are given in para. 1-6.4 of this Standard. For some commonly used fittings shown in Table 2-3, the minimum straight lengths of pipe indicated can be used. Detailed requirements are given in para. 2-5.2. A flow conditioner (as in para. 2-5.3), however, will permit the use of a shorter upstream pipe length. Furthermore, a flow conditioner must be installed upstream of the orifice plate where sufficient straight length to achieve the desired level of uncertainty is not available. Downstream of a header, the use of a flow conditioner is strongly recommended.

2-5.2 Minimum Upstream and Downstream Straight Pipe Requirements

(a) The minimum straight lengths of pipe to be installed upstream and downstream of the orifice plate for various fittings in the installation without flow conditioners are given in Table 2-3.

(b) When a flow conditioner is not used, the lengths specified in Table 2-3 must be regarded as the minimum values. For research and calibration work, it is recommended that the upstream values specified in Table 2-3 be increased as much as reasonably possible.

(c) When the straight lengths used are equal to or longer than the values specified in each Column A and General Note (d) of Table 2-3 for "zero additional uncertainty," it is not necessary to increase the uncertainty in discharge coefficient to take account of the effect of the particular installation. Although termed "uncertainty" in this instance, using upstream lengths shorter than those given in each Column A of Table 2-3 will result in flow measurement bias errors. Furthermore, orientation of the pressure taps with respect to the various fittings can affect the magnitude of the bias error.

(d) For a given fitting, when the upstream straight length is greater than or equal to the "0.5% Additional Uncertainty" value shown in each Column B of Table 2-3 and/or shorter than the value corresponding to "Zero Additional Uncertainty" (as shown in each Column A), an additional uncertainty of 0.5% shall be added arithmetically to the uncertainty in the discharge coefficient. As detailed in para. 2-5.2(c), although termed *uncertainty* in this instance, when using upstream straight length greater than or equal to the value shown in each Column B of Table 2-3 and shorter than the value corresponding to shown in each Column A of Table 2-3, a flow measurement bias error less than 0.5% will be in-

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troduced. Since both the direction (positive or negative) and the magnitude of this error are specific to the installation in question, this Standard addresses this unknown bias error as an increase in the uncertainty band.

(e) Part 2 of this Standard cannot be used to predict the value of any additional uncertainty when the upstream straight length is shorter than the "0.5% Additional Uncertainty" values specified in each column B of Table 2-3, or when both the upstream and downstream straight lengths are shorter than the "Zero Additional Uncertainty" values specified in each Column A of Table 2-3 are used.

(f) The valves included in Table 2-3 shall be fully open during the flow measurement process. It is recommended that control of the flow rate be achieved by valves located downstream of the orifice plate. Isolating

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(a07)

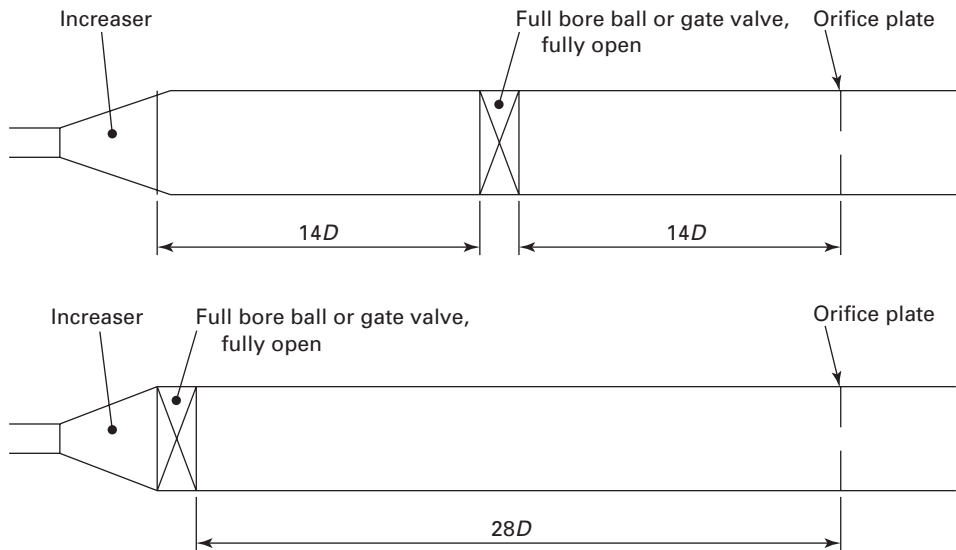## Table 2-3 Required Straight Lengths Between Orifice Plates and Fittings Without Flow Conditioners

Column descriptions (all on the Upstream (Inlet) Side of Orifice Plate except Column 14, which is the Downstream (outlet) Side of the Orifice Plate):

- **1** — Diameter Ratio β
- **2** — Single 90 deg Bend, Two 90 deg Bends in Any Plane (S > 30D) [Note (1)]
- **3** — Two 90 deg Bends in Same Plane: S-Configuration (30D ≥ S > 10D) [Note (1)]
- **4** — Two 90 deg Bends in Same Plane: S-Configuration (10D ≥ S) [Note (1)]
- **5** — Two 90 deg Bends in Perpendicular Planes (30D ≥ S ≥ 5D) [Note (1)]
- **6** — Two 90 deg Bends in Perpendicular Planes (5D > S) [Notes (1,2)]
- **7** — Single 90 deg Tee With or Without Extension Mitre 90 deg Bend
- **8** — Single 45 deg Bend, Two 45 deg Bends in Same Plane: S-Configuration (S ≥ 2D) [Note (1)]
- **9** — Concentric Reducer 2D to D Over Length of 1.5D to 3D
- **10** — Concentric Expander 0.5D to D Over Length of D to 2D
- **11** — Full Bore Ball Valve or Gate Valve Fully Open
- **12** — Abrupt Symmetrical Reduction
- **13** — Thermometer Pocket or Well of Diameter ≤ 0.03D [Notes (3,4)]
- **14** — Fittings (Columns 2 to 11) and Densitometer Pocket

β (1)	2 A	2 B	3 A	3 B	4 A	4 B	5 A	5 B	6 A	6 B	7 A	7 B	8 A	8 B	9 A	9 B	10 A	10 B	11 A	11 B	12 A	12 B	13 A	13 B	14 A	14 B
≤ 0.20	6	3	10	Note (5)	10	Note (5)	19	18	34	17	3	Note (5)	7	Note (5)	5	Note (5)	6	Note (5)	12	6	30	15	5	3	4	2
0.40	16	3	10	Note (5)	10	Note (5)	44	18	50	25	Note (5)	3	30	Note (5)	5	Note (5)	12	8	12	6	30	15	5	3	6	3
0.50	22	9	18	10	22	10	44	18	75	34	19	9	30	18	8	5	20	9	12	6	30	15	5	3	6	3
0.60	42	13	30	18	42	18	44	18	65 (6)	25	29	18	44	18	9	5	26	11	14	7	30	15	5	3	7	3.5
0.67	44	20	44	18	44	20	44	20	60	18	36	18	44	18	12	6	28	14	18	9	30	15	5	3	7	3.5
0.75	44	20	44	18	44	22	44	20	75	18	44	18	44	18	13	8	36	18	24	12	30	15	5	3	8	4

GENERAL NOTES:
(a) Values expressed as multiples of internal diameter, D.
(b) The minimum straight lengths required are the lengths between various fittings located upstream or downstream of the orifice plate and the orifice plate itself. Straight lengths shall be measured from the downstream end of the curved portion of the nearest (or only) bend or of the tee or the downstream end of the curved or conical portion of the reducer or the expander.
(c) Most of the bends on which the lengths in this table are based had a radius of curvature equal to 1.5D.
(d) Column A for each fitting gives lengths corresponding to "zero additional uncertainty" values [see para. 2-5.2(c)].
(e) Column B for each fitting gives lengths corresponding to "0.5% additional uncertainty" values [see para. 2-5.2(d)].

NOTES:
(1) S is the separation between the two bends measured from the downstream end of the curved portion of the upstream bend to the upstream end of the curved portion of the downstream bend.
(2) This is not a good upstream installation; a flow conditioner should be used where possible.
(3) The installation of thermometer pockets or wells will not alter the required minimum upstream straight lengths for the other fittings.
(4) A thermometer pocket or well of diameter between 0.03D and 0.13D may be installed provided that the values in each Column A and B are increased to 20 and 10 respectively. Such an installation is not, however, recommended.
(5) The straight length in each Column A gives zero additional uncertainty; data are not available for shorter straight lengths which could be used to give the required straight lengths for each Column B.
(6) 95D is required for $Re_D \times 10^6$ if S < 2D.

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Fig. 2-5   Layout Including a Full Bore Valve for $\beta = 0.6$

valves located upstream of the orifice plate shall be fully open, and these valves must be full bore. The valve should be fitted with stops for alignment of the ball or gate in the open position.

(g) Upstream valves that are bored to match the inside diameter of the adjacent pipe and are designed in such a manner that in the fully opened condition there are no steps, can be regarded as part of the upstream pipe length and do not need to have added lengths as in Table 2-3. Other valves should not be included upstream of the orifice plate. It is recommended that control of the flow rate be achieved by valves located downstream of the orifice plate.

(h) The values given in Table 2-3 were determined experimentally with fully developed and swirl-free flow upstream of the subject fitting. Since in practice such conditions are difficult to achieve, the following information can be used as a guide for normal installation practice.

(1) If several fittings of the type covered by Table 2-3 (other than the combinations of 90 deg bends already covered by this Table) are placed in series upstream of the orifice plate, the following paragraphs shall apply.

(a) Between the fitting immediately upstream of the orifice plate (Fitting 1) and the orifice plate itself, there shall be a straight length at least equal to the minimum length given in Table 2-3 appropriate for the specific orifice plate diameter ratio in conjunction with Fitting 1.

(a07) *(b)* Between Fitting 1 and the next fitting further upstream (Fitting 2), a minimum straight length equal to half the product of the diameter of the pipe between Fitting 1 and Fitting 2 and the number of diameters given in Table 2-3 for an orifice plate of diameter ratio 0.67 used in conjunction with Fitting 2 shall be included between Fittings 1 and 2, irrespective of the actual β for the orifice plate used. If either of the minimum straight

lengths is selected from Column B, a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty.

(c) If the upstream metering section has a full bore valve preceded by another fitting, then the valve can be installed at the outlet of the Fitting 2 from the orifice plate. The length between the valve and the Fitting 2 shall be added to the length between the orifice plate and the Fitting 1, specified in Table 2-3 (see also Fig. 2-5). Paragraph 2-5.2(h)(3) must also be satisfied (as it is in Fig. 2-5).

(2) In addition to the rule in para. 2-5.2(h)(1), a given fitting (treating any two consecutive 90 deg bends as a single fitting) must be located at a distance from the orifice plate at least as great as that given in Table 2-3. This is regardless of the number of fittings between the fitting in question and the orifice plate.

The distance between the orifice plate and the fitting shall be measured along the pipe axis. If the distance meets this requirement using the number of diameters in each Column B but not that in each Column A, then a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty. This additional uncertainty shall not be added more than once under the provisions of this paragraph and para. 2-5.2(h)(1).

(3) It is strongly recommended that a flow conditioner (see para. 1-6.4 of this Standard) be installed downstream of a metering system header (i.e., one whose cross section area is approximately equal to 1.5 times the cross sectional area of the operating flow meter tubes) since there will always be distortion of the flow profile and a high probability of swirl. When the second (or more distant) fitting from the orifice is a combination of bends, then in applying Table 2-3 the separation between the bends is calculated as a multiple of the diameter of the bends themselves.

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(a07) *(i)* Three cases of the application of paras. 2-5.2(h)(1) and 2-5.2(h)(2) are considered. In each case, the second fitting from the orifice plate is a two-bend combination in perpendicular planes (the separation between the bends is ten times the diameter of the bends) and the orifice plate has diameter ratio 0.4.

(1) If the first fitting is a full bore ball valve fully open (see Fig. 2-6a), the distance between the valve and the orifice plate must be at least 12*D* (from Table 2-3). Furthermore, between the two-bend combination in perpendicular planes and the valve, there must be at least 22*D* [from para. 2-5.2(h)(1)], and the distance between the two-bend combination in perpendicular planes and the orifice plate, there must be at least 44*D* [from para. 2-5.2(h)(2)]. If the valve has a laying length of 1*D*, an additional length of 9*D* is required. This length can be upstream, downstream, or partly upstream and partly downstream of the valve. Paragraph 2-5.2(h)(1)(c) could also be used to move the valve to be adjacent to the two-bend combination in perpendicular planes, provided that there is at least 44*D* from the two-bend combination in perpendicular planes to the orifice plate (see Fig. 2-6, sketch (b)).

(a07) *(2)* If the first fitting is a reducer from 2*D* to *D* over a length of 2*D* [see Fig. 2-6, sketch (c)], the distance between the reducer and the orifice plate must be at least 5*D* (from Table 2-3) and that between the two-bend combination in perpendicular planes and the reducer must be at least 22 × 2*D* [from para. 2-5.2(h)(1)]; the distance between the two-bend combination in perpendicular planes and the orifice plate must be at least 44*D* [from para. 2-5.2(h)(2)]. So no additional length is required because of para. 2-5.2(h)(3).

(3) If the first fitting is an increaser from 0.5*D* to *D* over a length of 2*D* (see Fig. 2-6, sketch (d)), the distance between the increaser and the orifice plate must be at least 12*D* (from Table 2-3). Furthermore, between the two-bend combination in perpendicular planes and the increaser, there must be at least 22 × 0.5*D* [from para. 2-5.2(h)(1)], and the distance between the two-bend combination in perpendicular planes and the orifice plate must be at least 44*D* [from para. 2-5.2(h)(2)]. So an additional length of 19*D* is required. This length can be upstream, downstream, or partly upstream and partly downstream of the expander.

2-5.3 Flow Conditioners

2-5.3.1 General. A flow conditioner can be used to reduce upstream straight lengths. See paras. 1-6.4.1 and 1-6.4.2 of this Standard for additional information.

Paragraphs 2-5.3.2 and 2-5.3.3 give the situations in which the 19-tube bundle flow straightener and the Zanker flow conditioner plate can be used upstream of orifice plates. Paragraphs 2-5.3.2.2 and 2-5.3.2.3 describe the situations in which the 19-tube bundle flow straightener and the Zanker flow conditioner plate can be used downstream of any fitting. Paragraph 2-5.3.2.3 describes some additional situations in which the 19-tube bundle flow straightener can be used to reduce the required upstream length.

Nonmandatory Appendix 2B describes some flow conditioners that can be used upstream of orifice plates and the requirements for straight pipe lengths associated with them. It is not intended that the inclusion of the flow conditioners described there limit the use of other flow conditioner designs that have been tested and proved to provide sufficiently small shifts in discharge coefficient.

2-5.3.2 The 19-Tube Bundle Flow Straightener

2-5.3.2.1 Description

2-5.3.2.1.1 Design. The 19-tube bundle flow straightener shall consist of nineteen (19) tubes arranged in a cylindrical pattern as shown in Fig. 2-7.

In order to reduce the swirl that can occur between the exterior tubes of the tube bundle flow straightener and the wall of the pipe, the maximum outside diameter of the flow straightener, D_f, must satisfy $0.95D \leq D_f \leq D$. The length, L, of the tubes shall be between 2*D* and 3*D*, preferably as close to 2*D* as possible.

2-5.3.2.1.2 Tubing of the 19-Tube Bundle Flow Straightener. It is necessary for all the tubes in the tube bundle to be of uniform smoothness, outer diameter and wall thickness. The individual tube wall thickness of the 19-tube bundle flow straightener shall be thin. All tubes shall have an internal chamfer on both ends. The wall thickness shall be less than 0.025*D*; this value is based on the wall thickness of the tubes used to collect the data on which Part 2 is based.

2-5.3.2.1.3 Fabrication of the 19-Tube Bundle Flow Straightener. The 19-tube bundle flow straightener must be fabricated to withstand the loads to which it will be subjected. Individual tubes should be welded together at the points of contact, at least at both ends of the tube bundle. It is important to ensure that the tubes are parallel to each other and to the pipe axis since, if this requirement is not adhered to, the straightener itself can introduce swirl into the flow. Centering spacers can be provided on the outside of the assembly to assist the installer in centering the device in the pipe; these can take the form of small lugs or small rods parallel to the pipe axis. After being inserted in the pipe, the tube bundle shall be securely fastened in place. Secure fastening, however, must not distort the tube bundle assembly with respect to symmetry within the pipe.

2-5.3.2.1.4 Pressure Loss. The pressure loss coefficient, K, for the 19-tube bundle flow straightener is approximately equal to 0.75, where K is given by Eq. (2-12):

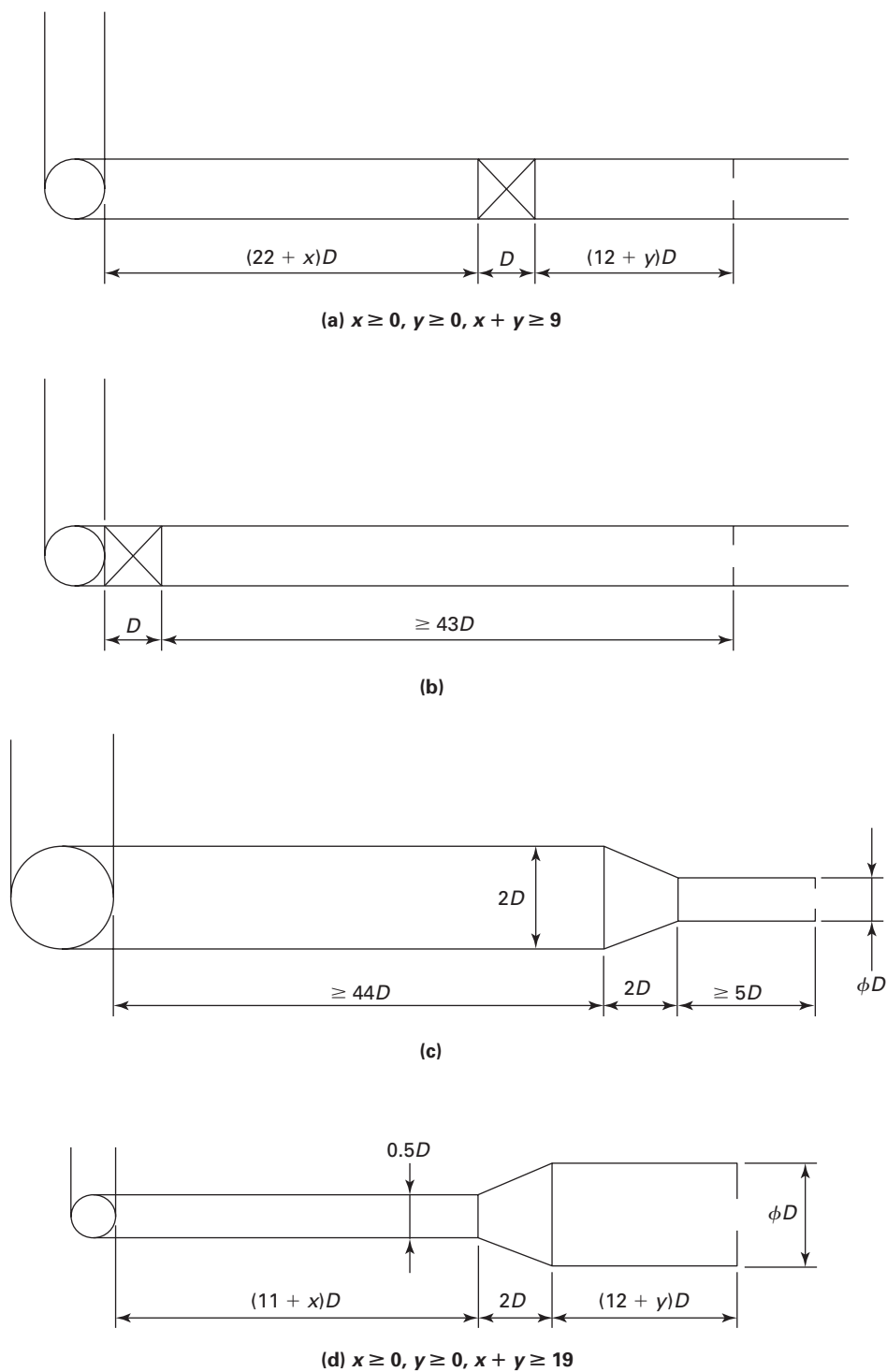$$K = \frac{\Delta p_c}{\frac{1}{2}\rho V^2} \tag{2-12}$$

where

Δp_c = pressure loss across the 19-tube bundle flow straightener

V = mean axial velocity of the fluid in the pipe

ρ = the fluid density

All units must be consistent.

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(a) $x \geq 0$, $y \geq 0$, $x + y \geq 9$

(b)

(c)

(d) $x \geq 0$, $y \geq 0$, $x + y \geq 19$

Fig. 2-6   Examples of Acceptable Installations

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"0.5% Additional Uncertainty" shown in each column B of Table 2-4.

(2) The downstream straight length is shorter than the value corresponding to "Zero Additional Uncertainty" shown in each Column A, but is either equal to or greater than the "0.5% Additional Uncertainty" value shown in each Column B of Table 2-3.

(d) Part 2 cannot be used to predict the value of any additional uncertainty when

(1) the straight length between orifice plate and 19-tube bundle flow straightener is not in accordance with the value corresponding to "0.5% Additional Uncertainty" shown in each Column B of Table 2-4.

(2) the downstream straight length is shorter than the "0.5% Additional Uncertainty" value specified in each Column B of Table 2-3.

(3) both the straight length between orifice plate and 19-tube bundle flow straightener is not in accordance with the value corresponding to "Zero Additional Uncertainty" shown in each Column A of Table 2-4 and the downstream straight length is shorter than the "Zero Additional Uncertainty" value specified in each Column A of Table 2-3.

(e) In the metering system, upstream valves that are bored to match the adjacent pipe and are designed in such a manner that in the fully opened condition there are no steps, can be regarded as part of the metering pipe length and do not need to be regarded as an upstream fitting, provided that when flow is being measured they are fully open. It is recommended that control of the flow rate be achieved by valves located downstream of the orifice plate.

(f) The values given in Table 2-3 were determined experimentally with fully developed and swirl-free flow upstream of the subject fitting. Since in practice such conditions are difficult to achieve, there shall be at least 15D of straight pipe between the fitting listed in Table 2-4 and the nearest fitting beyond that one, unless the columns relating to any fitting are used.

2-5.3.2.4 Example. If it is necessary to install a sin- **(a07)** gle bend upstream of an orifice plate of diameter ratio 0.6, there are two options using a 19-tube bundle flow straightener that will reduce the upstream length in comparison to the 42D required (see Table 2-3) if no flow conditioner is used. One approach is to permit an installation as in para. 2-5.3.2.2(b) (see Fig. 2-8, sketch (a)), which has the advantage that any fitting can be placed at any distance upstream of the single bend. Alternately, an installation as in Table 2-4 is permissible (see Fig. 2-8, sketch (b)), which gives a shorter straight length required down-

(a) Using Para. 2-5.3.2.2(b)

(b) Using Table 2-4

NOTES:
(1) Position of any fitting placed at any distance upstream of the single bend.
(2) Position of previous fitting placed before straight length upstream of the single bend.

**Fig. 2-8   Examples of Installations With a 19-Tube Bundle Flow Straightener
Downstream of a Single Bend**

stream of the bend but a straight length required upstream of the bend. If the upstream straight length to the bend is greater than or equal to 30*D*, Table 2-4 can also be used to provide a wider range of tube bundle locations (since these locations will rarely be required when designing installations, these options are not shown in Fig. 2-8).

2-5.3.3 The Zanker Flow Conditioner Plate. The Zanker Conditioner Plate described here is a development of the Zanker conditioner described in para. 1C-3.2.5 of Part 1 of this Standard. The Zanker Conditioner Plate has the same distribution of holes in a plate, but does not have the egg-box honeycomb attached to the plate. Instead, the plate thickness has been increased to $D/8$. It is not patented.

The Zanker Conditioner Plate shown in Fig. 2-9 meets the compliance test requirements given in para. 1-6.4.1(b) and 1-6.4.1(c) of this Standard, provided it meets the manufacturing specification in para. 5.3.2.3 and is installed in accordance with para. 5.3.2.3(a) and 5.3.2.3(b).

The Zanker flow conditioner plate consists of 32 bored holes arranged in a symmetrical circular pattern. The dimensions of the holes are a function of the pipe inside diameter D. The tolerance on the diameter of each hole is ± 0.1 mm (± 0.004 in.) for $D < 100$ mm (4 in.).

The perforated plate thickness, t_c, is such that $0.12D \leq t_c \leq 0.15D$. The flange thickness depends on the application; the outer diameter and flange face surfaces depend on the flange type and application.

The pressure loss coefficient, K, for Zanker Conditioner Plate is approximately equal to 3, where K is given by the following equation:

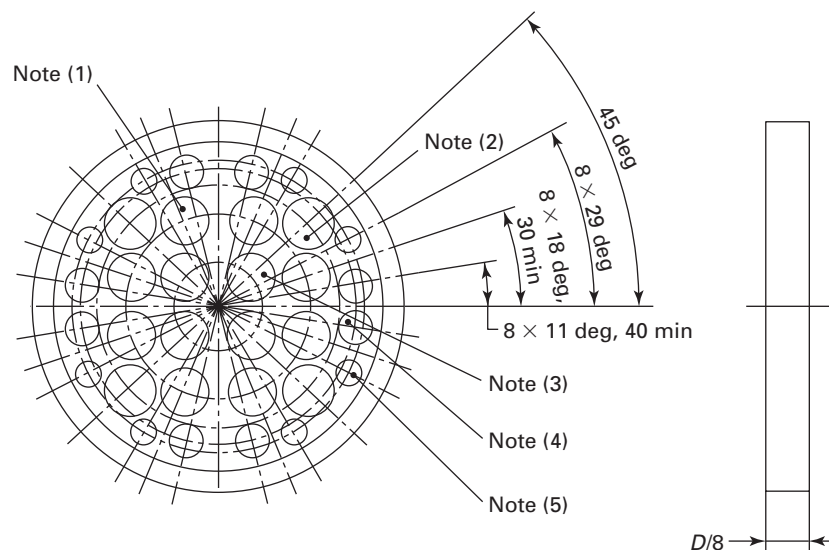$$K = \frac{\Delta p_c}{\frac{1}{2}\rho V^2} \tag{2-13}$$

where
Δp_c = pressure loss across the Zanker Conditioner Plate
V = mean axial velocity of the fluid in the pipe

2-5.3.3.1 Installation. Provided that $L_f \geq 18D$, it is **(a07)** acceptable to install the Zanker Conditioner Plate so that L_s, the distance between the downstream face of the Zanker Conditioner Plate and the orifice plate is such that $7.5D \leq L_s \leq (L_f - 8.5D)$, provided that $\beta \leq 0.67$.

This location is acceptable downstream of any fitting. A wider range of locations for the Zanker Conditioner Plate is permissible if the range of upstream fittings is restricted, if the overall length between the upstream fitting and the orifice plate is increased, or if the diameter ratio of the orifice plate is decreased. The distance to a bend (or bend combination) or a tee is measured to the downstream end of the curved portion of the nearest (or only) bend or of the tee. The distance to a reducer or expander is measured to the downstream end of the conical portion of the reducer or increaser.

NOTES:
(1) Hole diameter 0.139*D*, pitch circle diameter 0.56*D* ± 0.0056*D*, 8 holes.
(2) Hole diameter 0.1365*D*, pitch circle diameter 0.75*D* ± 0.0075*D*, 4 holes.
(3) Hole diameter 0.141*D*, pitch circle diameter 0.25*D* ± 0.0025*D*, 4 holes.
(4) Hole diameter 0.110*D*, pitch circle diameter 0.85*D* ± 0.0085*D*, 8 holes.
(5) Hole diameter 0.077*D*, pitch circle diameter 0.90*D* ± 0.009*D*, 8 holes.

Fig. 2-9 Zanker Flow Conditioner Plate

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NONMANDATORY APPENDIX 2B
ALTERNATE DISCHARGE COEFFICIENT
EQUATION FOR ORIFICE PLATES

The discharge coefficient equation shown in Eqs. (2B-1) and (2B-2) has been evaluated and accepted by the international technical community. It was developed under the joint auspices of the International Standards Organization (ISO), American Petroleum Institute (API), the American Gas Association (AGA), and the Gas Producers Association (GPA) and is prevalent in oil and gas flow measurement.

Although there are differences between these equations and those outlined in para. 2-4.3.2.1, for beta ratios between 0.35 and 0.60, and for line sizes 100 mm $\leq D \leq$ 600 mm (4 in. $\leq D \leq$ 24 in.), the discharge coefficient values calculated by Eqs. (2B-1) and (2B-2) have been found, in general, to vary from the discharge coefficient values given by Eqs. (2-4) and (2-5) by less than 0.10%. These equations are only valid when the measurement meets all the limits of use specified in: API MPMS 14.3.2, Fourth Edition; AGA Report No. 3, Part 2; and GPA 8185-00, Part 2.

$$C = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8$$
$$+ [0.0433 + 0.0712e^{-8.5L_1} - 0.01145e^{-6.0L_1}] (1 - 0.23A)\left[\frac{\beta^4}{1 - \beta^4}\right]$$
$$- 0.0116\beta^{1.1}(M'_2 - 0.52M'^{1.3}_2)(1 - 0.14A)$$
$$+ 0.000511\left(\frac{10^6\beta}{R_D}\right)^{0.7} + \beta^4(0.0210 + 0.0049A)\left(\frac{10^6}{R_D}\right)^{0.35} \quad (2B-1)$$

When $D < 71.12$ mm (2.8 in.), the following term shall be added to Eq. (2B-1):

(SI Units)

$$+0.003(1 - \beta) [2.8 - D/25.4)] \quad (2B-2)$$

(U.S. Customary Units)

$$+0.003(1 - \beta) (2.8 - D)$$

Note that use of orifice meters for fiscal measurement (custody transfer or billing) is often defined in contractual arrangements between parties. The user should verify which, if any, constraints are to be placed on the use of the orifice meter and which equation is to be used.

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Part 3
Nozzles and Venturi Nozzles

(a07) 3-1 SCOPE AND FIELD OF APPLICATION

Part 3 specifies the geometry and method of use (installation and operating conditions) of nozzles and venturi nozzles when they are inserted in a conduit running full to determine the flow-rate of the fluid flowing in the conduit.

It also provides background information for calculating the flow rate and should be applied in conjunction with the requirements given in Part 1 of this Standard, which contains general material applying to all the devices covered by this Standard, orifice plates, nozzles, and venturi tubes.

Part 3 applies only to nozzles and venturi nozzles in which the flow can be considered as single phase and remains subsonic throughout the measuring section and is steady or varies only slowly with time. It does not apply to the measurement of pulsating flow. In addition, each of these devices can only be used within specified limits of pipe size and Reynolds number. Thus Part 3 cannot be used for nominal pipe sizes less than 50 mm (2 in.), or more than 750 mm (30 in.), or for pipe Reynolds numbers below 10 000.

Part 3 addresses the ISA 1932 nozzle and the long radius nozzle, as well as with the venturi nozzle. The ISA 1932 and the long radius nozzles are fundamentally different and are described separately in this document. The venturi nozzle has the same upstream face as the ISA 1932 nozzle, but has a divergent section and, therefore, a different location for the downstream pressure taps. This design has a lower pressure loss than a nozzle with a similar geometry. For both of these nozzle types and for the venturi nozzle, direct calibration experiments have been made of sufficient quality, number, and data coverage to allow provision of coefficients within predictable limits of uncertainty and coherent systems of application.

3-2 REFERENCES AND RELATED DOCUMENTS

Normative references and definitions used within this document are contained in Part 1 of this Standard as are the associated symbols, subscripts, and definitions. References for this Part are listed below.

ISO/TR 3313:1998, Measurement of Fluid Flow in Closed Conduits—Guidelines on the Effects of Flow Pulsations on Flow-Measurement Instruments

ISO 4288:1996, Geometrical Product Specification (GPS)—

Surface Texture: Profile Method—Rules and Procedures for the Assessment of Surface Texture

ISO/TR 5168:1998, Measurement of Fluid Flow—Evaluation of Uncertainties

ISO/TR 9464:1998, Guidelines for the Use of ISO 5167-1:1991

Publisher: International Organization for Standardization (ISO), 1 rue de Varembe, Case Postale 56, CH-1211, Geneve 20, Switzerland/Suisse

3-3 PRINCIPLES OF THE METHOD OF MEASUREMENT AND COMPUTATION

The principle of the method of measurement is based on the installation of a nozzle or venturi nozzle into a pipeline in which a fluid is running full. The installation of the primary device causes a static pressure difference between the upstream side and the throat. Given the same conditions of use, whenever the device is geometrically similar to one on which direct calibration has been made, the rate of flow can be determined from the measured value of this pressure difference and from a knowledge of the fluid conditions.

The mass rate of flow can be determined by the following equation:

(SI Units)

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \; \varepsilon \; \frac{\pi}{4} \; d^2 \; \sqrt{2\Delta p\rho_1} \qquad (3\text{-}1)$$

(U.S. Customary Units)

$$q_m = 0.09970190 CYd^2 \sqrt{\frac{h_w\rho_1}{1 - \beta^4}}$$

$\Delta p\ (h_w)$ represents the differential pressure, as defined in Part 1 of this Standard. The diameters d and D mentioned in Eq. (3-1) are the values of the diameters at the working conditions. Measurements taken at any other conditions must be corrected for any expansion or contraction of the primary device and the pipe due to the temperature and pressure of the fluid during measurement.

The value of the volume rate of flow can be simply calculated since

$$q_v = \frac{q_m}{\rho} \qquad (3\text{-}2)$$

where

ρ = fluid density at the temperature and pressure for which the volume is stated

The uncertainty limits can be calculated using the procedure given in para. 1-7 of this Standard.

Computation for flow rate is performed by replacing the different terms on the right-hand side of Eq. (3-1) by their numeric values. It is necessary to know the density and the viscosity of the fluid at the working conditions. In the case of a compressible fluid, it is also necessary to know the isentropic exponent of the fluid at the working conditions. Tables 3A-1 through 3A-3 give the values of C as a function of β. Table 3A-4 gives expansibility factors, ε (Y), for different working conditions. These tables are not intended for precise interpolation and extrapolation is not permitted. The coefficient
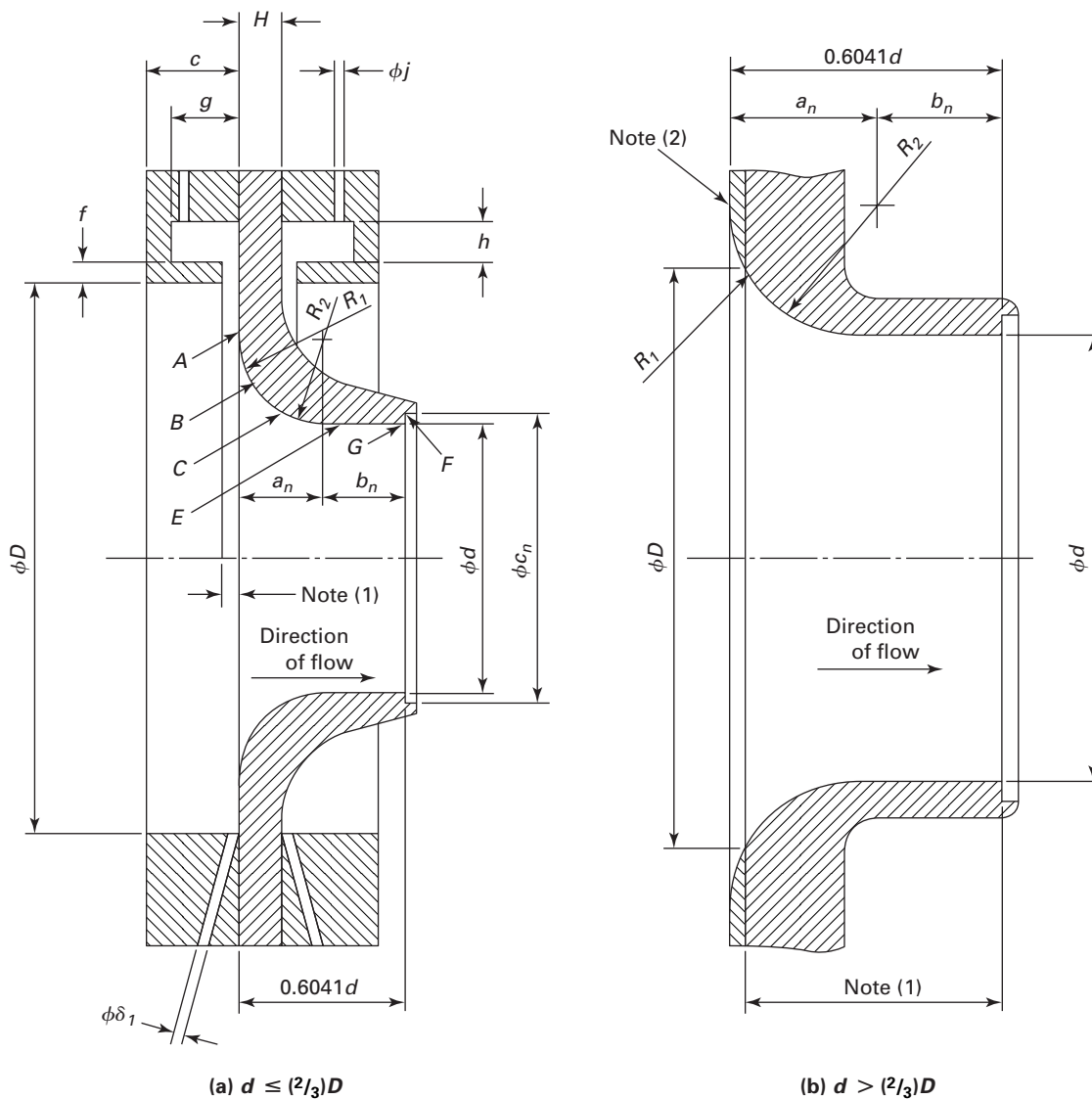
of discharge, C, may be dependent on R_D, which is itself dependent on q_m and is obtained by iteration (see Part 1 of this Standard for guidance regarding the choice of the iteration procedure and initial estimates).

3-4 NOZZLES AND VENTURI NOZZLES

This Standard addresses three nozzle designs:
(a) the ISA 1932 nozzle (given in para. 3-4.1)
(b) the long radius nozzle (given in para. 3-4.2)
(c) the Venturi nozzle (given in para. 3-4.3)

The ISA 1932 nozzle and the long radius nozzle are fundamentally different; the Venturi nozzle has the

(a) $d \leq (^2/_3)D$

(b) $d > (^2/_3)D$

NOTES:
(1) See para. 3-4.1.2(g).
(2) Portion to be machined off.

Fig. 3-1   ISA 1932 Nozzle

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same inlet design as the ISA 1932 nozzle, but has a divergent section and, therefore, a different location for the downstream pressure taps. This design has a lower pressure loss than the ISA 1932 nozzle and the long radius nozzle. Limits of use for all three types are given in paras. 3-4.1.6.1, 3-4.2.6.1 and 3-4.3.4.1.

3-4.1 ISA 1932 Nozzle

(a07)   **3-4.1.1   General Shape.** The part of the nozzle inside the pipe is circular. The nozzle consists of a convergent section, rounded profile, and a cylindrical throat. Figure 3-1 shows the cross-section of an ISA 1932 nozzle at a plane passing through the centerline of the throat. The letters in the following text refer to those shown on Fig. 3-1. Note that the use of the ISA 1932 nozzle is rare in North America, but still sees widespread use in countries that use ISO standards.

3-4.1.2   Nozzle Profile

(a) The profile of the nozzle can be characterized by a flat inlet part, *A*, perpendicular to the centerline; a convergent section defined by two arcs of circumference, *B* and *C*; a cylindrical throat, *E*; and a recess, *F*. The recess, *F* is optional; in some instances, it may prevent damage to the edge, *G*.

(b) The flat inlet part, *A* is limited by a circumference centered on the axis of revolution, with a diameter of 1.5*d*, and by the inside circumference of the pipe, of diameter *D*. When $d = 0.6667D$, the radial width of this flat part is zero.

When *d* is greater than 0.6667*D*, the upstream face of the nozzle does not include a flat inlet part within the pipe. In this case, the nozzle is manufactured as if *D* is greater than 1.5*d* and the inlet flat part is then faced off so that the largest diameter of the convergent profile is just equal to *D* [see para. 3-4.1.2(g) and Fig. 4-1, sketch (b)].

(c) The arc of circumference, *B* is tangential to the flat inlet part, *A* when $d < 0.6667D$, while its radius,

   (1) $R_1 = 0.2d \pm 0.02d$ for $\beta < 0.5$
   (2) $R_1 = 0.2d \pm 0.006d$ for $\beta \geq 0.5$

Its center is located 0.2*d* from the inlet plane and 0.75*d* from the axial centerline.

(d) The arc of circumference, *C* is tangential to the arc of circumference, *B* and to the throat, *E*. Its radius,

   (1) $R_2 = d/3 \pm 0.033d$ for $\beta < 0.5$
   (2) $R_2 = d/3 \pm 0.01d$ for $\beta \geq 0.5$

Its center is located 5*d*/6 (i.e., *d*/2 + *d*/3) from the axial centerline and at

$$a_n = \frac{12 + \sqrt{39}}{60}\, d = 0.3041d \qquad (3-3)$$

from the flat inlet part, *A*.

(e) The throat, *E* has a diameter, *d*, and a length $b_n = 0.3d$.

The value of the diameter of the throat shall be taken as the mean of the measurements of at least four diameters distributed in axial planes and at approximately equal angles to each other. The throat shall be cylindri-

cal. No diameter of any cross-section shall differ by more than 0.05% from the value of the mean diameter.

(f) The recess, *F* has a diameter c_n equal to at least 1.06*d* and a length no greater than 0.03*d*. The ratio of the height $(c_n - d)/2$ of the recess to its axial length shall not be greater than 1.2.

The outlet edge, *G* shall be sharp.

(g) The total length of the nozzle, excluding the recess, *F*, as a function of β is equal to 0.6041*d* for $0.3 \leq \beta \leq 0.6667$ and for $0.6667 < \beta \leq 0.8$

$$\left[0.4041 + \left(\frac{0.75}{\beta} - \frac{0.25}{\beta^2} - 0.5225\right)^{0.5}\right]d \qquad (3-4)$$

(h) The profile of the convergent inlet shall be checked by means of a template. Two diameters of the convergent inlet in the same plane perpendicular to the axial centerline shall not differ from each other by more than 0.1% of their mean value.

(i) The surface of the upstream face and the throat shall be polished such that they have a roughness criterion, $R_a \leq 10^{-4}\, d$.

3-4.1.3   Downstream Face

(a) The thickness, *H* shall not exceed 0.1*D*.

(b) Apart from the above condition, the profile and the surface finish of the downstream face are not specified (see para. 3-4.1.1).

3-4.1.4   Material and Manufacture.
The ISA 1932 nozzle can be manufactured from any material and in any way, provided that it remains in accordance with the foregoing description during flow measurement.

3-4.1.5   Pressure Taps

(a) Corner pressure taps shall be used upstream of the nozzle. The upstream pressure taps can be either single taps or annular slots. Both types of tap can be located either in the pipe or its flanges or in carrier rings as shown in Fig. 3-1.

The spacing between the centerlines of individual upstream taps and face, *A* is equal to half the diameter of the taps themselves, so that the tap holes break through the wall flush with face, *A*. The centerline of individual upstream taps shall meet the centerline of the primary device at an angle of 90 deg ± 3 deg.

The diameter, δ_1, of a single upstream tap and the width, *a*, of annular slots are specified below. The minimum diameter is determined in practice by the need to prevent blockage and to give satisfactory performance.

   (1) clean fluids and gases
      (a) for $\beta \leq 0.65$, $0.005D \leq a$ or $\delta_1 \leq 0.03D$
      (b) for $\beta > 0.65$, $0.01D \leq a$ or $\delta_1 \leq 0.02D$
   (2) any value of β
      (a) for clean fluids, 1 mm (0.04 in.) $\leq a$ or $\delta_1 \leq 10$ mm (0.40 in.*)*
      (b) for gases, in the case of annular chambers, 1 mm (0.04 in.) $\leq a \leq 10$ mm (0.40 in.)
      (c) for gases and for liquefied gases, in the case of single taps, 4 mm (0.15 in.) $\leq \delta_1 \leq 10$ mm (0.40 in.)

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The annular slots shall break through the inside wall of the pipe over the entire perimeter, with no break in continuity. If this is not possible, each annular chamber shall connect with the inside of the pipe by at least four openings, the axes of which are at equal angles to one another, and the individual opening area of which is least 12 mm^2 (0.019 in.^{2}).

The internal diameter, b, of the carrier ring shall be greater than or equal to the diameter, D, of the pipe, to ensure that they do not protrude into the pipe, but shall be less than or equal to $1.04D$. Furthermore, the following condition shall be met:

$$\frac{b - D}{D} \times \frac{c}{D} \times 100 \leq \frac{0.1}{0.1 + 2.3\beta^4} \qquad (3\text{-}5)$$

The length, c, of the upstream ring (see Fig. 3-1) shall not be greater than $0.5D$. The thickness, f, of the slot shall be greater than or equal to twice the width, a, of the annular slot. The area of the cross-section of the annular chamber, gh, shall be greater than or equal to half the total area of the opening connecting this chamber to the inside of the pipe.

All surfaces of the ring that are in contact with the measured fluid shall be clean and shall have a well-machined finish. The pressure taps connecting the annular chambers to the secondary devices are pipe wall taps, circular at the point of breakthrough and with a diameter, j, between 4 mm and 10 mm (0.015 in. and 0.39 in.).

The upstream and downstream carrier rings need not necessarily be symmetrical in relation to each other, but they shall both conform to the preceding requirements. The diameter of the pipe shall be measured as specified in para. 3-5.4(b), the carrier ring being regarded as part of the primary device. This also applies to the distance requirement given in para. 3-5.4(d) so that s shall be measured from the upstream edge of the recess formed by the carrier ring.

(b) The downstream pressure taps can either be corner taps as described in para. 3-4.1.5(a), or as described in the remainder of this section. The distance between the center of the tap and the upstream face of the nozzle shall be

    (1) $\leq 0.15D$ for $\beta \leq 0.67$

    (2) $\leq 0.20D$ for $\beta > 0.67$

When installing the pressure taps, the thickness of the gaskets and/or sealing material must be taken into account.

The centerline of the tap shall meet the pipe centerline and be at an angle of 90 deg ± 3 deg to it. The hole on the inside wall of the pipe shall be circular. The edges shall be flush with the internal surface of the pipe wall and as sharp as possible. To ensure the elimination of all burrs or wire edges at the inner edge, rounding is permitted, but shall have a radius less than one-tenth of the pressure tap diameter. No irregularity shall appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or on the pipe wall close to the pressure tap. Con-

Table 3-1 Upper Limits of Relative Roughness of the Upstream Pipe for ISA 1932 Nozzles

β	$10^4\, R_a/D$
≤0.35	8.0
0.36	5.9
0.38	4.3
0.40	3.4
0.42	2.8
0.44	2.4
0.46	2.1
0.48	1.9
0.50	1.8
0.60	1.4
0.70	1.3
0.77	1.2
0.80	1.2

GENERAL NOTE: Most of the data on which this table is based were collected at $R_D \leq 1\ (10^6)$. At higher R_D, more stringent limits on pipe roughness are likely required.

formity of the pressure taps with the requirements of this paragraph can be judged by visual inspection.

The diameter of pressure taps shall be less than $0.13D$ and less than 13 mm (0.5 in.). No restriction is placed on the minimum diameter, which is determined by the need to prevent blockage and to give satisfactory dynamic performance. The upstream and downstream taps shall have the same diameter.

The pressure taps shall be circular and cylindrical over a length of at least 2.5 times the internal diameter of the tap, measured from the inner wall of the pipeline. The centerlines of the pressure taps can be located in any axial plane of the pipeline. The axis of the upstream tap and that of the downstream tap can be located in different axial planes.

3-4.1.6 Coefficients of ISA 1932 Nozzles

3-4.1.6.1 Limits of Use. The ISA 1932 Nozzle shall be used in accordance with this Part when

(a) 50 mm (2 in.) $\leq D \leq$ 500 mm (20 in.)

(b) $0.30 \leq \beta \leq 0.80$

(c) $7\ (10^4) \leq R_D \leq 1\ (10^7)$ for $0.30 \leq \beta < 0.44$

(d) $2\ (10^4) \leq R_D \leq 1\ (10^7)$ for $0.44 \leq \beta \leq 0.80$

In addition, the relative roughness of the pipe shall conform to the values given in Table 3-1.

Most of the experiments on which the values of the discharge coefficient, C, given in this Part are based, were carried out in pipes with a relative roughness $R_a/D \leq 1.2\ (10^{-4})$. Pipes with higher relative roughness can be used if the roughness for a distance of at least $10D$ upstream of the nozzle is within the limits given in Table 3-1. Information as to how to determine R_a is given in Part 1 of this Standard.

3-4.1.6.2 Discharge Coefficient, *C*. The discharge coefficient, *C*, is given by the following equation:

$$C = 0.9900 - 0.2262\beta^{4.1} - (0.00175\beta^2$$
$$- 0.0033\beta^{4.15})\left(\frac{10^6}{R_D}\right)^{1.15} \tag{3-6}$$

Values of C as a function of β and R_D are given for convenience in Table 3A-1. These values are not intended for precise interpolation and extrapolation is not permitted.

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3-4.1.6.3 Expansibility Factor, ε (Y). The expansibility factor, ε (Y), is calculated by means of Eq. (3-7):

$$\varepsilon\,(Y) = \left\{ \left(\frac{\kappa\tau^{2/\kappa}}{\kappa - 1} \right)\left(\frac{1 - \beta^4}{1 - \beta^4\tau^{2/\kappa}} \right)\left[\frac{1 - \tau^{(\kappa-1)/\kappa}}{1 - \tau} \right] \right\}^{0.5} \quad (3\text{-}7)$$

where
τ = pressure ratio (p_2/p_1)
κ = isentropic exponent

This equation is applicable only for values of D, β, and R_D as specified in para. 3-4.1.6.1. Test results for determination of ε (Y) are known for air, steam, and natural gas. There is no known objection to using the same equation for other gases for which the isentropic exponent is known. The equation is applicable, however, only if the flow is not choked and $p_2/p_1 \geq 0.80$.

Values of the expansibility factor ε (Y) for a range of isentropic exponents, pressure ratios, and diameter ratios are given for convenience in Table 3A-4 in Appendix 3A. This table is not intended for precise interpolation and extrapolation is not permitted.

3-4.1.7 Uncertainties

3-4.1.7.1 Uncertainty of Discharge Coefficient, C. When D, β, R_D, and R_a/D are assumed to be known without error, the relative uncertainty of the value of C is equal to
(a) $\pm$ 0.80% for $\beta \leq 0.60$
(b) $\pm$ ($2\beta - 0.4$)% for $\beta > 0.60$

(a07) **3-4.1.7.2 Uncertainty of Expansibility Factor, ε (Y).** The relative uncertainty, %, of ε (Y) is equal to

(SI Units)

$$\pm\, 2\Delta p/p_2\% \quad (3\text{-}8)$$

(U.S. Customary Units)

$$\pm\, 2h_w/(27.73p_1)\%$$

This uncertainty assumes that β, Δp (h_w), p_1, and κ (the isentropic exponent of the line fluid) are known without error.

3-4.1.8 Pressure Loss, $\Delta\varpi$. The pressure loss, $\Delta\varpi$ (h), for the ISA 1932 nozzle is approximately related to the differential pressure Δp (h_w) by the Eq. (3-9)

(SI Units)

$$\Delta\varpi = \frac{\sqrt{1 - \beta^4(1 - C^2)} - C\beta^2}{\sqrt{1 - \beta^4(1 - C^2)} + C\beta^2}\, \Delta p \quad (3\text{-}9)$$

(U.S. Customary Units)

$$h = \frac{\sqrt{1 - \beta^4(1 - C^2)} - C\beta^2}{\sqrt{1 - \beta^4(1 - C^2)} + C\beta^2}\, (0.03606247h_w)$$

This pressure loss is the difference in static pressure between the pressure measured at the wall on the up-stream side of the primary device at a section where the influence of the approach impact pressure adjacent to the device is still negligible (approximately $1D$ upstream of the primary device) and that measured on the downstream side of the primary device where the static pressure recovery by expansion of the jet can be considered as just completed (approximately $6D$ downstream from the discharge of the primary device).

The pressure loss coefficient, K, for the ISA 1932 nozzle is

$$K = \left[\frac{\sqrt{1 - \beta^4(1 - C^2)}}{C\beta^2} - 1 \right]^2 \quad (3\text{-}10)$$

where K is defined by the following equation:

(SI Units)

$$K = \frac{\Delta\varpi}{\frac{1}{2}\,\rho_1 V_1^2} \quad (3\text{-}11)$$

(U.S. Customary Units)

$$K = \frac{h}{\frac{1}{2}\,\rho_1 V_1^2}$$

3-4.2 Long Radius Nozzles

3-4.2.1 General. There are two types of long radius nozzle.
(a) High-Beta nozzles ($0.25 \leq \beta \leq 0.8$)
(b) Low-Beta nozzles ($0.20 \leq \beta \leq 0.5$)
For β values between 0.25 and 0.50, either design can be used. Figure 3-2 illustrates the geometric shapes of long radius nozzles, showing cross-sections passing through the throat centerlines. The reference letters used in the text refer to those shown on Fig. 3-2. Both types of nozzle consist of a convergent inlet, whose shape is a quarter ellipse, and a cylindrical throat.

That part of the nozzle that is inside the pipe shall be circular in cross-section, with the possible exception of the holes of the pressure taps.

3-4.2.2 Profile of High-Beta Nozzle
(a) The inner face can be characterized by a convergent section, A, a cylindrical throat, B, and a plain end, C.
(b) The convergent section, A has the shape of a quarter ellipse. The center of the ellipse is at a distance $D/2$ from the axial centerline. The major centerline of the ellipse is parallel to the axial centerline. The value of half the major axis is $D/2$. The value of half the minor axis is $(D - d)/2$.

The profile of the convergent section shall be checked by means of a template. Any two diameters of the convergent section measured in the same plane perpendicular to the centerline shall not differ from each other by more than 0.1% of their mean value.
(c) The throat, B has a diameter, d, and a length $0.6d$.
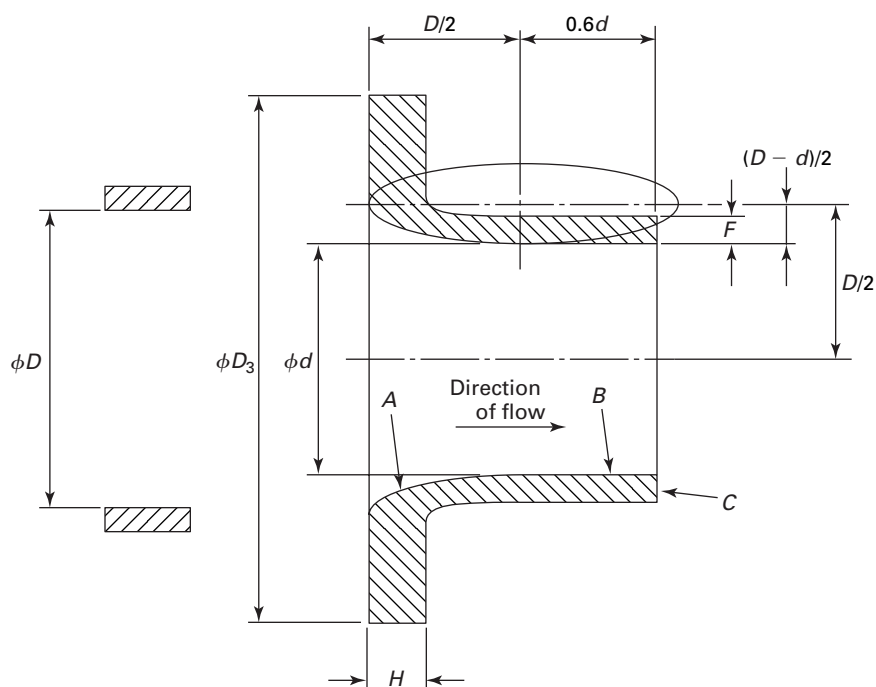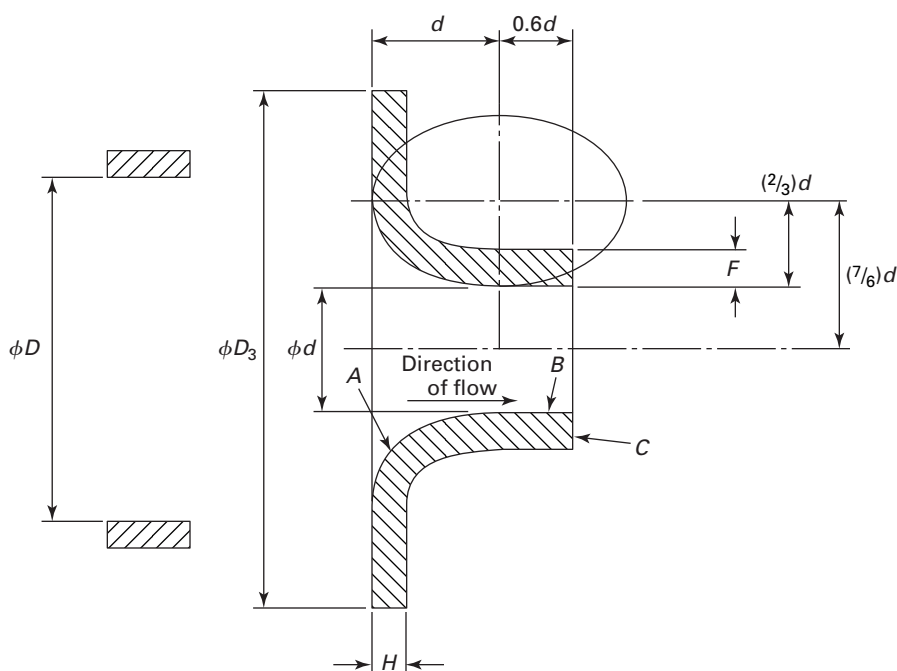The value d of the diameter of the throat shall be taken as the mean of the measurements of at least four diame-

(a) High Ratio 0.25 ≤ β ≤ 0.8

(b) Low Ratio 0.2 ≤ β ≤ 0.5

Fig. 3-2   Long Radius Nozzles

ters distributed in axial planes and at approximately equal angles to each other. The throat shall be cylindrical. Any diameter of any cross-section shall not differ by more than 0.05% from the value of the mean diameter. Measurement at a sufficient number of cross sections shall be made to determine that the throat does not diverge in the direction of flow. Within the stated uncertainty limits, however, the throat can be slightly convergent.

(d) The distance between the pipe wall and the outside face of the throat shall be no less than 3 mm (0.12 in.).

(e) The thickness, H shall be greater than or equal to 3 mm (0.12 in.) and less than or equal to $0.15D$. The thickness of the throat, F shall be greater than or equal to between 3 mm unless $D \leq 65$ mm (2.5 in.), in which case, F shall be no less than 2 mm (0.08 in.). The thickness shall be sufficient to prevent distortion due to fabrication and/or machining.

(f) The surface of the inner face shall have a roughness criterion $R_a \leq 10^{-4} d$.

(g) The shape of the downstream (outside) face is not specified but shall comply with paras. 3-4.2.2(d) and (e), and the last sentence of para. 3-4.2.1.

3-4.2.3 Profile of Low-Beta Nozzle

(a) The requirements given in para. 3-4.2.2 for the high-beta nozzle apply also to the low-beta nozzle with the exception of the shape of the ellipse, which is given in para. 3-4.2.3(b).

(b) The convergent inlet, A has the shape of a quarter ellipse. The center of the ellipse shall be $7d/6$ (i.e., $d/2 + 2d/3$) from the axial centerline. The major axis of the ellipse is parallel to the axial centerline. The value of half the major axis is d. The value of half the minor axis is $2d/3$.

3-4.2.4 Material and Manufacture.
The long radius nozzle can be manufactured from any material and in any way, provided that it remains in accordance with the foregoing description during flow measurement.

3-4.2.5 Pressure Taps

(a) The centerline of the upstream tap shall be at $1D$ $(+0.2D, -0.1D)$ from the inlet face of the nozzle. The centerline of the downstream tap shall be at $0.50D \pm 0.01D$ from the inlet face of the nozzle, except in the case of a low ratio nozzle with $\beta < 0.3188$. For a low ratio nozzle with $\beta < 0.3188$, the centerline of the downstream tap shall be at $1.6d$ $(+0, -0.02D)$ from the inlet face of the nozzle. Under no circumstances shall the downstream tap be located further downstream than the nozzle outlet. When installing the pressure taps, the thickness of the gaskets and/or sealing material shall be accounted for.

(a07) *(b)* The centerline of the tap shall meet the pipe centerline and be at an angle of 90 deg $\pm$ 3 deg. The hole on the inside wall of the pipe shall be circular. The edges shall be flush with the internal surface of the pipe wall and as sharp as possible. To ensure the elimination of all burrs or wire edges at the inner edge, rounding is permitted, but shall have a radius less than one-tenth of the pressure tap diameter. No irregularity shall appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or on the pipe wall close to the pressure tap.

The diameter of pressure taps shall be less than $0.13D$ and less than 13 mm (0.5 in.). No restriction is placed on the minimum diameter, which is determined in practice by the need to prevent blockage and to give satisfactory dynamic performance. The upstream and downstream taps shall have the same diameter.

The pressure taps shall be circular and cylindrical over a length of at least 2.5 times the internal diameter of the tap, measured from the inner wall of the pipeline. The centerlines of the pressure taps can be located in any axial plane of the pipeline. The axes of the upstream and downstream taps can be located in different azimuthal orientations, but are preferably located in the same azimuthal orientations.

3-4.2.6 Coefficients of Long Radius Nozzles

3-4.2.6.1 Limits of Use. The long radius nozzles **(a07)** shall only be used in accordance with this Part 3 when
(a) 50 mm (2 in.) $\leq D \leq$ 630 mm (25 in.)
(b) $1 (10^4) \leq R_D \leq 1 (10^7)$
(c) $0.2 \leq \beta \leq 0.8$
(d) $R_a/D \leq 3.2 (10^{-4})$ in the upstream pipe

Pipes with higher relative roughness can be used if the roughness for a distance of at least $10D$ upstream of the nozzle is within the limit given above. Information as to how to determine R_a is given in Part 1 of this Standard. Most of the data on which this roughness limit is based were collected at $R_D \leq 1 (10^6)$. At higher R_D, more stringent limits on pipe roughness are likely required.

3-4.2.6.2 Discharge Coefficient, C. The discharge coefficient is the same for both types of long radius nozzle when the taps are in accordance with para. 3-4.2.5.

The discharge coefficient, C, is given by the following equation, when referring to the upstream pipe Reynolds number R_D:

$$C = 0.9965 - 0.00653\beta^{0.5}\left(\frac{10^6}{R_D}\right)^{0.5} \tag{3-12}$$

When referring to the Reynolds number at the throat R_d, this equation becomes

$$C = 0.9965 - 0.00653\left(\frac{10^6}{R_d}\right)^{0.5} \tag{3-13}$$

and in this case, C is independent of the diameter ratio, β. Values of C as a function of β and R_D are given for convenience in Table 3A-2. These values are not intended for precise interpolation and extrapolation is not permitted.

3-4.2.6.3 Expansibility Factor, ε (Y). The indications given in para. 3-4.1.6.3 apply also to the expansibility factor for long radius nozzles, but within the limits of use specified in para. 3-4.2.6.1.

3-4.2.7 Uncertainties

3-4.2.7.1 Uncertainty of Discharge Coefficient, C. When β and R_d are assumed to be known without error, the relative uncertainty of the value of C is 2.0% for all values of β between 0.2 and 0.8.

(a07)   3-4.2.7.2 Uncertainty of Expansibility Factor, ε (Y).
The relative uncertainty, in percent, of ε (Y) is equal to

(SI Units)

$$\pm\, 2\Delta p/p_2\% \qquad (3\text{-}14)$$

(U.S. Customary Units)

$$\pm\, 2h_w/(27.73p_1)\%$$

This uncertainty assumes that β, Δp (h_w), p_1, and κ (the isentropic exponent of the line fluid) are known without error.

3-4.2.8   Pressure Loss, $\Delta\varpi$ (h). Paragraph 3-4.1.8 applies equally to the pressure loss of long radius nozzles.
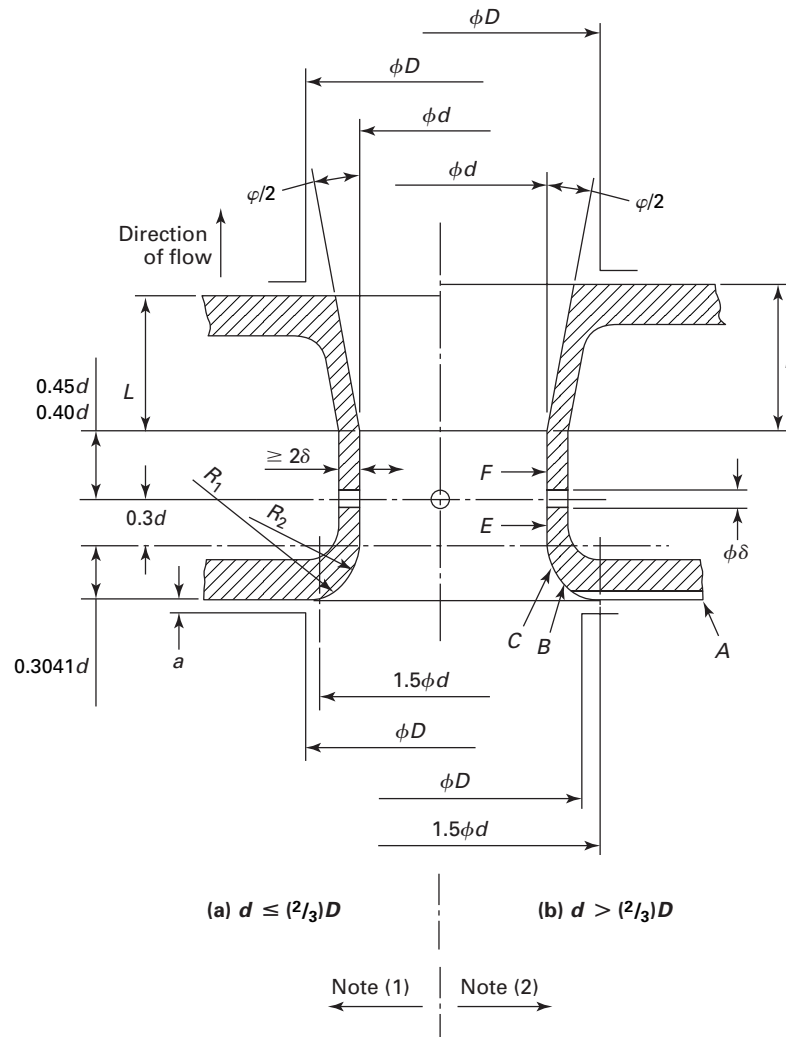
3-4.3 Venturi Nozzles

3-4.3.1   General Shape
(a) The profile of the venturi nozzle (see Fig. 3-3) is axisymmetric. It consists of a convergent section, with a rounded profile, a cylindrical throat, and a divergent section.
(b) The upstream face is identical with that of an ISA 1932 nozzle (see Fig. 3-1).
(c) The flat inlet part, A is limited by a circumference centered on the axis of revolution, with a diameter of 1.5d, and by the inside circumference of the pipe, of diameter D. When $d = 0.6667D$, the radial width of this flat portion is zero.

When d is greater than 0.6667D, the upstream face of the nozzle does not include a flat inlet part within the pipe. In

NOTES:
(1) Truncated divergent section.
(2) Nontruncated divergent section.

Fig. 3-3   Venturi Nozzle

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pressure taps with respect to the various fittings can affect the magnitude of the bias error.

(d) For a given fitting, when the upstream straight length is greater than or equal to the "0.5% Additional Uncertainty" value shown in each Column B of Table 3-3 and shorter than the value corresponding to "Zero Additional Uncertainty" (as shown in each Column A), an additional uncertainty of 0.5% shall be added arithmetically to the uncertainty in the discharge coefficient. As detailed in para. 3-5.2.3, although termed "uncertainty" in this instance, when using upstream straight length greater than or equal to the value shown in each Column B of Table 3-3 and shorter than the value corresponding to each Column A of Table 3-3, a flow measurement bias error less than 0.5% will be introduced. Since both the direction (positive or negative) and the magnitude of this error are specific to the installation in question, this Standard addresses this unknown bias error as an increase in the uncertainty band.

(e) Part 3 of this Standard cannot be used to predict the value of any additional uncertainty when the upstream straight length is shorter than the "0.5% Additional Uncertainty" values specified in each Column B of Table 3-3, nor when both the upstream and downstream straight lengths are shorter than the "Zero Additional Uncertainty" values specified in each Column A of Table 3-3 are used.

(f) The valves included in Table 3-3 shall be fully open during the flow measurement process. It is recommended that control of the flow rate be achieved by valves located downstream of the primary element. Isolating valves located upstream of the primary element shall be fully open, and these valves must be full bore. The valve should be fitted with stops for alignment of the ball or gate in the open position.

(g) Upstream valves that are bored to match the inside diameter of the adjacent pipe and are designed in such a manner that in the fully opened condition there are no steps, can be regarded as part of the upstream pipe length, and do not need to have added lengths as in Table 3-3. Other valves should not be included upstream of the primary element. It is recommended that control of the flow rate be achieved by valves located downstream of the primary element.

(h) The values given in Table 3-3 were determined experimentally with fully developed and swirl-free flow upstream of the subject fitting. Since such conditions are difficult to achieve, the following information can be used as a guide for normal installation practice:

(1) If the nozzle or venturi nozzle is installed in a pipe leading from an upstream open space or large vessel, either directly or through any other fittings covered by Table 3-3, the total length of pipe between the open space and the primary device shall never be less than 30*D*. If a fitting covered by Table 3-3 is installed then the straight lengths specified in the table shall also apply between this fitting and the primary device.

NOTE: A metering system header is not an open space or large vessel in this instance. A large vessel must have a cross-section area of at least ten times that of the metering tube. In the case of a normal header (cross-sectional area is typically 1.5 times the cross-sectional area of the operating flow meter tubes), it is strongly recommended that a flow conditioner be installed downstream of the header (see para. 1-6.4 of this Standard) since there will always be distortion of the flow profile and a high probability of swirl.

(2) If several fittings of the type covered by Table 3-3 (other than the combinations of 90 deg bends already covered by this Table) are placed in series upstream of the primary device, the following paragraphs shall apply:

(a) Between the fitting immediately upstream of the primary device (Fitting 1) and the primary device itself, there shall be a straight length at least equal to the minimum length given in Table 3-3 appropriate for the specific nozzle or venturi nozzle diameter ratio in conjunction with Fitting 1.

(b) Between Fitting 1 and the next fitting further **(a07)** from the nozzle or venturi nozzle (Fitting 2): Irrespective of the actual β of the primary device used, a minimum straight length equal to half the number of diameters given in Table 3-3 for a 0.7 diameter ratio primary device used in conjunction with Fitting 2 must be included between Fittings 1 and 2.
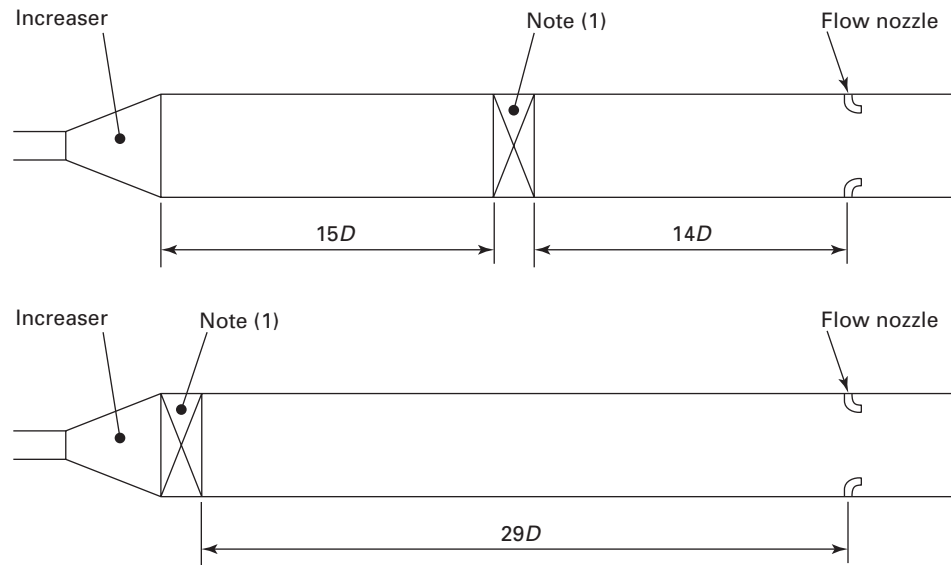
If either of the minimum straight lengths is selected from each Column B of Table 3-3, a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty. If the length between two or more consecutive 90-deg bends is more than 15*D*, these shall be treated as a single fitting in accordance with Table 3-3, Column 2.

(c) If the upstream metering section has a full bore valve preceded by another fitting, then the valve can be installed at the outlet of the second fitting from the primary device. The length between the valve and the second fitting shall be added to the length between the primary device and the first fitting, specified in Table 3-3 (see also Fig. 3-6). Note that para. 3-5.2(h)(3) must also be satisfied.

(3) In addition to the rule in para. 3-5.2(h)(2), any fitting (treating any two consecutive 90 deg bends as a single fitting) must be located at a distance from the primary device at least as great as that given in Table 3-3. This is regardless of the number of fittings between the fitting in question and the primary device.

The distance between the nozzle or venturi nozzle and the fitting shall be measured along the pipe axis. If the distance meets this requirement using the number of diameters in each Column B but not that in each Column A, then a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty. This additional uncertainty shall not be added more than once under the provisions of paras. 3-5.2(h)(2) and 3-5.2(h)(3).

(i) Three cases of the application of paras. 3-5.2(h)(2) **(a07)** and 3-5.2(h)(3) are considered. In each case, the second

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NOTE:
(1) Full bore ball or gate valve, fully open.

Fig. 3-6   Layout Including a Full Bore Valve for $\beta = 0.6$

fitting from the nozzle or venturi nozzle is a two-bend combination in perpendicular planes and the nozzle or venturi nozzle has diameter ratio 0.65.

If the first fitting is a full bore ball valve fully open (see Fig. 3-7, sketch (a)), the distance between the valve and the primary device must be at least $16D$ (from Table 3-3). Furthermore, between the two-bend combination in perpendicular planes and the valve, there must be at least $31D$ [from para. 3-5.2(h)(2)], and the distance between the two-bend combination in perpendicular planes and the primary device, there must be at least $54D$ [from 3-5.2(h)(3)]. If the valve has length $1D$, an additional length of $6D$ is required. This length can be upstream, downstream, or partly upstream and partly downstream of the valve. Paragraph 3-5.2(h)(2)(c) could also be used to move the valve to be adjacent to the two-bend combination in perpendicular planes provided that there is at least $54D$ from the two-bend combination in perpendicular planes to the primary device [see Fig. 3-7, sketch (b)].

If the first fitting is a reducer from $2D$ to D over a length of $2D$ [see Fig. 3-7, sketch (c)] the distance between the reducer and the nozzle must be at least $11D$ (from Table 3-3) and that between the two-bend combination in perpendicular planes and the reducer must be at least $31 \times 2D$ [from para. 3-5.2(h)(2)]; the distance between the two-bend combination in perpendicular planes and the nozzle must be at least $54D$ [from para. 3-5.2(h)(3)]. No additional length is required because of para. 3-5.2(h)(3).

If the first fitting is an expander from $0.5D$ to D over a length of $2D$ [see Fig. 3-7, sketch (d)], the distance between the expander and the nozzle or venturi nozzle

must be at least $25D$ (from Table 3-3). Furthermore, between the two-bend combination in perpendicular planes and the expander, there must be at least $31 \times 0.5D$ [from para. 3-5.2(h)(2)], and the distance between the two-bend combination in perpendicular planes and the primary device must be at least $54D$ [from para. 3-5.2(h)(3)]. An additional length of $11.5D$ is required. This length can be upstream, downstream, or partly upstream and partly downstream of the expander.
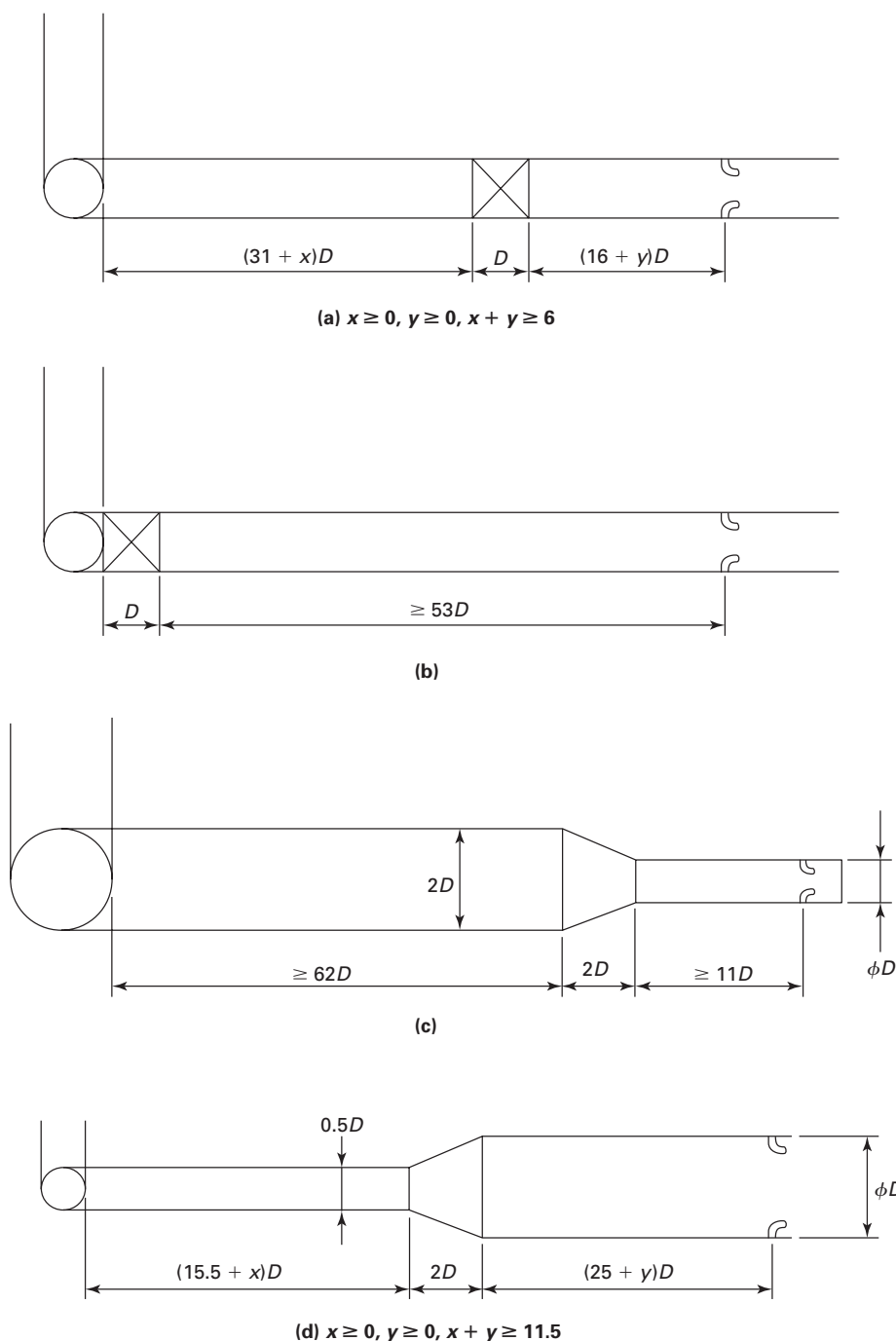
3-5.3 Flow Conditioners

A flow conditioner can be used to reduce upstream straight lengths. See paras. 1-6.4.1 and 1-6.4.2 for additional information. All test work shall be carried out using the same type of nozzle as is being used for the measurement of flow.

3-5.4 Circularity of Pipe Cross-Section

(a) The length of the upstream pipe section adjacent to the primary device (or to the carrier ring if there is one) shall be at least $2D$ and cylindrical. The pipe is said to be cylindrical when no diameter in any plane differs by more than 0.3% from the mean value of D obtained from the measurements specified in para. 3-5.4(b).

(b) The value for the pipe diameter D shall be the mean of the internal diameters over a length of $0.5D$ upstream of the upstream pressure tap. The mean internal diameter shall be the arithmetic mean of measurements of at least twelve diameters: four diameters (positioned at approximately equal angles to each

(a) $x \geq 0,\ y \geq 0,\ x + y \geq 6$

(b)

(c)

(d) $x \geq 0,\ y \geq 0,\ x + y \geq 11.5$

GENERAL NOTE: See para. 3-5.2(i).

Fig. 3-7 Examples of Acceptable Installations

other) and distributed in each of at least three cross sectional planes. These planes shall be evenly distributed over a length of $0.5D$. Two of these planes shall be 0 and $0.5D$ from the upstream tap, and one shall be in the plane of the weld (in the case of a weld-neck construction). If there is a carrier ring (see Fig. 3-4), this value of $0.5D$ shall be measured from the upstream edge of the carrier ring.

(c) Beyond $2D$ from the primary device, the upstream **(a07)** pipe run between the primary device and the first upstream fitting or disturbance can be made up of one or more sections of pipe.

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Between $2D$ and $10D$ from the nozzle, no additional uncertainty in the discharge coefficient is incurred if the diameter step (the difference between the diameters) between any two sections does not exceed 0.3% of the mean value of D obtained from the measurements specified in para. 3-5.4(b). Moreover, the actual step caused by misalignment and/or change in diameter must not exceed 0.3% of D at any point on the internal circumference of the pipe. Mating flanges, therefore, require the bores to be matched and the flanges aligned on installation. Dowels or self-centering gaskets can be used.

Beyond $10D$ from the nozzle, no additional uncertainty in the discharge coefficient is involved provided that the diameter step (the difference between the diameters) between any two sections does not exceed 2% of the mean value of D obtained from the measurements specified in para. 3-5.4(b). Moreover, the actual step caused by misalignment and/or change in diameter must not exceed 2% of D at any point of the internal circumference of the pipe. If the pipe diameter upstream of the step is greater than that downstream of it, the permitted diameter and actual steps are increased from 2% to 6% of D. On each side of the step, the pipe shall have a diameter between $0.98D$ and $1.06D$. Beyond $10D$ from the nozzle, the use of gaskets between sections will not violate this requirement provided that in use they are no thicker than 3.2 mm (0.125 in.), and they do not protrude into the flow.

Beyond the first location where an expander could be fitted in accordance with Column 6A of Table 3-3, no additional uncertainty in the discharge coefficient is incurred provided the diameter step (the difference between the diameters) between any two sections does not exceed 6% of the mean value of D obtained from the measurements specified in para. 3-5.4(b). Moreover, the actual step caused by misalignment and/or change in diameter must not exceed 6% of D at any point of the internal circumference of the pipe. The first location where an expander could be fitted in accordance with Column 6A of Table 3-3 depends on the diameter ratio of the primary device, e.g., it is $22D$ from the primary device if $\beta = 0.6$.

(d) An additional uncertainty of 0.2% shall be added arithmetically to the uncertainty for the discharge coefficient if the diameter step ΔD between any two sections exceeds the limits given in para. 3-5.4(c), but complies with the following relationships:

$$\frac{\Delta D}{D} \leq 0.002 \left(\frac{\frac{s}{D} + 0.4}{0.1 + 2.3\beta^4} \right) \qquad (3\text{-}19)$$

$$\frac{\Delta D}{D} \leq 0.05 \qquad (3\text{-}20)$$

where s is the distance of the step from the upstream pressure tap or, if a carrier ring is used, from the upstream edge of the recess formed by the carrier ring.

(e) If a step is greater than any one of the limits given in the inequalities above, the installation is not in accordance with Part 3. For further guidance refer to para. 1-5.1(a) of this Standard.

(f) No diameter of the downstream straight length, considered along a length of a least $2D$ from the upstream face of an ISA 1932 nozzle or a long radius nozzle, shall differ from the mean diameter of the upstream straight length by more than 3%. This can be judged by checking a single diameter of the downstream straight length.

The diameter of the pipe immediately downstream of an untruncated venturi nozzle shall not be less than 90% of the diameter at the end of the divergent section. This means that, in most cases, pipes having the same nominal bore as that of the venturi nozzle tube can be used.

3-5.5 Location of Primary Device and Carrier Rings

(a) The primary device shall be placed in the pipe in such a way that the fluid flows from the upstream face towards the throat.

(b) The primary device shall be perpendicular to the centerline of the pipe to within 1 deg.

(c) The primary device shall be centered in the pipe. The distance e_x between the centerline of the throat and the centerlines of the pipe on the upstream and downstream sides shall be

$$e_x \leq \frac{0.005D}{0.1 + 2.3\beta^4} \qquad (3\text{-}21)$$

If e_x does not conform to Eq. (3-21), then it falls beyond the scope of this Standard.

(d) When carrier rings are used, they shall be centered such that they do not protrude into the pipe at any point.

3-5.6 Method of Fixing and Gaskets

(a) The method of fixing and tightening shall be such that once the primary device has been installed in the proper position, it remains so. When holding the primary device between flanges, it is necessary to allow for its free thermal expansion and to avoid buckling and distortion.

(b) Gaskets or sealing rings shall be made and inserted in such a way that they do not protrude at any point inside the pipe or across the pressure taps or slots when corner taps are used. They shall be as thin as possible, with due consideration taken in maintaining the relationship as defined in paras. 3-4.1.5(b) or 3-4.2.5(a) as appropriate.

(c) If gaskets are used between the primary device and the annular chamber rings, they shall not protrude inside the annular chamber.

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The internal surface of the conical section of the convergent section is taken as being a surface of revolution if two diameters situated in the same plane perpendicular to the axis of revolution do not differ from the value of the mean diameter by more than 0.4%. It shall be checked in the same way that the joining curvature with a radius R_1 is a surface of revolution.

4-4.2.3 The Throat Section. The throat, C, shall be cylindrical with an inside diameter, d. It is limited upstream by the plane containing the intersection (or prolongations) of the cone frustum, B, with the throat, C and downstream by the plane containing the intersection (or prolongations) of the throat, C, with the cone frustum, E. The length of the throat, C, shall be equal to $d \pm 0.03d$ regardless of method of manufacture.

The throat, C is connected to the convergent section, B, by a curvature of radius R_2 and to the divergent section, E by a curvature of radius R_3. The values of R_2 and R_3 depend on the type of ASME venturi tube.

The diameter, d shall be measured in the plane of the throat pressure taps in such a manner as to minimize the uncertainty of the measurement. The number of measurements shall be at least equal to the number of pressure taps (with a minimum of four). The diameters shall be measured near each pair of pressure taps and also between these pairs. The arithmetic mean value of all these measurements shall be taken as the value of d in the calculations.

Diameters shall also be measured in planes other than the plane of the pressure taps. No diameter along the throat shall differ by more than 0.1% of the value of the mean diameter.

The throat of the ASME venturi tube shall be machined or be of equivalent smoothness over the whole of its length to the surface roughness specified in para. 4-4.2.6. The throat shall be checked that the joining curvatures into the throat with radii R_2 and R_3 are surfaces of revolution as described in para. 4-4.2.2. This requirement is satisfied when two diameters, situated in the same plane perpendicular to the axis of revolution, do not differ from the value of the mean diameter by more than 0.1%.

The values of the radii of curvature R_2 and R_3 shall be checked by means of a template. The deviation between the template and the ASME venturi tube shall evolve in a regular way for each curvature so that the single maximum deviation that is measured occurs at approximately midway along the template profile. The value of this maximum deviation shall not exceed 0.02d.

4-4.2.4 The Divergent Section. The divergent section, E, shall be conical and shall have an included angle between 7 deg and 15 deg. Its smallest diameter shall not be less than the throat diameter. This Standard provides pressure loss values for meters with divergent section included angles of 7 deg and 15 deg only; no information is given for intermediate angles.

4-4.2.5 Truncation. An ASME venturi tube is called *truncated* when the outlet diameter of the divergent section is less than the diameter, D and *not truncated* or *full* when the outlet diameter is equal to diameter, D. The divergent portion can be truncated up to 35% of its length without altering the value or tolerance of the discharge coefficient. Such truncation, however, will increase the pressure loss of the device. This Standard provides pressure loss values for divergent sections without truncation; no information is given for truncated recovery sections.

4-4.2.6 Roughness. The roughness criterion R_a of the throat and that of the adjacent radii shall be as small as possible and shall always be less than $10^{-4}d$. The divergent section is typically unmachined. Its internal surface shall be clean and smooth. Other parts of the ASME venturi tube have specified roughness limits depending on the type considered.

4-4.2.7 Characteristics of an ASME Venturi Tube With an "As-Cast" Convergent Section. The internal surface of the convergent section, B, is sand-cast. It shall be free from cracks, fissures, depressions, irregularities, and impurities. The roughness criterion R_a for the convergent surface shall be less than $10^{-4}D$.

The minimum length of the entrance cylinder, A, shall be equal to the smaller of the following two values: D and $0.25D + 250$ mm (10 in.) (see para. 4-4.2.1). The internal surface of the entrance cylinder, A, may be left "as-cast" provided that it has the same surface finish as the convergent section, B.

The radius of curvature R_1 shall be equal to $1.375D \pm 0.275D$. The radius of curvature R_2 shall be equal to $3.625d \pm 0.125d$.

The length of the cylindrical part of the throat shall be not less than $d/3$. In addition, the length of the cylindrical part between the end of the radius R_2 and the plane of the pressure taps, as well as the length of the cylindrical part between the plane of the throat pressure taps and the beginning of the radius R_3, shall be not less than $d/6$ (see also para. 4-4.2.3 for the throat length).

The radius of curvature R_3 shall lie between $5d$ and $15d$. Its value increases as the divergent angle decreases. A value of approximately $10d$ is recommended.

4-4.2.8 Characteristics of an ASME Venturi Tube With (a07) a Machined Convergent Section. The minimum length of the entrance cylinder, A, shall be equal to D. The entrance cylinder and the convergent section shall have a surface finish equal to that of the throat (see para. 4-4.2.6).

The radius of curvature R_1 shall be 0.25D maximum. The radius of curvature R_2 shall be 0.25d maximum. The length of the cylindrical throat, C, shall be equal to $d \pm 0.03d$.

In addition, the length of the cylindrical part between the end of the radius R_2 and the beginning of the radius R_3, shall be no less than 0.89d. The plane of the low pres-

sure tap(s) shall be centered in the cylindrical portion of the throat to within $\pm 0.02d$. The radius of curvature R_3 shall be 0.25d maximum.

4-4.2.9 Characteristics of an ASME Venturi Tube With a Rough-Welded Convergent Section. The minimum length of the entrance cylinder, A, shall be equal to D. There shall be no joining curvature between the entrance cylinder, A, and the convergent section, B, other than that resulting from welding. There shall be no joining curvature between the convergent section, B, and the throat, C, other than that resulting from welding. There shall be no joining curvature between the throat, C, and the divergent section, E. The internal surface of the entrance cylinder, A, and the convergent section, B shall be clean and free from encrustation and welding deposits. The roughness criterion R_a for the surface shall be about $5 (10^{-4})D$. The internal welded seams shall be flush with the surrounding surfaces. They shall not be located in the vicinity of the pressure taps.

4-4.3 Materials and Manufacture

(a) Materials. The ASME venturi tube can be manufactured from any material, provided that it is in accordance with the foregoing description and will remain so during use.

(b) It is recommended that the convergent section, B, and the throat, C, be joined as one part. It is recommended that in the case of a machined convergent, the throat and the convergent section be manufactured from one piece of material. If made in two separate parts they shall be assembled before the internal surface is finally machined.

(c) Particular care shall be given to the centering of the divergent section, E, on the throat, C. There shall be no step in diameters between the two parts. This can be established either visually or by touch.

4-4.4 Pressure Taps

4-4.4.1 The upstream and throat pressure taps shall be made in the form of separate pipe wall pressure taps interconnected by annular chambers or piezometer rings or, if there are four taps, a "Triple-T" arrangement (see para. 1-4.4.3 of this Standard).

4-4.4.2 Tap Size. If d is greater than or equal to 33.3 mm (1.30 in.), the diameter of these taps shall be between 4 mm (0.15 in.) and 10 mm (0.40 in.), but shall never be greater than 0.1D for the upstream taps and 0.13d for the throat pressure taps. If d is less than 33.3 mm (1.30 in.), the diameter of the throat pressure taps shall be between 0.1d and 0.13d and the diameter of the upstream pressure taps shall be between 0.1d and 0.1D. It is recommended that pressure taps as small as compatible with the fluid be used, e.g., viscosity and clarity.

4-4.4.3 Number of Pressure Taps. At least four pressure taps shall be provided for the upstream and throat

pressure measurements. The centerlines of the pressure taps shall meet the centerline of the ASME venturi tube, shall form equal angles with each other and shall be contained in planes perpendicular to the centerline of the ASME venturi tube.

4-4.4.4 Quality of Pressure Taps. The hole on the inside wall of the pipe shall be circular. The edges shall be flush with the internal surface of the pipe wall and as sharp as possible. To ensure the elimination of all burrs or wire edges at the inner edge, rounding is permitted, but shall have a radius less than one-tenth of the pressure tap diameter. No irregularity shall appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or on the pipe wall close to the pressure tap.

4-4.4.5 Length of Pressure Taps. The pressure taps shall be cylindrical over a length at least 2.5 times the internal diameter of the tap measured from the inner wall of the pipeline.

4-4.4.6 Location of Pressure Taps. The location of a pressure tap is the distance, measured on a straight line parallel to the centerline of the ASME venturi tube, between the centerline of the pressure tap and the reference planes defined below.

For the ASME venturi tube with an "as-cast" convergent section, the spacing between the upstream pressure taps situated on the entrance cylinder (A) and the plane of intersection between the entrance cylinder (A) and the prolongation of convergent section (B) shall be:

(a) $0.5D \pm 0.25D$ for 100 mm (4 in.) $\leq D \leq$ 150 mm (6 in.)

(b) $0.5D (+ 0.0D, - 0.25D)$ for 150 mm (6 in.) $< D \leq$ 1 200 mm (48 in.)

For ASME venturi tubes with a machined convergent section and with a rough-welded convergent, the spacing between the upstream pressure taps and the plane of intersection between the entrance cylinder, A, and the convergent section, B (or their prolongations) shall be $0.5D \pm 0.05D$.

For all types of ASME venturi tube, the spacing between the plane containing the axes of the points of breakthrough of the throat pressure taps and the intersection plane of the convergent section, B, and the throat, C (or their prolongations) shall be $0.5d \pm 0.02d$.

4-4.4.7 Pressure Taps With Annular Chambers. The area of the free cross-section of the annular chamber of the pressure taps shall be greater than or equal to half the total area of the tap holes connecting the chamber to the pipe. It is recommended, however, that the chamber section mentioned above shall be doubled when the ASME venturi tube is used with a minimum upstream straight length from a fitting causing asymmetric flow.

4-4.5 Discharge Coefficient, *C*

4-4.5.1 Limits of Use. Whatever the type of ASME venturi tube, a simultaneous use of extreme values for D,

β, and R_D should be avoided because the uncertainties given in para. 4-4.7 will likely be greater. For installations outside the limits defined in paras. 4-4.5.2, 4-4.5.3, and 4-4.5.4 for D, β, and R_D, it remains necessary to calibrate separately the primary element in its actual conditions of service. The effects of D, β, and R_a/D on C are not yet sufficiently known for it to be possible to give reliable values of C outside the limits defined for each type of ASME venturi tube (See Nonmandatory Appendix 4B).

4-4.5.2 Discharge Coefficient of the ASME Venturi Tube With an "As-Cast" Convergent Section. ASME venturi tubes with an "as-cast" convergent section can only be used in accordance with this Part of this Standard when

(a) 100 mm (4 in.) $\leq D \leq$ 1 200 mm (48 in.)

(b) $0.30 \leq \beta \leq 0.75$

(c) $2\ (10^5) \leq R_D \leq 6\ (10^6)$

Under these conditions, the value of the discharge coefficient, $C = 0.984$.

4-4.5.3 Discharge Coefficient of the ASME Venturi Tube With a Machined Convergent Section. ASME venturi tubes with a machined convergent section can only be used in accordance with Part 4 when

(a) 50 mm (2 in.) $\leq D \leq$ 250 mm (10 in.)

(b) $0.30 \leq \beta \leq 0.75$

(a07) *(c)* $2\ (10^5) \leq R_D \leq 2\ (10^6)$

Under these conditions, the value of the discharge coefficient, $C = 0.995$.

4-4.5.4 Discharge Coefficient of the ASME Venturi Tube With a Rough-Welded Convergent Section. ASME venturi tubes with a rough-welded convergent section can only be used in accordance with Part 4 when

(a) 100 mm (4 in.) $\leq D \leq$ 1 200 mm (48 in.)

(b) $0.30 \leq \beta \leq 0.75$

(c) $2\ (10^5) \leq R_D \leq 6\ (10^6)$

Under these conditions, the value of the discharge coefficient, $C = 0.985$.

4-4.6 Expansibility Factor

The expansibility factor, $\varepsilon\ (Y)$, is calculated by means of the following equation:

$$\varepsilon\ (Y) = \left\{ \left(\frac{\kappa \tau^{2/\kappa}}{\kappa - 1} \right) \left(\frac{1 - \beta^4}{1 - \beta^4 \tau^{2/\kappa}} \right) \left[\frac{1 - \tau^{(\kappa-1)/\kappa}}{1 - \tau} \right] \right\}^{0.5} \quad (4\text{-}3)$$

where

τ = pressure ratio (P_2/P_1)
κ = isentropic exponent

This equation is applicable only for values of D, β, and R_D as specified in 4-4.5.2, 4-4.5.3, or 4-4.5.4, as appropriate. Test results for determination of $\varepsilon\ (Y)$ are only known for air, steam, and natural gas. There is no known objection to using the same equation for other gases for which the isentropic exponent is known. The equation is applicable, however, only if $P_2/P_1 \geq 0.80$.

Values of the expansibility factor $\varepsilon\ (Y)$ for a range of isentropic exponents, pressure ratios, and diameter ratios are given for convenience in Table 4A-1 of this Standard. This table is not intended for precise interpolation and extrapolation is not permitted.

4-4.7 Uncertainty of the Discharge Coefficient, *C*

4-4.7.1 ASME Venturi Tube With an "As-Cast" Convergent Section. The relative uncertainty of the discharge coefficient as given in para. 4-4.5.2 is equal to 0.75%.

4-4.7.2 ASME Venturi Tube With a Machined Convergent Section. The relative uncertainty of the discharge coefficient as given in para. 4-4.5.3 is equal to 1.0%.

4-4.7.3 ASME Venturi Tube With a Rough-Welded Convergent Section. The relative uncertainty of the discharge coefficient as given in para. 4-4.5.4 is equal to 1.5%.

4-4.8 Uncertainty of the Expansibility Factor, ε *(Y)*

The relative uncertainty, in percent, of $\varepsilon\ (Y)$ is equal to

(SI Units)

$$\pm\ (4 + 100\ \beta^8)(\Delta p / p_1) \quad (4\text{-}4)$$

(U.S. Customary Units)

$$\pm\ (4 + 100\ \beta^8)(0.03606247 h_w / p_1)$$

This uncertainty assumes that β, $\Delta p\ (h_w)$, p_1, and κ (the isentropic exponent of the line fluid) are known without error.

4-4.9 Pressure Loss

4-4.9.1 Definition of the Pressure Loss. The pressure loss caused by an ASME venturi tube can be determined by pressure measurements made prior and subsequent to the installation of the venturi tube in a pipe through which there is a given flow.

In Fig. 4-2, $\Delta p'$ is the pressure difference measured between a point at least $1D$ upstream from the upstream end of the venturi and a point $6D$ downstream from the downstream end of the venturi, prior to installation of the venturi tube. $\Delta p''$ is the difference in pressure measured between the same pressure taps after installation of the venturi. The pressure loss caused by the venturi tube is given by $\Delta p'' - \Delta p'$.
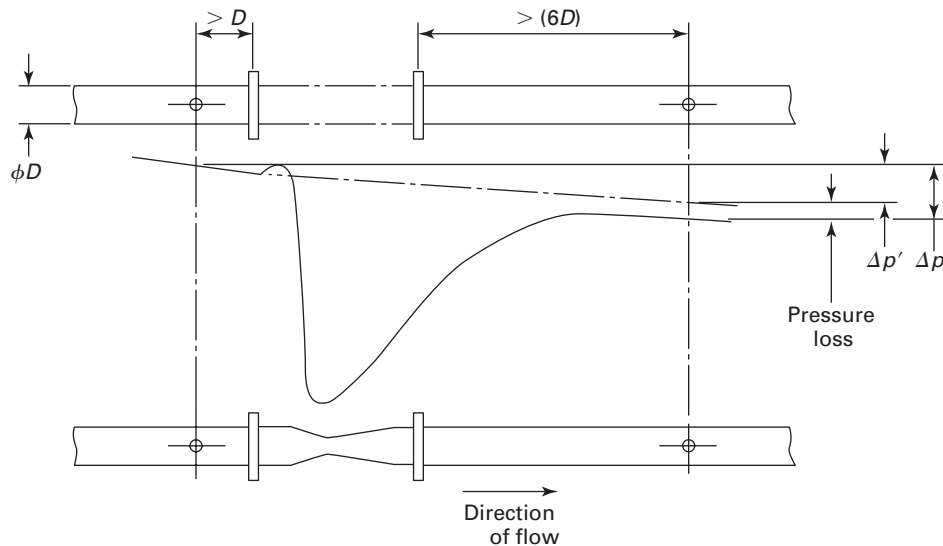
4-4.9.2 Relative Pressure Loss. The relative pressure loss, ξ, is the ratio value of the pressure loss $\Delta p'' - \Delta p'$ related to the differential pressure $\Delta p\ (h_w)$:

(SI Units)

$$\xi = \frac{\Delta p'' - \Delta p'}{\Delta p} \quad (4\text{-}5)$$

(U.S. Customary Units)

$$\xi = \frac{\Delta p'' - \Delta p'}{h_w}$$

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Fig. 4-2   Pressure Loss Across an ASME Venturi Tube

The relative pressure loss depends on

(a) the diameter ratio (ξ decreases when β increases)

(b) the Reynolds number (ξ decreases when R_D increases)

(c) the gross and fine geometry of the venturi tube, e.g., angle of the divergent, manufacturing of the convergent, surface finish of the different parts, etc. (ξ increases when ϕ and R_a/D increase)

(d) the installation conditions (good alignment, roughness of the upstream conduit, etc.)

For guidance, the relative value of the pressure loss can be accepted as being generally between 5% and 20%. Nonmandatory Appendix 4B also provides some information on the effect of these different factors on the pressure loss values.

4-5   INSTALLATION REQUIREMENTS

4-5.1   General

General installation requirements for pressure differential devices are contained in para. 1-6 of this Standard and shall be followed in conjunction with the additional installation requirements for venturi tubes given in this section. The general requirements for flow conditions at the primary device are given in para. 1-6.3 of this Standard. The requirements for use of a flow conditioner are given in para. 1-6.4 of this Standard. For some commonly used fittings shown in Table 4-1, the minimum straight lengths of pipe indicated shall be used. Detailed requirements are given in para. 4-5.2.

4-5.2   Minimum Upstream and Downstream Straight Pipe Length Requirements

(a) The minimum straight lengths of pipe to be installed upstream of the ASME venturi tube and follow-

ing the various fittings in the installation without flow conditioners or straighteners are given in Table 4-1.

For devices with the same β, the lengths specified in Table 4-1 for ASME venturi tubes are shorter than those specified in Parts 2 and 3 of this Standard for orifice plates, nozzles, and venturi nozzles. This is due to the attenuation of flow nonuniformities taking place within the contraction section of the ASME venturi tube.

(b) When a flow conditioner or straightener is not used, the lengths specified in Table 4-1 must be regarded as the minimum values. For research and calibration work, it is recommended that the upstream values specified in Table 4-1 be increased as much as reasonably possible.

(c) When the straight lengths used are equal to or longer than the values specified in each Column A of Table 4-1 for "zero additional uncertainty," it is not necessary to increase the uncertainty in discharge coefficient to take account of the effect of the particular installation. Although termed "uncertainty" in this instance, using upstream lengths shorter than those given each Column A of Table 3-3 will result in flow measurement bias errors. Furthermore, orientation of the pressure taps with respect to the various fittings can affect the magnitude of the bias error.

(d) For a given fitting, when the upstream straight length is greater than or equal to the "0.5% Additional Uncertainty" value shown in each Column B of Table 4-1 and shorter than the value corresponding to "Zero Additional Uncertainty" (as shown in each Column A), an additional uncertainty of 0.5% shall be added arithmetically to the uncertainty in the discharge coefficient. As detailed in para. 4-5.2(c), although termed "uncertainty" in this instance, when using upstream straight length greater than or equal to the value shown in each Column B of Table 3-3 and shorter than the value corresponding to shown in each Column A of Table 3-3, a

Table 4-1   Required Straight Lengths for Classical Venturi Tubes

Diameter Ratio, β	Single 90 deg Bend [Note (1)]		Two or More 90 deg Bends in Same or Different Planes [Note (1)]		Reducer 1.33D to D Over Length of 2.3D		Expander 0.67D to D Over Length of 2.5D		Reducer 3D to D over Length of 3.5D		Expander 0.75D to D Over Length of D		Full Bore Ball or Gate Valve Fully Open	
1	2		3		4		5		6		7		8	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.30	8	3	8	3	4	Note (2)	4	Note (2)	2.5	Note (2)	2.5	Note (2)	2.5	Note (2)
0.40	8	3	8	3	4	Note (2)	4	Note (2)	2.5	Note (2)	2.5	Note (2)	2.5	Note (2)
0.50	9	3	10	3	4	Note (2)	5	4	5.5	2.5	2.5	Note (2)	3.5	2.5
0.60	10	3	10	3	4	Note (2)	6	4	8.5	2.5	3.5	2.5	4.5	2.5
0.70	14	3	18	3	4	Note (2)	7	5	10.5	2.5	5.5	3.5	5.5	3.5
0.75	16	8	22	8	4	Note (2)	7	6	11.5	3.5	6.5	4.5	5.5	3.5

GENERAL NOTES:
(a) Values expressed as multiples of internal diameter D.
(b) The minimum straight lengths required are the lengths between various fittings located upstream of the classical Venturi tube and the classical Venturi tube itself. Straight lengths shall be measured from the downstream end of the curved portion of the nearest (or only) bend or the downstream end of the curved or conical portion of the reducer or expander to the upstream pressure tapping plane of the classical Venturi tube.
(c) If temperature pockets or wells are installed upstream of the classical Venturi tube, they shall not exceed 0.13D in diameter and shall be located at least 4D upstream of the upstream tapping plane of the Venturi tube.
(d) For downstream straight lengths, fittings or other disturbances (as indicated in this Table) or densitometer pockets situated at least four throat diameters downstream of the throat pressure tapping plane do not affect the accuracy of the measurement (see paras. 4-5.2(c) and 4-5.2(e)).
(e) Column A for each fitting gives lengths corresponding to "zero additional uncertainty" values (see para. 4-5.2(c)).
(f) Column B for each fitting gives lengths corresponding to "0.5% additional uncertainty" values (see para. 4-5.2(d)).

NOTES:
(1) The radius of curvature of the bend shall be greater than or equal to the pipe diameter.
(2) The straight length in each Column A gives zero additional uncertainty, data are not available for shorter straight lengths that could be used to give the required straight lengths for each Column B.

flow measurement bias error less than 0.5% will be introduced. Since both the direction (positive or negative) and the magnitude of this error are specific to the installation in question, this Standard addresses this unknown bias error as an increase in the uncertainty band.

(e) Part 4 of this Standard cannot be used to predict the value of any additional uncertainty when the upstream straight length is shorter than the "0.5% Additional Uncertainty" values specified in each Column B of Table 4-1, nor when the downstream straight length is shorter than the value specified in Note (d) of Table 4-1.

(f) The valves included in Table 4-1 shall be set fully open during the flow measurement process. It is recommended that control of the flow rate be achieved by valves located downstream of the venturi tube. Isolating valves located upstream of the venturi tube shall be set fully open, and these valves shall be full bore. The valve should be fitted with stops for alignment of the ball or gate, in the open position.

(g) Upstream valves that are bored to match the inside diameter of the adjacent pipe and are designed in such a manner that in the fully opened condition there are no steps can be regarded as part of the upstream pipe length and do not need to have added lengths as in Table 4-1.

(h) The values given in Table 4-1 were determined experimentally with fully developed and swirl-free flow upstream of the subject fitting. Since in practice such conditions are difficult to achieve, the following information can be used as a guide for normal installation practice.

(1) If several fittings of the type covered by Table 4-1 (other than the combinations of 90 deg bends already covered by this Table) are placed in series upstream of the venturi tube, the following shall be applied:

(a) The minimum length criterion given in Table 4-1 must be adopted for the fitting immediately upstream of the venturi tube (Fitting 1) and the venturi tube itself.

(b) *Between Fitting 1 and the Next Fitting Farther From* **(a07)** *the Venturi Tube (Fitting 2).* Irrespective of the actual β of the venturi tube used, a minimum straight length equal to half the number of diameters given in Table 4-1 for a 0.7 diameter ratio venturi tube used in conjunction with Fitting 2 must be included between Fittings 1 and 2.

If either of the minimum straight lengths is selected from each Column B of Table 4-1, a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty. If the length between two or more consecutive 90 deg bends is greater than $15D$, these shall be treated as a single fitting (two-bend combination) in accordance with Table 4-1, Column 2.

(c) If the upstream metering section has a full bore valve preceded by another fitting, then the valve can be installed at the outlet of the second fitting from the primary device. The length between the valve and the second fitting shall be added to the length between the primary device and the first fitting, specified in Table 4-1 (Fig. 4-3). Paragraph 4-5.2(h)(2) must also be satisfied (as it is in Fig. 4-3).

(2) In addition to the rule in para. 4-5.2(h)(1), any fitting (treating any two consecutive 90 deg bends as a single fitting) must be located at a distance from the venturi tube at least as great as that given in Table 4-1. This is regardless of the number of fittings between the fitting in question and the venturi tube.

The distance between the venturi tube and the fitting shall be measured along the pipe axis. If the distance meets this requirement using the number of diameters in each Column B, but not that in each Column A, then a 0.5% additional uncertainty shall be added arithmetically to the discharge coefficient uncertainty. This additional uncertainty shall not be added more than once under the provisions of paras. 4-5.2(h)(1) and 4-5.2(h)(2).

(a07) *(i)* Two examples of the application of paras. 4-5.2(h)(1) and 4-5.2(h)(2) are considered. In each case, the second fitting from the venturi tube is a two-bend combination in perpendicular planes and the venturi tube has a diameter ratio of 0.75.

EXAMPLES:
(1) If the first fitting is a full bore ball valve fully open (see Fig. 4-4, sketch (a)), the distance between the valve and the venturi tube must be at least $5.5D$ (from Table 4-1). Furthermore, between the two-bend combination in perpendicular planes and the valve, there must be at least $9D$ [from para. 4-5.2(h)(1)], and the distance between the two-bend combination in perpendicular planes and the venturi tube, there must be at least $22D$ [from para. 4-5.2(h)(2)]. If the valve has length $1D$, an additional length of $6.5D$ is required. This length can be upstream, downstream, or partly upstream and partly downstream of the valve. Paragraph 4-5.2(h)(1)(c) could also be used to move the valve to be adjacent to the two-bend combination in perpendicular planes provided that there is at least $22D$ from the two-bend combination in perpendicular planes to the venturi tube (see Fig. 4-4, sketch (b)).
(2) If the first fitting is an increaser from $0.67D$ to D over a length of $2.5D$ (see Fig. 4-4, sketch (c)), the distance between the increaser and the venturi tube must be at least $7D$ (from Table 4-1). Furthermore, between the two-bend combination in perpendicular planes and the increaser, there must be at least $9 \times 0.67D$ [from para. 4-5.2(h)(1)], and the distance between the two-bend combination in perpendicular planes and the venturi tube must be at least $22D$ [from para. 4-5.2(h)(2)]. An additional length of $6.5D$ is required. This length can be upstream, downstream, or partly upstream and partly downstream of the increaser.

4-5.3 Flow Conditioners and Flow Straighteners

A flow conditioner can be used to reduce upstream straight lengths. See paras. 1-6.4.1 and 1-6.4.2 of this Standard for additional information.

NOTES:
(1) Expander, $0.67D$ to D over a length of $2.5D$.
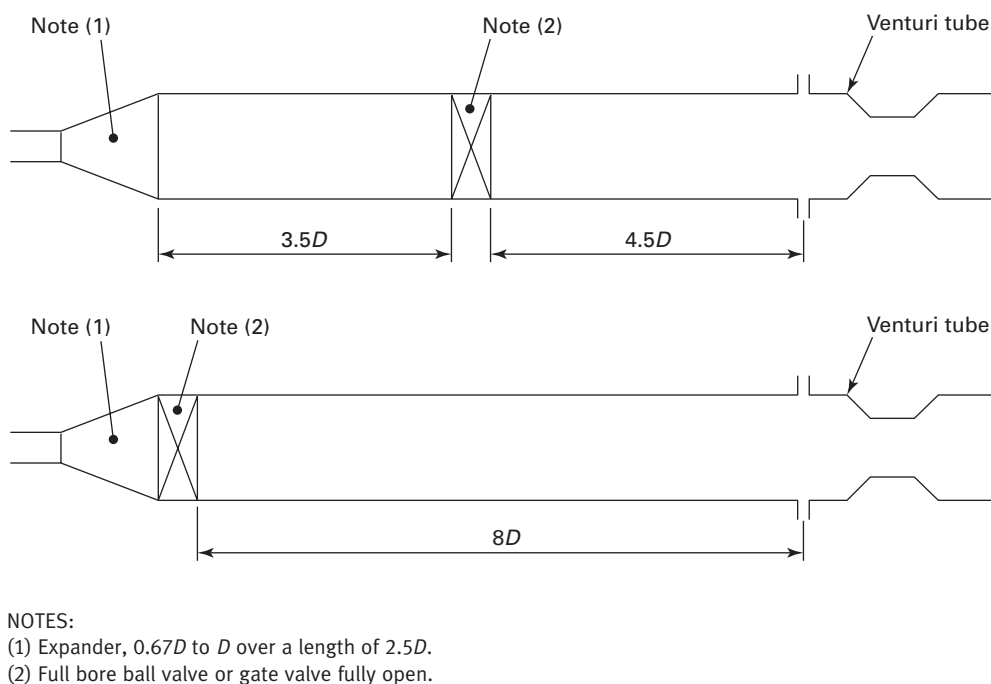(2) Full bore ball valve or gate valve fully open.

Fig. 4-3   Layout Including a Full Bore Valve for $\beta = 0.6$