

ASME MFC-7–2016

[Revision and Redesignation of ASME/ANSI MFC-7M–1987 (R2014)]

Measurement of Gas Flow by Means of Critical Flow Venturis and Critical Flow Nozzles

AN AMERICAN NATIONAL STANDARD



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FOREWORD

This Standard was prepared by Subcommittee 7 (SC 7) of the ASME Standards Committee on Measurement of Fluid Flow in Closed Conduits; it has been revised from ASME MFC-7M-1987 in its entirety. During the preparation, reference was made to older ASME standards and documents, including ASME MFC-3M-2004 and ASME PTC 19.5-2004, and to international standards including ISO 9300:2005 and ISO/IEC Guide 98-3:2008. In addition, information was gathered from many published papers and from the experience of the Subcommittee members and other knowledgeable engineers. This standard is a blend of the available technical information and best practices, and it is intended to be a practical guide to the proper use of critical flow venturis (CFV) and critical flow nozzles (CFN).

Changes made during the revision of this Standard are summarized as follows:

(a) The Scope and Field of Application was revised to clarify usage of the terms “critical flow venturi” and “critical flow nozzle.”

(b) A few symbols and definitions have been added, and many have been clarified and updated.

(c) Manufacturing tolerances have been updated to be more verifiable and to accommodate smaller CFVs.

(d) The discharge coefficient equations have been brought into alignment with extensive research results and ISO 9300.

(e) Recommendations for the calculation of thermophysical properties have been directed almost entirely toward the NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP), which is maintained by the National Institute of Standards and Technology (NIST).

(f) Uncertainty calculation methods have been extensively modified to be consistent with more modern methods and ISO/IEC Guide 98-3:2008. A statement of uncertainty is now required in order to be compliant with this Standard.

(g) The Nonmandatory Appendices have been modified to provide two new comprehensive examples, including uncertainty calculation, and to derive and clarify the mass flow equation, the real gas critical flow function, other gas property calculations, and humid air considerations.

(h) An “unchoking test procedure” is provided in a Nonmandatory Appendix.

Critical flow venturis are especially suited as transfer standards and reference flowmeters for calibration and testing and for precise flow control applications. CFVs provide a stable flow of compressible fluids, and per this Standard can and should be associated with a precise statement of uncertainty for the measured flow. Although this Standard is a complete guide that provides specific requirements and methods for the proper use of CFVs and CFNs, some latitude and variations in application are allowed if necessary tests are performed and proper judgment is applied.

Suggestions for improvement of this Standard will be welcomed. They should be sent to The American Society of Mechanical Engineers; Attn: Secretary, MFC Main Committee; Two Park Avenue; New York, NY 10016-5990.

This revision was approved as an American National Standard on January 6, 2016.

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MEASUREMENT OF GAS FLOW BY MEANS OF CRITICAL FLOW VENTURIS AND CRITICAL FLOW NOZZLES

1 SCOPE AND FIELD OF APPLICATION

This Standard applies only to the steady flow of single-phase gases through critical flow venturis (CFV) of shapes specified herein [also sometimes referred to as critical flow nozzles (CFN), sonic nozzles, or critical flow venturi nozzles]. This Standard applies to CFVs with diverging sections on the downstream side of the throat. When a CFN (no diverging section) is discussed, it is explicitly noted. This Standard specifies the method of use (installation and operating conditions) of CFVs. This Standard also gives information necessary for calculating the mass flow of the gas and its associated uncertainty.

This Standard applies only to CFVs and CFNs in which the flow is critical. Critical flow exists when the mass flow through the CFV is the maximum possible for the existing upstream conditions. At critical flow or choked conditions, the average gas velocity at the CFV throat closely approximates the local sonic velocity.

This Standard specifically applies to cases in which

- (a) it can be assumed that there is a large volume upstream of the CFV or upstream of a set of CFVs mounted in a parallel flow arrangement (in a common plenum), thereby achieving higher flow; or
- (b) the pipeline upstream of the CFV is of circular cross section with throat to pipe diameter ratio equal to or less than 0.25

2 REFERENCES

The following publications are referenced in this Standard. The latest edition of ASME publications should be used.

ASME MFC-3M, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi

ASME PTC 19.5, Flow Measurement

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

ISO 9300:2005, Measurement of gas flow by means of critical flow Venturi nozzles

ISO/IEC Guide 98-3:2008, Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement

Publisher: International Organization for Standardization (ISO) Central Secretariat, Chemin de Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland (www.iso.org)

NIST Standard Reference Database 23, NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 9.1

Publisher: National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899 (www.nist.gov)

3 SYMBOLS AND DEFINITIONS

3.1 Symbols and Nomenclature

See Table 3.1-1.

3.2 Definitions

3.2.1 Temperature Measurement

measured gas temperature: temperature of the gas after being irreversibly brought to rest against the temperature probe.

Table 3.1-1 Nomenclature Used in This Standard

Symbol	Name	Dimensions	SI Unit	U.S. Customary Unit
A^*	Area of CFV throat	L^2	m^2	ft^2
A_2	Area of CFV exit	L^2	m^2	ft^2
b_0, b_1, n	Coefficients for empirical C_d equation	Dimensionless	Dimensionless	Dimensionless
c	Sound speed	LT^{-1}	m/s	ft/sec
C_d	Discharge coefficient	Dimensionless	Dimensionless	Dimensionless
C_i^*	Ideal gas critical flow function	Dimensionless	Dimensionless	Dimensionless
C_p^*	Polytropic gas critical flow function	Dimensionless	Dimensionless	Dimensionless
C_R^*	Real gas critical flow function	Dimensionless	Dimensionless	Dimensionless
c_p	Constant pressure specific heat	$L^2T^{-2}\theta^{-1}$	$kJ/kg\ K$	$Btu/lbm\ ^\circ R$
c_v	Constant volume specific heat	$L^2T^{-2}\theta^{-1}$	$kJ/kg\ K$	$Btu/lbm\ ^\circ R$
D	Diameter of upstream conduit	L	m	ft
d	Diameter of CFV throat	L	m	ft
h	Specific enthalpy	L^2T^{-2}	J/kg	Btu/lbm
h_t	Total specific enthalpy	L^2T^{-2}	J/kg	Btu/lbm
k	Coverage factor	Dimensionless	Dimensionless	Dimensionless
M	Molar mass	$MM^{-1}mole^{-1}$	$kg/kg\ mole$	$lbm/lbm\ mole$
\dot{m}	Mass flow	MT^{-1}	kg/s	lbm/sec
Ma	Mach number: ratio of gas velocity to sound speed	Dimensionless	Dimensionless	Dimensionless
\dot{m}_{th}	Theoretical mass flow for one-dimensional isentropic flow of a real gas	MT^{-1}	kg/s	lbm/sec
P^*	Absolute static pressure of the gas at CFV throat	$ML^{-1}T^{-2}$	Pa	$lbf/in.^2$
P^*/P_0	Critical pressure ratio: ratio of throat pressure to inlet stagnation pressure	Dimensionless	Dimensionless	Dimensionless
P_0	Absolute stagnation (or total) pressure of the gas at CFV inlet	$ML^{-1}T^{-2}$	Pa	$lbf/in.^2$
P_1	Absolute static pressure of the gas in the upstream conduit	$ML^{-1}T^{-2}$	Pa	$lbf/in.^2$
P_2	Absolute static pressure of the gas at CFV exit	$ML^{-1}T^{-2}$	Pa	$lbf/in.^2$
P_2/P_0	Back pressure ratio: ratio of CFV exit static pressure to inlet stagnation pressure	Dimensionless	Dimensionless	Dimensionless
r_c	Radius of curvature of CFV inlet	L	m	ft
Re_d	CFV throat Reynolds number	Dimensionless	Dimensionless	Dimensionless
R_f	Recovery factor or temperature probe constant	Dimensionless	Dimensionless	Dimensionless
R_u	Universal gas constant: 8 314.4598 J/(mol · K) [1,545.3467 ft · lbf/(mol · °R)]	$ML^2T^{-2}\theta^{-1}$	$J/(mol \cdot K)$	$ft \cdot lbf/(mol \cdot ^\circ R)$
s	Specific entropy of the gas	$L^2\theta^1T^{-2}$	$J/(kg\ K)$	$Btu/(lbm\ ^\circ R)$
T^*	Absolute static temperature at CFV throat	θ	K	$^\circ R$
T_0	Absolute stagnation (or total) temperature of the gas	θ	K	$^\circ R$
T_1	Absolute static temperature of the gas at CFV inlet	θ	K	$^\circ R$
T_{m1}	Measured temperature	θ	K	$^\circ R$
U	Expanded uncertainty (with specified coverage factor, k)	...	...	...
u	Standard uncertainty ($k = 1$)	...	...	...
u_c	Combined standard uncertainty ($k = 1$)	...	...	...
V	One-dimensional gas velocity	LT^{-1}	m/s	ft/sec
V^*	Velocity of gas at the throat equal to the sonic velocity	LT^{-1}	m/s	ft/sec
Z	Compressibility factor	Dimensionless	Dimensionless	Dimensionless

Table 3.1-1 Nomenclature Used in This Standard (Cont'd)

Symbol	Name	Dimensions	SI Unit	U.S. Customary Unit
β	Beta ratio: d/D	Dimensionless	Dimensionless	Dimensionless
γ	Ratio of specific heats	Dimensionless	Dimensionless	Dimensionless
κ	Isentropic (or polytropic) exponent	Dimensionless	Dimensionless	Dimensionless
μ_0	Dynamic viscosity of the gas at stagnation conditions	$ML^{-1}T^{-1}$	kg/m s	lbm/ft sec
ν_{eff}	Effective degrees of freedom	Dimensionless	Dimensionless	Dimensionless
ρ^*	Gas density at CFV throat	ML^{-3}	kg/m ³	lbm/ft ³
Superscript				
*	Value at the CFV throat based on one-dimensional, choked flow	...	...	...
Subscripts				
0	Stagnation property	...	...	...
1	Inlet conduit or upstream piping	...	...	...
2	CFV exit	...	...	...
i	Ideal gas	...	...	...
max	Maximum	...	...	...

recovery factor: parameter used to correct the temperature of the gas after being irreversibly brought to rest against the temperature probe.

$$R_f = \frac{T_{m1} - T_1}{T_0 - T_1} \quad (3-1)$$

stagnation (or total) temperature of a gas: temperature that would exist in the gas if the flowing gas stream were brought to rest by an isentropic process.

static temperature of a gas: actual bulk temperature of the flowing gas.

3.2.2 Critical Flow Venturis

CFV exit plane: surface at the exit of the divergent section.

CFV inlet plane: surface at the entrance of the convergent section.

critical flow venturi: a flowmeter having a geometrical configuration with a constant curvature convergent section to a minimum cross-sectional area (i.e., throat) at which sonic conditions exist followed by a conical divergent section.

critical (or choked) flow: maximum flow for a particular venturi that can exist for the given upstream conditions; the flow that exists when the ratio of the downstream static pressure, P_2 , to the upstream absolute pressures, P_0 , is such that the fluid velocity reaches sonic conditions at the throat. This condition is termed “choked” flow, and the flow is proportional to the inlet stagnation pressure.

critical pressure ratio: the ratio of the absolute static pressure at the CFV throat to the absolute stagnation pressure for which gas mass flow through the CFV is a maximum.

maximum back pressure ratio: the ratio of the highest absolute CFV exit static pressure to the absolute CFV upstream stagnation pressure at which the flow becomes critical.

throat: the cross section of the CFV with minimum diameter.

3.2.3 Pressure Measurement

stagnation (or total) pressure of a gas: pressure that would exist in the gas if the flowing gas stream were brought to rest by an isentropic process. Only the value of the absolute stagnation pressure is used in this Standard.

static pressure of a gas: the pressure of the flowing gas, which can be measured by connecting a pressure gauge to a wall pressure tap. Only the value of the absolute static pressure is used in this Standard.

wall pressure tap: a hole drilled in the wall of a conduit, the inside edge of which is flush with the inside surface of the conduit.

3.2.4 Flow

mass flow: the mass of gas per unit time passing through the CFV. In this Standard, mass flow is always the steady-state or equilibrium mass flow.

steady state: the conditions under which the inlet and other measured pressures and temperatures at a CFV do not change in a transient or periodic manner by more than two times the resolution of the transducers or two times the standard uncertainty of the measurement during the period of testing or measurement.

3.2.5 Thermodynamic Properties

entropy: a property related to the disorder of a thermodynamic system, often assumed to have a constant value in theoretical analysis of flow through a CFV, i.e., stagnation entropy equals the throat enthalpy, $s_0 = s^*$.

isentropic exponent (κ): a thermodynamic variable defined by

$$\kappa \equiv \frac{\rho}{p} \left(\frac{\partial p}{\partial \rho} \right)_s = \frac{\rho c^2}{p} \quad (3-2)$$

NOTES:

- (1) For a perfect gas, the isentropic exponent equals the specific heat ratio, $\kappa = \gamma$.
- (2) For a polytropic process, the value of κ remains fixed so that the static pressure divided by the density raised to the polytropic exponent is constant ($P/\rho^\kappa = \text{constant}$). This expression is derived by integrating $\kappa = \rho/P (\partial P/\partial \rho)_s$ for an isentropic process with a constant value of the polytropic exponent.
- (3) In real gases, the forces exerted between molecules, as well as the volume occupied by the molecules, have a significant effect on gas behavior. In a perfect gas, intermolecular forces and the volume occupied by the molecules are neglected.

real gas critical flow function: a dimensionless coefficient used to correct the CFV mass flow for real gas effects, defined by the equation

$$C_R^* = \frac{\rho^* c^* \sqrt{R_u T_0}}{P_0 \sqrt{M}} \quad (3-3)$$

where

- c^* = the sound velocity at the throat
- M = molar (or molecular) weight
- P_0 = the stagnation pressure
- R_u = the universal gas constant
- T_0 = the stagnation temperature
- ρ^* = the gas density at the nozzle throat

NOTES:

- (1) The throat density, ρ^* , and sound speed, c^* , are computed using a real gas equation of state for a one-dimensional, isentropic, isoenergetic flow model (see Nonmandatory Appendix C). For an isentropic process the entropy is constant ($s = \text{constant}$) while for an isoenergetic process the total enthalpy is constant ($h + V^2/2 = \text{constant}$).
- (2) If the gas flowing through the CFV behaves ideally (i.e., real gas effects are negligible) and γ remains constant as the gas expands from the CFV inlet to the throat, C_R^* simplifies to the ideal gas critical flow function (C_i^*) and is a function only of the specific heat ratio.

$$C_i^* = \sqrt{\gamma \left(\frac{2}{1+\gamma} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (3-4)$$

The specific heat ratio should be determined using a low-uncertainty thermodynamic property database. It is evaluated as a function of the gas composition, and the measured upstream temperature and pressure.

- (3) If the CFV flow can be accurately modeled by a polytropic process, C_R^* simplifies to the polytropic gas critical flow function (C_p^*) and is a function of the polytropic exponent and the compressibility factor evaluated at the stagnation conditions.

$$C_p^* = \sqrt{\frac{\kappa}{Z_0} \left(\frac{2}{1+\kappa} \right)^{\frac{\kappa+1}{\kappa-1}}} \quad (3-5)$$

The polytropic exponent and compressibility factor should be determined using a low-uncertainty thermodynamic property database. The polytropic exponent is evaluated as a function of gas composition, and the measured upstream temperature and pressure.

- (4) In practice, sometimes C_R^* is estimated by either C_i^* or C_p^* . If the gas behavior is not ideal (i.e., $Z \neq 1$) or if the CFV flow process is not polytropic (i.e., $\kappa \neq \text{constant}$), neither of these idealized critical flow functions equals C_R^* . Consequently, mass flow calculations using either C_i^* or C_p^* will have higher uncertainty than corresponding calculations using C_R^* . For the lowest uncertainty, mass flow calculations should be based on C_R^* .

specific heat ratio: a thermodynamic variable defined by the ratio of the constant pressure, c_p , to constant volume, c_v , specific heats

$$\gamma = \frac{c_p}{c_v} \quad (3-6)$$

speed of sound: the speed that a sound wave travels

$$c = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_s} \quad (3-7)$$

where P and ρ are the absolute static pressure and density, respectively, and s refers to constant entropy.

stagnation enthalpy: thermodynamic variable equal to the specific enthalpy evaluated at the stagnation pressure and temperature, $h_0 = h(T_0, P_0)$.

total specific enthalpy: the sum of the specific enthalpy and the kinetic energy per unit mass, $h_t = h + V^2/2$.

NOTES:

- (1) The total specific enthalpy equals the specific stagnation enthalpy for a steady, isentropic flow ($h_t = h_0$). This result is commonly referred to as the "isoenergetic condition."
- (2) The total specific enthalpy is a thermodynamic property at the CFV throat since the fluid velocity equals the sound speed,

$$h_t^* = h^* + \frac{c^{*2}}{2}.$$

3.2.6 Dimensionless Quantities

discharge coefficient: the dimensionless ratio of the actual flow to the theoretical flow

$$C_d = \frac{\dot{m}}{\dot{m}_{th}} \quad (3-8)$$

This coefficient corrects for viscous effects in the boundary layer and sonic line curvature effects in the far field (i.e., in the irrotational flow outside of the boundary layer region). For the CFV design and installation conditions specified in this Standard, it is a function of the throat Reynolds number.

Mach number: the ratio of the fluid velocity to the velocity of sound in the fluid at the same temperature and pressure

$$Ma = V/c \quad (3-9)$$

NOTE: For a one-dimensional isentropic flow the Mach number equals unity at the CFV throat, such that the fluid velocity equals the sound speed ($V^* = c^*$).

throat Reynolds number: dimensionless parameter calculated from the mass flow, \dot{m} , and the dynamic viscosity, μ_0 , evaluated at the CFV inlet stagnation conditions using the throat diameter, d , as the length scale

$$Re = \frac{4\dot{m}}{\pi d \mu_0} \quad (3-10)$$

4 BASIC EQUATIONS

4.1 State Equation

The behavior of a real gas can be described by

$$p = \frac{\rho R_u T Z}{M} \quad (4-1)$$

4.2 CFV Mass Flow Equations

Assuming that the flow is one-dimensional and isentropic (i.e., frictionless and adiabatic), the value of the theoretical mass flow through a CFV is

$$\dot{m}_{th} = \frac{A^* C_R^* P_0}{\sqrt{(R_u/M) T_0}} \quad (4-2)$$

A discharge coefficient C_d is needed to correct for the fact that the flow is neither entirely one-dimensional nor isentropic. Equation (4-2) becomes

$$\dot{m} = C_d \dot{m}_{th} = \frac{C_d A^* C_R^* P_0}{\sqrt{(R_u/M)T_0}} \quad (4-3)$$

If the throat diameter is known perfectly, C_d will be less than unity because the mass flow, \dot{m} , will be less than ideal due to curvature of the throat sonic line as well as subsonic velocities through the viscous boundary layer adjacent to the CFV wall.

NOTE: Paragraph 8.1 provides information for computing C_d if it is not obtained by calibration, and para. 8.2 provides information for computing C_R .

5 APPLICATIONS FOR WHICH THE METHOD IS SUITABLE

Each application should be evaluated to determine whether a CFV is suitable for the conditions and requirements. An important advantage of a CFV is that the flow through it is independent of the downstream pressure as long as the pressure conditions up- and downstream from the CFV lead to critical flow at the throat. The following are some other considerations:

(a) To calculate flow through a CFV, the only measurements required are the gas composition, and the pressure and temperature upstream of the CFV. These measurements enable the throat conditions to be calculated from thermodynamic considerations. A low-uncertainty measurement of the throat diameter is also required if C_d values are determined using the empirical equations in this Standard. In contrast, if the CFV is flow calibrated, only a nominal value of the diameter is necessary (see examples in Nonmandatory Appendix B). CFVs are applicable when there is no phase change as the gas accelerates from the inlet to the throat and the flow is not a function of the downstream pressure (i.e., the CFV is choked). Care must be taken when using an equation of state at or near the dew point of the gas so that correct gas phase properties are determined. Studies have shown that condensation rates in the presence of favorable pressure gradients and rapidly falling temperatures are much slower than the transit time of the fluid from the CFV entrance to the CFV throat. Therefore, the CFV will operate correctly and yield the correct flow, provided that the calculations for the speed of sound and density at the throat are correct.

(b) The velocity in the CFV throat is the maximum possible for the given upstream stagnation conditions; therefore, the sensitivity to installation effects is minimized, except for swirl, which must not exist in the inlet plane of the CFV.

(c) Unlike the subsonic differential pressure device, CFV flow is proportional to the inlet stagnation pressure and not to the square root of a measured differential pressure.

(d) The maximum flow range that can be obtained for a given CFV is limited to the range of inlet pressures that are available above the inlet pressure at which the flow becomes critical.

(e) The most common applications for CFVs are the calibration of other meters (working or reference standards) and verification or comparison of primary flow standards (check or transfer standards) in flow control applications and in product testing.

6 STANDARD CRITICAL FLOW VENTURIS

6.1 General Requirements

6.1.1 Discharge Coefficient. The discharge coefficient, C_d , for a CFV may be obtained by either the empirical method (using empirical or theoretical equations of C_d versus Reynolds number) or the calibration method (calibration of the particular CFV in a flow laboratory). When using empirical C_d values, the specifications for size, shape, and surface conditions are pertinent to obtaining the performance specified in this Standard. In these cases the CFV should be inspected to determine conformance to construction specifications of this Standard. In the case of laboratory-determined C_d values, compliance with the following construction specifications is less pertinent. When it is not practical to manufacture CFVs to the surface finish and curvature specifications herein, CFV performance must be demonstrated through calibration against a flow reference.

6.1.2 Materials. CFVs should be manufactured from material suitable for the intended application, such as the following:

(a) The material should be capable of being finished to the surface condition specified in this Standard. Some materials are unsuitable because of pits, voids, and other nonhomogeneities.

(b) The material, together with any surface treatment used, should not be subject to corrosion in the intended service. Experience has shown that 300 series stainless steel is often a suitable material.

(c) The material should be dimensionally stable and should have known and repeatable thermal expansion characteristics (if it is to be used at a temperature other than that at which the throat diameter has been measured), so throat diameter corrections and uncertainty estimates can be made. A period of time is generally required to achieve steady-state temperature conditions, and the flow reported by the CFV will change gradually as equilibrium is approached. The amount that the flow changes as steady state is approached depends on flow conditions, CFV geometry, ambient temperature conditions, gas type, and response time of the instrumentation. Generally, the time necessary to achieve steady state should be determined experimentally.

6.1.3 Surface Finish. The throat and toroidal inlet up to the conical divergent section of the CFV should be smoothly finished. Where it can be measured, the arithmetic average roughness height should not exceed $15 \times 10^{-6}d$. If the roughness cannot be measured the CFV should be flow calibrated. The throat and toroidal inlet up to the conical divergent section should be free from dirt, films, and other contamination. The form of the conical divergent portion of the CFV should be controlled such that any steps, discontinuities, irregularities, and lack of concentricity do not exceed 1% of the local diameter. If there is a diameter discontinuity in the divergent portion of the CFV, then the diameter should increase (not decrease) in the direction of flow. The arithmetic average roughness of the conical divergent section should not exceed $10^{-4}d$.

6.2 Standard CFV Geometries

Two different designs are possible for standard CFVs: a toroidal throat design and a cylindrical throat design. The toroidal throat design is the most widely used and is the primary focus of this Standard. However, for completeness, guidance is also given for the cylindrical throat design.

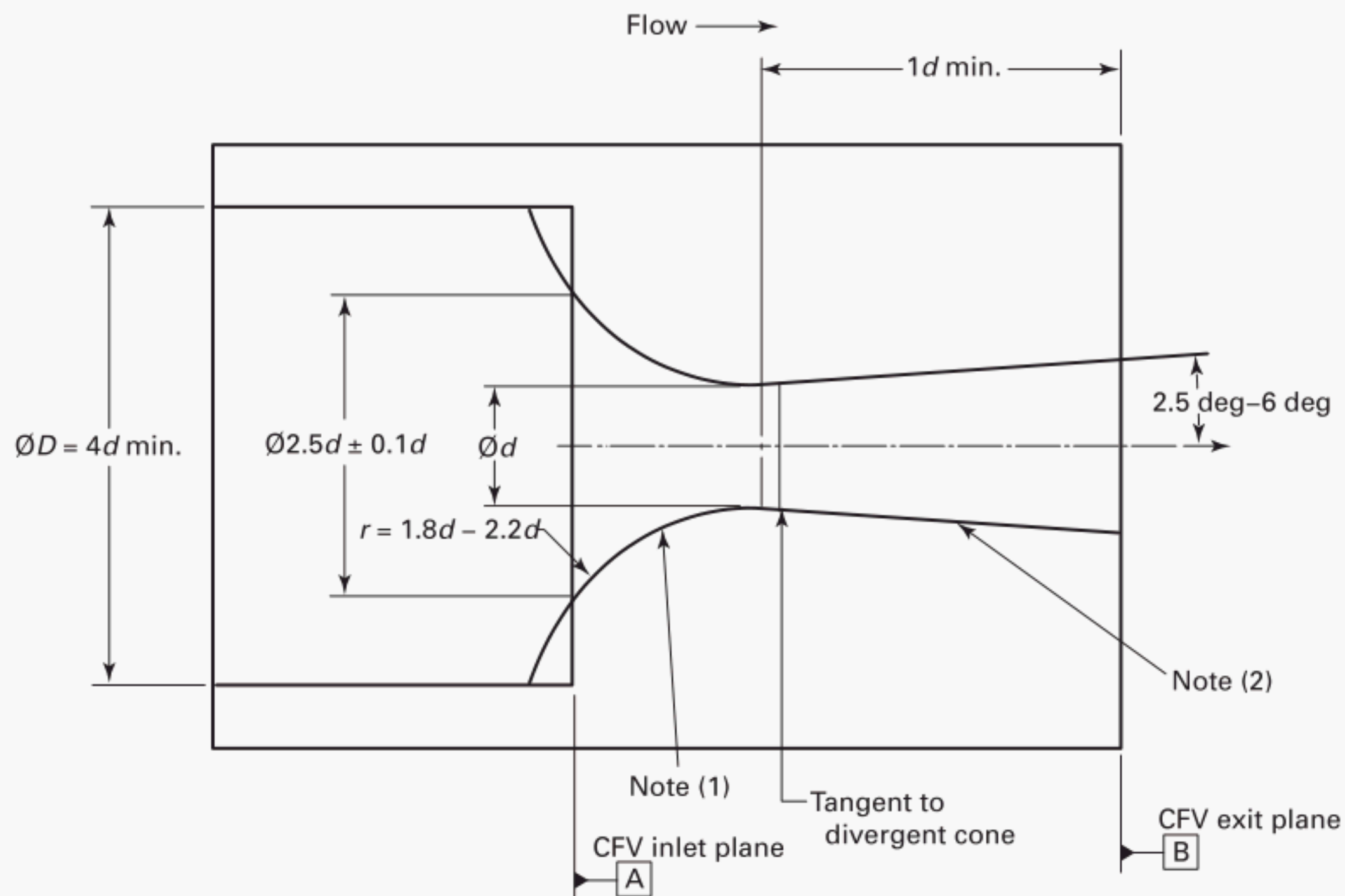
NOTE: Critical nozzles (i.e., CFNs with no divergent section) are not a recommended design (although they are allowed) due to poor pressure recovery and the greater possibility of flow performance being affected by downstream disturbances (i.e., flow pulsations). However, the same flow equations and discharge coefficients apply to CFNs as to CFVs.

6.2.1 Toroidal Throat CFVs. A toroidal throat CFV should meet the following requirements:

- (a) It should conform to Fig. 6.2.1-1.
- (b) For purposes of locating other elements of the CFV critical flow metering system, the inlet plane of the CFV is defined as the plane perpendicular to the axis of symmetry that intersects the inlet at a diameter equal to $2.5d \pm 0.1d$.
- (c) The convergent part of the CFV (inlet) is a portion of a torus that extends through the minimum area section (throat). The curvature of this surface continues to become tangent to the divergent section. The contour of the inlet upstream of a diameter equal to $2.5d$ is not specified, except that the surface at each axial location has a diameter equal to or greater than the extension of the toroidal contour.
- (d) The inlet toroidal surface of the CFV beginning at a diameter of $2.5d$ perpendicular to the axis of symmetry (see Fig. 6.2.1-1) and extending to the point of tangency should not deviate from the shape of a torus by more than $0.001d$. The radius of curvature of this toroidal surface in the plane of symmetry should be $1.8d$ to $2.2d$.
- (e) The divergent portion of the CFV downstream of the point of tangency with the torus should form a frustum of a cone with a half-angle of 2.5 deg to 6 deg. The length of the conical section should not be less than one throat diameter.
- (f) If these manufacturing tolerances cannot be achieved or verified by inspection, then flow calibration is recommended.

6.2.2 Cylindrical Throat CFVs. A cylindrical throat CFV should meet the following requirements:

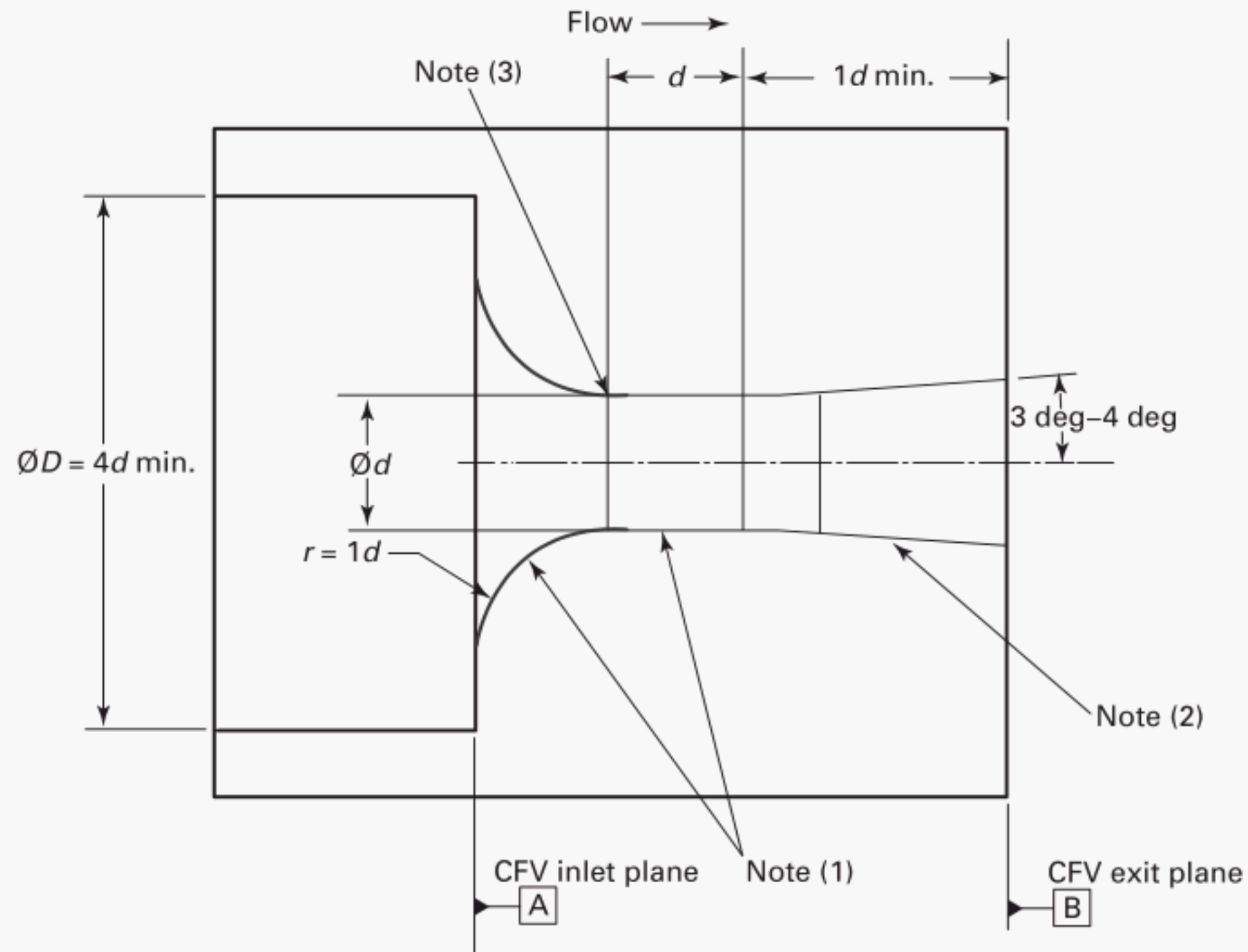
- (a) It should conform to Fig. 6.2.2-1.
- (b) The inlet plane is defined as the plane tangent to the inlet contour of the CFV and perpendicular to the CFV centerline.
- (c) The convergent part of the CFV (inlet) is a quarter of a torus tangent to the inlet plane and to the cylindrical throat. The radius of curvature of the convergent part of the CFV and the throat length is equal to the throat diameter, d . The length of the throat should equal the throat diameter within $0.05d$.
- (d) The inlet toroidal surface of the CFV should not deviate from the shape of a torus by more than $0.001d$.
- (e) The throat diameter should be the mean of at least four diameters measured at approximately equal angles to each other at the exit plane of the cylindrical throat. These diameters should not vary from the mean by more than $0.001d$.
- (f) The transition between the convergent section and the throat should be inspected visually, and no defect should be observed. Where it can be measured, the whole inlet surface must be properly polished so that the arithmetic average roughness height does not exceed $15 \times 10^{-6}d$. If the roughness cannot be measured, the CFV should be flow calibrated. The transition between the cylindrical throat and the conical divergent section should

Fig. 6.2.1-1 Toroidal Throat CFV Geometry

GENERAL NOTE: When it is not practical to manufacture CFVs to the surface finish and curvature specifications herein, CFV performance shall be demonstrated through calibration.

NOTES:

- (1) In this region the surface shall not exceed $15 \times 10^{-6}d$ arithmetic average roughness, and the contour shall not deviate from toroidal form by more than $0.001d$.
- (2) In this region the surface shall not exceed $10^{-4}d$ arithmetic average roughness.

Fig. 6.2.2-1 Cylindrical Throat CFV Geometry

GENERAL NOTE: When it is not practical to manufacture CFVs to the surface finish and curvature specifications herein, CFV performance shall be demonstrated through calibration.

NOTES:

- (1) In this region the surface shall not exceed $15 \times 10^{-6}d$ arithmetic average roughness, and the contour shall not deviate from toroidal and cylindrical form by more than $0.001d$.
- (2) In this region the surface shall not exceed $10^{-4}d$ arithmetic average roughness.
- (3) For the transition region, see para. 6.2.2(f).

also be visually inspected, and no defect should be observed. When a defect of transition is observed, it must be checked that the local radius of curvature is never lower than $0.5d$ all along the inlet surface (convergent section and cylindrical throat).

(g) The divergent section of the CFV should be a frustum of a cone with a half-angle of $3.5 \text{ deg} \pm 0.5 \text{ deg}$. The length of the divergent section should not be less than the throat diameter.

(h) If these manufacturing tolerances cannot be achieved or verified by inspection, then flow calibration is recommended.

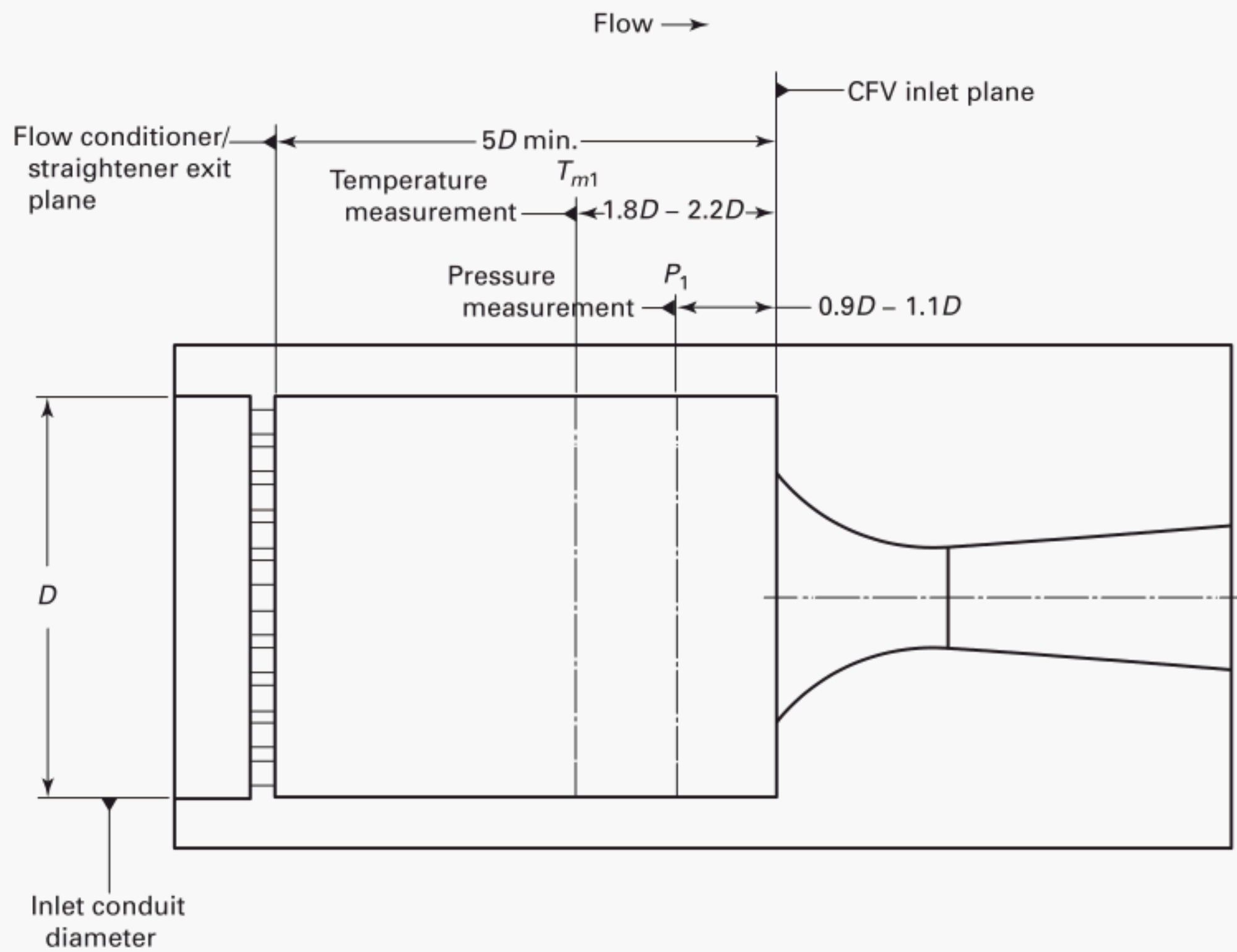
7 INSTALLATION REQUIREMENTS

7.1 General

This Standard covers installation when either

- (a) the pipeline upstream of the CFV is of circular cross section with $\beta \leq 0.25$ or
- (b) there is a large volume (plenum) upstream of the CFV such that β is effectively zero

For the case in (a), the CFV should be installed in a system meeting the requirements of para. 7.2. For the case in (b), the CFV should be installed in a system meeting the requirements of para. 7.3. In both cases swirl must not exist upstream of the CFV. Where a pipeline is used upstream of the CFV, swirl-free conditions can be ensured by installing a flow straightener as shown in Fig. 7.1-1 at a distance $>5D$ upstream of the CFV inlet plane or any type of other flow conditioners of recognized type having equivalent or better performance (see ASME MFC-3M).

Fig. 7.1-1 Inlet Conduit Schematic

7.2 Upstream Pipeline

The CFV should be installed in a straight circular conduit that is concentric within $0.02D$ with the centerline of the CFV. The inlet conduit up to $3D$ upstream of the CFV should not deviate from circularity by more than $0.01D$ and should have an arithmetic roughness height that does not exceed $10^{-4}D$. In order to meet the coefficient specifications of this Standard, the diameter of the inlet conduit should be a minimum of $4d$. It should be noted that the use of β ratios larger than 0.25 increases the effect of upstream disturbances, and corrections are necessary to the measured pressure and temperature (see para. 8.3).

In cases where upstream installation constraints are such that this requirement cannot be met, specific tests are recommended to investigate the influence of the installation conditions on the uncertainty of the flow measurement or the determination of C_d .

In most cases, the mass flow calculations used in this Standard will apply for $\beta > 0.25$; however, when real gas corrections are significant, the ideal calculations of the stagnation pressure and temperature (see para. 8.3) will no longer apply and corrections need to be made.

7.3 Large Upstream Volume (Plenum)

It can be assumed that there is a large volume upstream of the CFV if there is no wall closer than $5d$ to the axis of the CFV or to the inlet plane of the CFV (as defined in para. 3.2.2).

When multiple CFVs are used in parallel, testing should be done to ensure that performance is not degraded by interference between CFVs.¹

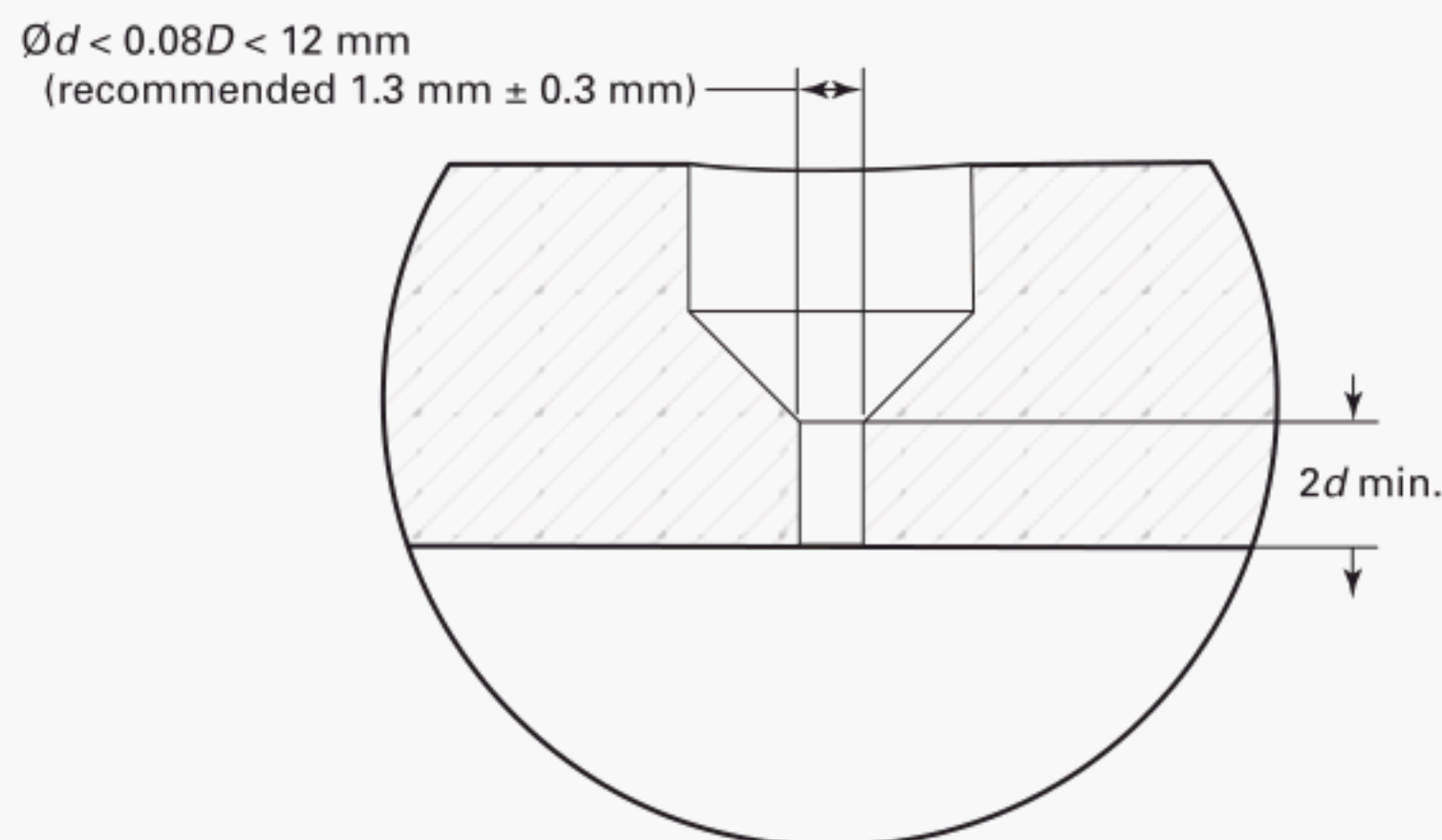
NOTE: When determining the spacing requirements for CFVs mounted in parallel, the distance to the wall should also be considered.

¹ For guidance for CFV spacing, see the following references:

Choi, Y. M., Park, K.-A., Park, J. T., Choi, H. M., and Park, S. O., Interference Effects of Three Sonic Nozzles of Different Throat Diameters in the Same Meter Tube, *Flow Meas. Instrum.*, 10, pp. 175–181, 1999.

Johnson, A. N., Li, C. H., Wright, J. D., Kline, G. M., and Crowley, C. J., Critical Flow Venturi Manifold Improves Gas Flow Calibrations, *Eighth International Symposium for Fluid Flow Measurement*, Colorado Springs, Colorado, USA, 2012.

Stevens, R. L., Development and Calibration of the Boeing 18 kg/sec Airflow Calibration Transfer Standard, *International Symposium on Fluid Flow Measurement*, Arlington, Virginia, USA, pp. 80–96, 1986.

Fig. 7.5-1 Pressure Tap Schematic

7.4 Downstream Requirements

No requirements are imposed on the outlet conduit except that it shall not restrict the flow so as to prevent critical flow in the CFV.

7.5 Pressure Measurement

When a circular conduit is used upstream of the primary device, the upstream static pressure should be measured at wall pressure taps located $0.9D$ to $1.1D$ from the inlet plane of the CFV (see Fig. 7.1-1). The pressure tap may be located upstream or downstream of this position, provided it has been demonstrated that the measured pressure can be used to reliably give the CFV inlet stagnation pressure.

When it can be assumed that there is a large volume upstream of the CFV, the upstream pressure tap should be located in a wall perpendicular to the inlet face of the CFV and within a distance of $10d \pm 1d$ from that plane. The pressure tap may be located upstream or downstream of this position, provided it has been demonstrated that the pressure measured can be used to reliably give the CFV inlet stagnation pressure.

For the pressure taps mentioned in the preceding paragraph, the centerline of the circular pressure tap should meet the centerline of the primary device and be at right angles to it. The edges should be free from burrs and be square or lightly rounded to a radius not exceeding 0.1 diameter of the pressure tap. Conformity of the pressure taps, with the two foregoing descriptions, is to be judged by visual inspection. When an upstream pipeline is used, the diameters of pressure taps should be $1.3 \text{ mm} \pm 0.3 \text{ mm}$ ($0.05 \text{ in.} \pm 0.02 \text{ in.}$) but no more than $0.08D$ or 12.7 mm (0.5 in.), whichever is less. The pressure tap should be cylindrical for a minimum length of two tap diameters (see Fig. 7.5-1).

The downstream pressure will be measured by a conduit wall tap to ensure that critical flow is maintained. The recommended location for the wall tap is within 0.5 conduit diameter downstream from the exit plane of the CFV so that the back pressure ratios specified in para. 8.4 are valid. However, locations further downstream can also be used, provided there is no substantial pressure change. Other tap locations may be used to check for critical flow conditions if an unchoking test is performed using that tap location.

In some applications, the outlet pressure can be determined without a pressure tap. For example, the CFV may discharge directly into the atmosphere or other region of known pressure. In these applications, the outlet pressure need not be measured.

7.6 Drain Holes

During measurement, flow must be single-phase upstream and in the throat with no condensation, and all surfaces must retain their cleanliness and surface finish. If this cannot be guaranteed, the measurement shall not be claimed to conform to this Standard.

If there is a possibility for condensate, the conduit may be provided with drain holes for the removal of condensate or other foreign substances that may collect in some applications. There must be no flow through these drain holes while the flow measurement is in progress. If drain holes are required, they should be located upstream of the CFV upstream pressure tap. The size of the drain holes is dependent on the viscosity of the fluid to be drained, but diameters are typically 6 mm to 12 mm . The axial distance from the drain hole to the plane of the upstream pressure

Table 8.1-1 Coefficients for Calculating Empirical C_d Values

CFV Type	Re_d Range	b_0	b_1	n
Toroidal	2.1×10^4 to 3.2×10^7	0.9959	2.720	0.5
Cylindrical	3.5×10^5 to 1.1×10^7	0.9976	0.1388	0.2

tap should be greater than $1D$, and the hole should be located at the bottom or low in the upstream pipe and in a different plane from the pressure tap.

7.7 Temperature Measurement

The inlet temperature shall be measured using one or more sensors located upstream of the CFV. When an upstream pipeline is used, the recommended location of these sensors is $1.8D$ to $2.2D$ upstream of the inlet plane of the CFV. The diameter of the sensing element shall be not larger than $0.04D$, and the element shall not be aligned with a wall pressure tap in the flow direction. If it is impractical to use a sensing element of diameter less than $0.04D$, the sensing element shall be located so that it can be demonstrated that it does not affect the pressure measurement. The sensor may be located further upstream, provided that it has been demonstrated that the measured temperature can be used reliably to give the bulk gas temperature averaged over the CFV inlet.

Particular care should be exercised to ensure reliable temperature measurements considering such effects attributed to temperature sampling errors, time response of the temperature sensor, stem conduction, self-heating (for resistance temperature sensors), radiation effects, and heat transfer due to temperature gradient effects. Appropriate care, such as using insulation and selecting appropriate sensors, should be taken to minimize these effects.

8 CALCULATION METHODS

The mass flow through a CFV should be computed using eq. (4-3). Example calculations can be found in Nonmandatory Appendix B. In paras. 8.1 through 8.4, methods for calculation of C_d , C_R , P_0 , T_0 , and the maximum back pressure ratio are given.

8.1 Discharge Coefficient

The discharge coefficient, C_d , corrects the theoretical flow, \dot{m}_{th} , calculated from 1-D isentropic theory [eq. (4-2)] to give actual mass flow through a CFV. The discharge coefficient is less than unity so that the actual mass flow is lower than theoretical mass flow. Physically, $C_d < 1$ because there is a boundary layer along the CFV wall and there are momentum effects in the convergent section. Excluding the transition regime where the boundary layer transitions from laminar to turbulent flow, the discharge coefficient decreases with decreasing Re_d (decreasing mass flow or CFV diameter). CFV flows with either a laminar or a turbulent boundary layer have been successfully characterized by correlating C_d as a function of Re_d^{-n} .

The discharge coefficient can be obtained either by direct calibration against a flow reference standard (calibration method) or by using an equation based on prior research and theoretical methods (empirical method).

NOTE: For the empirical method, the throat diameter or cross-sectional area (A^*) of the CFV must be measured to achieve good flow uncertainty, whereas in the calibration method a nominal value for A^* is sufficient as long as the same value is used for both calibration and application. For small throat diameter CFVs, A^* is difficult to measure with low uncertainty, and flow calibration is generally preferred. If the nominal value of A^* is an underestimate, it is possible to obtain C_d values > 1 from the calibration method. However, if the same nominal value for the throat area is used during both the calibration and application phases, the CFV mass flow will be unaffected by the error in the nominal value of A^* . See section 9 and the example in Nonmandatory Appendix B for uncertainty effects due to errors in throat cross section area measurements.

For the empirical method, experimental discharge coefficient values for toroidal and cylindrical CFVs have been fitted to the following equation (see Table 8.1-1):²

$$C_d = b_0 - b_1 Re_d^{-n} \quad (8-1)$$

The uncertainty at a 95% confidence level for the discharge coefficients obtained from eq. (8-1) is 0.3%. Discharge coefficients are given in Tables A-1 and A-2 in Nonmandatory Appendix A.

² Arnberg, B. T., and Ishibashi, M., Discharge Coefficient Equations for Critical-Flow Toroidal-Throat Venturi Nozzles, FEDSM2001-18030, Proceedings of the ASME Fluids Engineering Summer Meeting, New Orleans, Louisiana, USA, May 2001.

NOTES:

- (1) The uncertainties in the fitted equations for C_d are as large as 0.3% in part because the boundary layer transition from laminar to turbulent flow in the CFV causes a discontinuity in the discharge coefficient versus Reynolds number curve. The Reynolds number at which transition occurs is approximately 1×10^6 but depends on several factors (i.e., local curvature at the CFV throat, small geometric defects near the throat) and therefore is not known for a particular CFV without calibration against a flow reference. CFV flow uncertainty as low as 0.1% can be obtained by calibrating the CFV against a flow reference standard.
- (2) The empirical method should not be used when measuring the flow of gases with significant vibrational relaxation effects (e.g., CO_2 and SF_6). Gases with energy in the vibrational modes can have C_d values that differ from the empirical method by 2% or more.³

CFVs that were precisely machined to match the geometry prescribed in this Standard have been manufactured and calibrated to show agreement with analytical C_d values within 0.04%.^{4,5} C_d values calculated by analytical means also agree with experimental results for less precisely machined CFVs within 0.1%.^{6,7} This makes CFVs an economical way to measure large gas flows with uncertainty of 0.3% or better as long as transition is avoided.

8.2 Computation of Real Gas Critical Flow Function

The critical flow function is a dimensionless thermodynamic property that accounts for real gas effects on CFV mass flow. It is defined by

$$C_R^* = \frac{\rho^* c^* \sqrt{R_u T_0}}{P_0 \sqrt{M}} \quad (8-2)$$

For specified stagnation conditions P_0 and T_0 , the throat density, ρ^* , and sound speed, c^* , are calculated based on a one-dimensional, isentropic, isoenergetic flow model. Thermodynamic properties are calculated using a database that accounts for real gas effects. The isentropic condition requires that the throat entropy equals the stagnation entropy while the isoenergetic condition stipulates that the total enthalpy at the throat equals the stagnation enthalpy. Both the throat entropy, s^* , and total enthalpy, h_t^* , are independent thermodynamic variables, and therefore they determine the thermodynamic state at the CFV throat. The real gas critical flow function, C_R^* , is determined by finding the unique throat density and sound speed corresponding to the thermodynamic state at the CFV throat (see Fig. 8.2-1). An iterative procedure is generally required to determine ρ^* and c^* from the known entropy and total enthalpy (see Nonmandatory Appendix C for details).

Computations for C_R^* require a low-uncertainty thermodynamic database. In this Standard, C_R^* is computed using the REFPROP thermodynamic database.⁸ This database documents the uncertainty of experimentally measured properties, includes numerous gases (e.g., O_2 , CO_2 , N_2 , H_2 , Ar, C_2H_4 , and He), provides flexibility to create user-defined gas mixtures (e.g., natural gas, dry air, and humid air; see Nonmandatory Appendices C and D), and is maintained and kept up to date by the National Institute of Standards and Technology (NIST). In addition, the database internally solves the one-dimensional, isentropic, isoenergetic flow model for C_R^* . In this way C_R^* values are calculated as a function of gas composition, the stagnation pressure, and the stagnation temperature. Nonmandatory Appendix C shows values of C_R^* for selected gases and stagnation conditions.

If the flow measurement application does not require the lowest uncertainty then the ideal gas critical flow function (C_i^*) or the polytropic gas critical flow function (C_p^*) can be used instead of C_R^* (see Fig. 8.2-2).

³ Johnson, A. N., Merkle, C. L., Moldover, M. R., and Wright, J. D., Relaxation Effects in Small Critical Nozzles, *ASME J. of Fluids Engng.*, 128, pp. 170–176, 2006.

⁴ Ishibashi, M., and Takamoto, M., Discharge Coefficient of Superaccurate Critical Nozzle Accompanied With the Boundary Layer Transition Measured by Reference Superaccurate Critical Nozzles Connected in Series, *FEDSM2001-18036, Proceedings of the ASME Fluids Engineering Summer Meeting*, New Orleans, Louisiana, USA, May 2001.

⁵ Ishibashi, M., and Takamoto, M., Theoretical Discharge Coefficient of a Critical Circular-Arc Nozzle With Laminar Boundary Layer and Its Verification by Measurements Using Super-Accurate Nozzles, *Flow Meas. Instrum.*, 11, pp. 305–314, 2000.

⁶ Johnson, A. N., and Wright, J. D., Comparison Between Theoretical CFV Models and NIST's Primary Flow Data in the Laminar, Turbulent, and Transition Flow Regimes, *ASME J. of Fluids Engng.*, 130, 2008.

⁷ Mickan, B., Kramer, R., Dopheide, D., Johnson, A., Wright, J., Hotze, H.-J., Hinze, H.-M., and Vallet, J.-P., Comparisons by PTB, NIST, and LNE-LADG in Air and Natural Gas with Critical Venturi Nozzles Agree Within 0.05%, *Sixth International Symposium for Fluid Flow Measurement*, Queretaro, Mexico, A.4.4, 2006.

⁸ Lemmon, E. W., Huber, M. L., and McLinden, M. O., *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties — REFPROP*, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, Maryland, USA, 2013.

Fig. 8.2-1 Percent Difference Between the Ideal Gas Critical Flow Function, C_i^* , and the Real Gas Critical Flow Function, C_R^* , at $T_0 = 295$ K

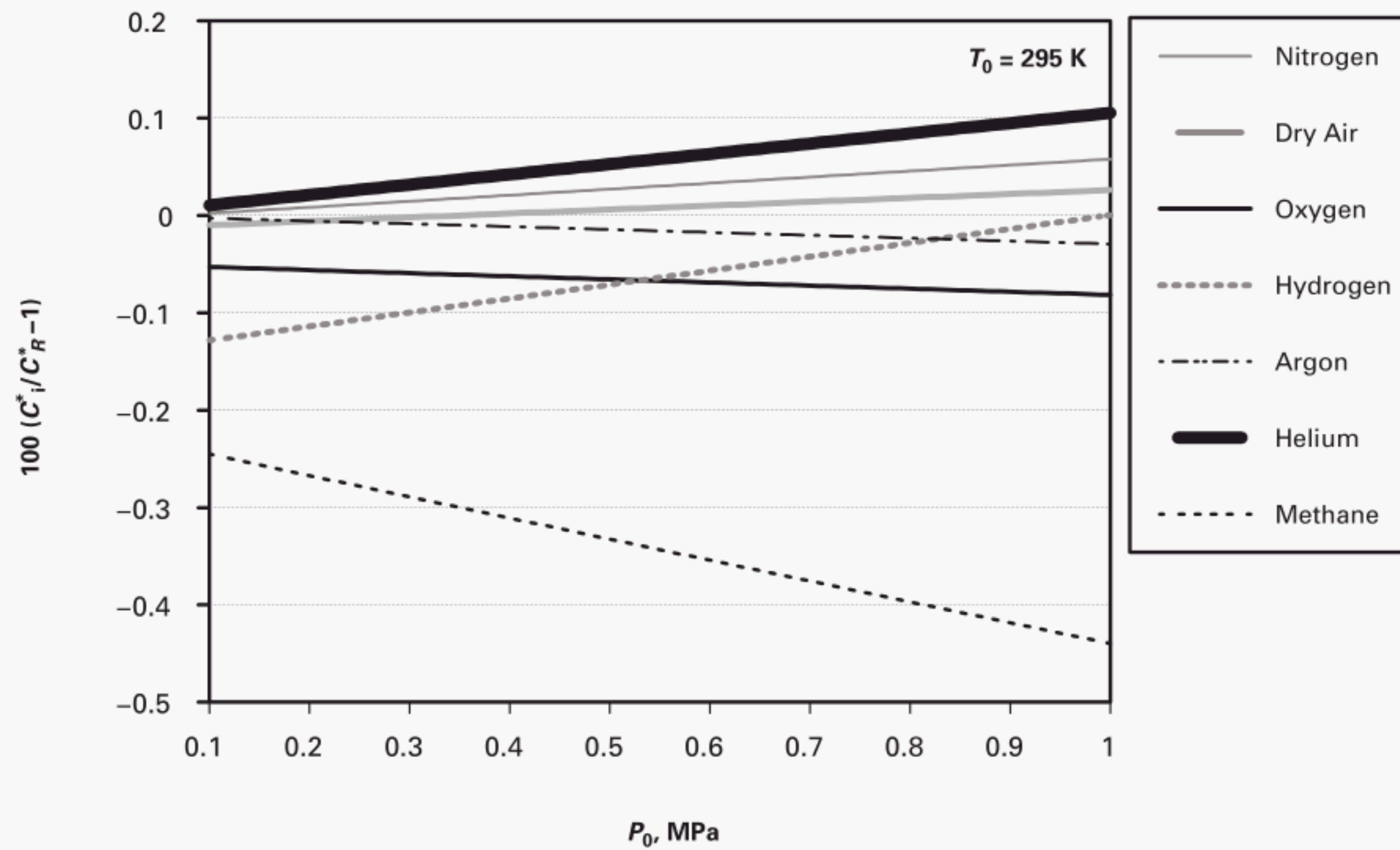
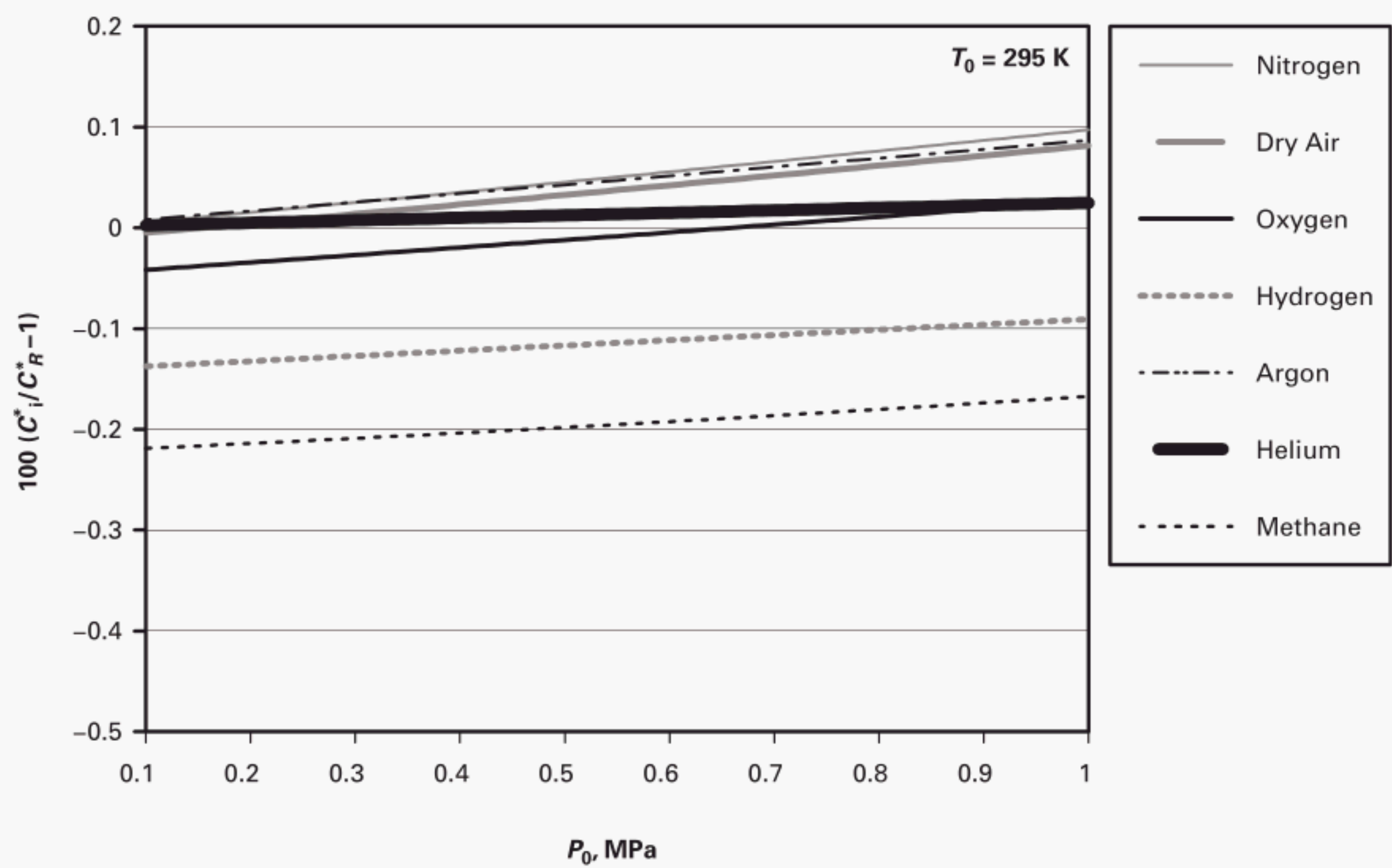


Fig. 8.2-2 Percent Difference Between the Polytropic Gas Critical Flow Function, C_p^* , and the Real Gas Critical Flow Function, C_R^* , at $T_0 = 295\text{ K}$



NOTES:

- (1) If the discharge coefficient of a CFV is determined by flow calibration against a reference standard, and then used in the same gas at the same stagnation temperature and pressure, then the critical flow function should be computed using the same method for both the calibration and the application. In this case, any error introduced from using an approximate value of the critical flow factor during the calibration phase will identically cancel when the same value of the critical flow function is used in the application phase.
- (2) If the discharge coefficient of a CFV is determined by flow calibration against a reference standard, and then used in a different gas at the stagnation conditions that yield the same Reynolds number, then the real gas critical flow function, C_R^* , should be used in both the calibration and the application in order to achieve the best uncertainty.

8.3 Conversion of Measured Pressure and Temperature to Stagnation Conditions

If the upstream plenum can be assumed to be infinitely large (i.e., $\beta = 0$), then the inlet Mach number can be taken to be zero ($Ma_1 = 0$). However, if flow is directed into the CFV through upstream piping with an internal diameter such that $\beta \leq 0.25$, then the Mach number in the pipe section can be calculated by

$$Ma_1 = \frac{1}{\beta^2} \left(\frac{2}{\kappa + 1} \right)^{(\kappa-3)/(2\kappa-2)} \left[1 - \sqrt{1 - 2\beta^4 \left(\frac{2}{\kappa + 1} \right)^{2/(\kappa-1)}} \right] \quad (8-3)$$

The inlet stagnation pressure can be determined from the relationship

$$P_0 = P_1 \left(1 + \frac{\kappa - 1}{2} Ma_1^2 \right)^{\kappa/(\kappa-1)} \quad (8-4)$$

and the inlet stagnation temperature may be determined from

$$T_0 = T_{m1} \left[1 + \frac{\kappa - 1}{2} Ma_1^2 (1 - R_f) \right] \quad (8-5)$$

NOTES

- (1) For CFV installations with $\beta \leq 0.25$, the magnitude of the difference between the measured pressure and the computed stagnation pressure is less than 0.1% as shown in Fig. 8.3-1. Therefore the Mach number, stagnation pressure, and stagnation temperature can be calculated with comparable uncertainty if the specific heat ratio, γ , is substituted for the polytropic exponent, κ . For example, the stagnation temperature could be computed with $T_0 = T_{m1} [1 + 0.5(\gamma - 1) Ma_1^2 (1 - r_f)]$. When calculations of the ideal gas critical flow function, C_i^* , or when $\beta > 0.25$, low-uncertainty values of γ are required. When $\beta \leq 0.25$, estimated values of γ are adequate for calculating the Mach number, stagnation pressure, and stagnation temperature. For example, $\gamma = 5/3$ for ideal monatomic gases, $7/5$ for ideal diatomic gases, and $9/7$ for ideal triatomic gases can be used for the calculations.
- (2) Temperature measurements are made by inserting a probe into the flow line. The temperature measured by the probe, T_{m1} in the equation, will be a function of the probe design, the fluid properties, the flow field at the probe, and the wall temperature. The measured temperature, T_{m1} , will be between the actual flowing static temperature, T_1 , and the stagnation temperature, T_0 . For CFVs with $\beta \leq 0.25$ the difference between T_1 , T_{m1} , and T_0 will be small. However, if $\beta > 0.25$, the stagnation temperature and pressure corrections can be significant and should be made.
- (3) In cases where a significant temperature correction is required ($\beta > 0.25$) the recovery factor, R_f , which is known, tested, or estimated, can be used to correct the measured temperature. The recovery factor is approximately constant for a given probe design and flow situation. The value of the recovery factor can range from 0.5 to 0.99. This Standard recommends a value of 0.75, a common value for many temperature probes.

8.4 Maximum Permissible Downstream Pressure (Maximum Back Pressure Ratio)

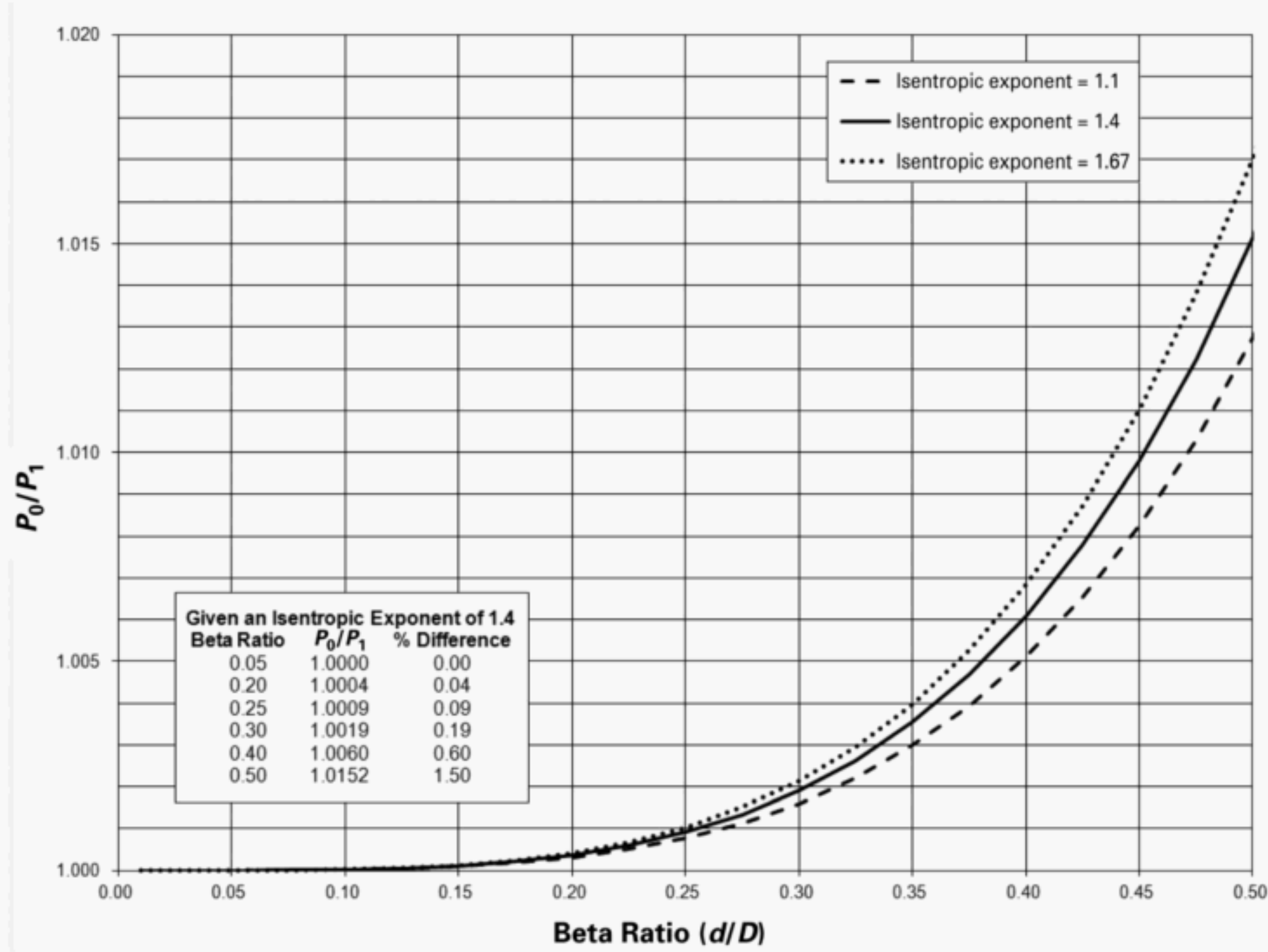
For CFVs operating at throat Reynolds numbers greater than 2×10^5 and with diffusers longer than $1d$, the maximum permissible downstream pressure can be estimated by the relationship

$$(P_2/P_0)_{\max} = 0.8 [(P_2/P_0)_i - r^*] + r^* \quad (8-6)$$

where

$$r^* = \left(\frac{2}{\kappa + 1} \right)^{\kappa/(\kappa-1)} \quad (8-7)$$

Fig. 8.3-1 Difference Between Static and Stagnation Pressure for Various Beta Ratios and Isentropic Exponent Values



and

$$(P_2/P_0)_i = \left(1 + \frac{\kappa - 1}{2} Ma_2^2\right)^{-\kappa/(\kappa-1)} \quad (8-8)$$

and

$$Ma_2 = (A_2/A^*) \left(\frac{2}{\kappa + 1}\right)^{(\kappa-3)/(2\kappa-2)} \left\{1 - \sqrt{1 - 2 \left[\frac{1}{(A_2/A^*)}\right]^2 \left(\frac{2}{\kappa + 1}\right)^{2/(\kappa-1)}}\right\} \quad (8-9)$$

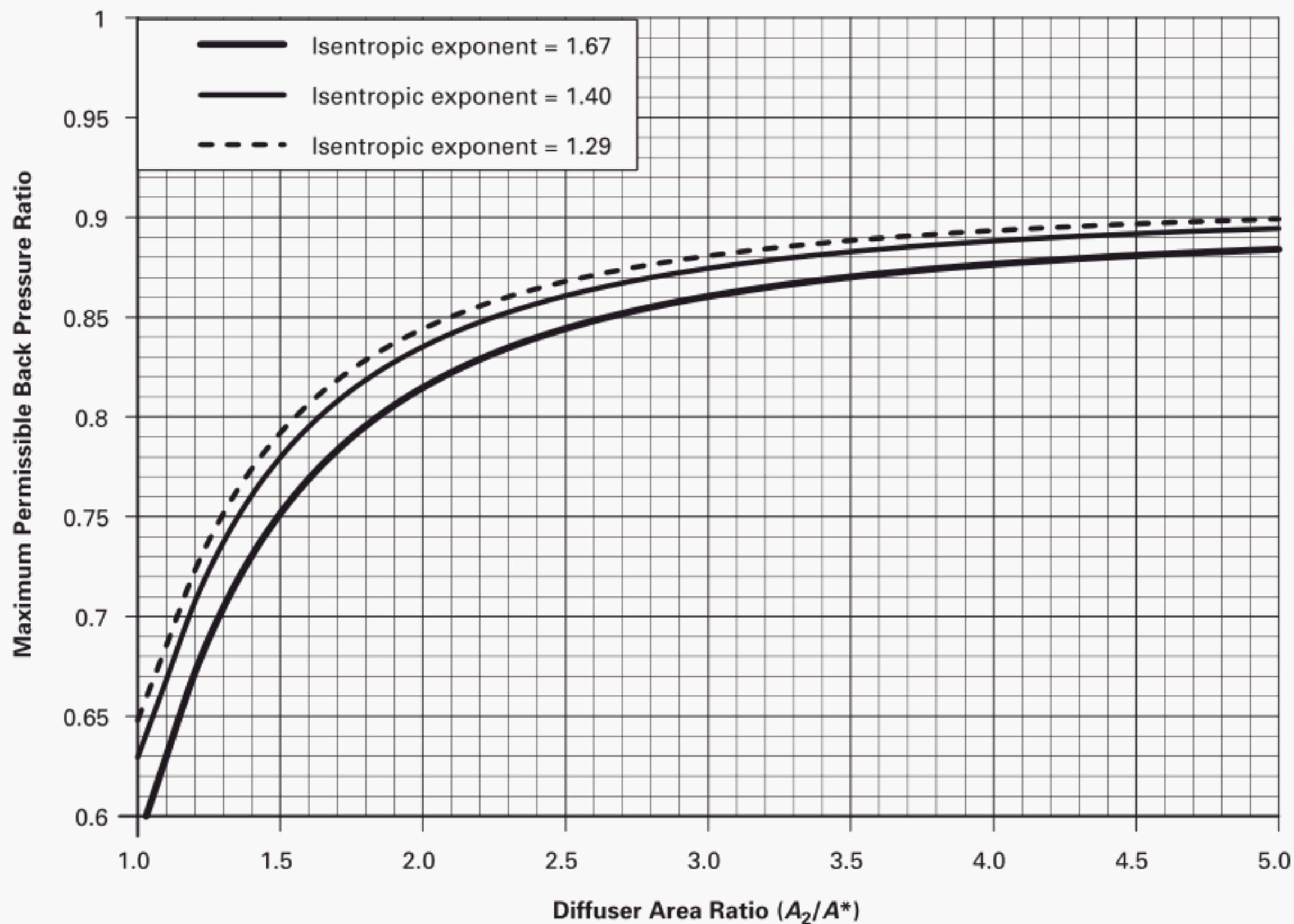
The value of $(P_2/P_0)_i$ is determined from the one-dimensional compressible flow of an ideal gas relationship as a function of area ratio (A_2/A^*) of the divergent section. Sample values of $(P_2/P_0)_{\max}$ may be found in Fig. 8.4-1.

Higher back pressure ratios than shown can be used, provided it can be verified that the flow is critical. For Reynolds numbers greater than 2×10^5 , the pressure ratio P_2/P_0 is not significantly affected by extending the cone length such that the exit area is greater than four times the throat area, i.e., beyond seven diameters for a cone half-angle of 4 deg.

For CFVs operating at throat Reynolds numbers from 5×10^4 to 2×10^5 , it is recommended that users maintain a minimum back pressure ratio equal to the critical pressure ratio, r^* , or perform an unchoking test on their CFVs.

For CFVs operating at throat Reynolds numbers below 5×10^4 , it is recommended that users maintain a back pressure ratio of $(P_2/P_0)_{\max} = 0.30$ or perform an unchoking test on their CFVs. For some CFV diffuser geometries operated at these low Reynolds numbers, a decrease in C_d is observed from a back pressure ratio of approximately 0.35 to 0.50. This diffuser performance inversion, sometimes referred to as “premature unchoking” can be minimized by using 3-deg to 4-deg half-angles and diffuser lengths of $10d$ or greater.

Fig. 8.4-1 Recommended Maximum Back Pressure Ratio Versus Diffuser Area Ratio for Various Isentropic Exponent Values



GENERAL NOTE: Fig. 8.4-1 applies only for throat Reynolds numbers greater than 2×10^5 .

Pressure ratios as high as 0.95 can be obtained for some CFVs at high Reynolds numbers. An unchoking test should be conducted to determine the $(P_2/P_0)_{\max}$.

The procedure for performing an unchoking test can be found in Nonmandatory Appendix E.⁹

9 UNCERTAINTY OF CFV FLOW MEASUREMENTS

9.1 General Considerations

The uncertainty associated with each measurement of mass flow is an essential consideration and shall be calculated and reported whenever a measurement is claimed to conform to this Standard. The uncertainty for a mass flow measurement may be expressed in relative terms as a percentage, in relative (dimensionless) terms, or in absolute terms with the same units as the given mass flow. Uncertainty may be expressed as a standard uncertainty, u (at a confidence level of 68%), or as a combined standard uncertainty u_c , or as an expanded uncertainty U , which is usually the final result with a 95% confidence level. The uncertainty for mass flow as determined using eq. (4-3) is most simply evaluated using relative uncertainties expressed as a percentage. The quantities and notation herein refer to relative uncertainties expressed as percentages of the average value. Uncertainty calculations should conform to the procedures given in the following paragraphs of this Standard.¹⁰

⁹ Maximum back pressure guidelines for CFVs with specific diffuser geometry operated with dry air in the Re range from 12,000 to 250,000 can be found in Carter, M., Sims, B., Britton, C., and McKee, R., Choking Pressure Ratio Guidelines for Small Critical Flow Venturis and the Effects of Diffuser Geometry, 16th International Flow Measurement Conference, Paris, France, 2013.

¹⁰ ISO/IEC Guide 98-3:2008.

In general, the expanded uncertainty for a measurand, $U(\text{mran})$, can be calculated from the combined standard uncertainty, $u_c(\text{mran})$, comprised of the relative Type A uncertainty, $u_A(\text{mran})$, which is obtained using statistics, and the relative Type B uncertainty, $u_B(\text{mran})$, which is obtained using methods other than statistics. These are combined by root sum of squares (RSS) as follows:

$$U(\text{mran}) = k \times u_c(\text{mran}) = k \sqrt{u_A(\text{mran})^2 + u_B(\text{mran})^2} \quad (9-1)$$

where k is the coverage factor, and $k = 1$ indicates a 68% confidence level and $k = 2$ is generally appropriate to calculate a 95% confidence level uncertainty. The Type A uncertainty, $u_A(\dot{m})$, is the standard deviation, at 68% confidence level, of the replicated measurements of mass flow from the repeatability and reproducibility test results. The relative Type B uncertainty, $u_B(\dot{m})$, is obtained from evaluations of the uncertainty of the components in the equation used to calculate the mass flow. It is common and usually more convenient to perform uncertainty calculations in relative uncertainty terms as shown in the practical computation methods that follow. Using relative uncertainty terms allows the use of normalized sensitivity coefficients, which are the exponents of the respective factors in the governing equation for the quantity being assessed.

Using a coverage factor $k = 2$ to obtain a 95% confidence level in uncertainty is appropriate when the system has many degrees of freedom, as is normally assumed for Type B uncertainty components. The degrees of freedom for the Type A component, calculated from the standard deviation of n repeated measurements, is $n - 1$, and this can lead to larger values of k when the number of replicates is approximately 20 or less. The Welch-Satterthwaite formula¹⁰ allows calculation of effective degrees of freedom and, when the repeatability (Type A component) is small relative to the Type B components, leads to a coverage factor of approximately 2 for 95% confidence level. The Welch-Satterthwaite formula is applied in the examples in Nonmandatory Appendix B. There and in most applications, $k = 2$ is an acceptable value to obtain 95% confidence level uncertainties.

9.2 Practical Computation of Uncertainty

Equation (4-3), the governing equation for mass flow, \dot{m} , through a CFV, is

$$\dot{m} = \frac{C_d A^* C_R^* P_0}{\sqrt{(R_u/M) T_0}}$$

The uncertainty of a flow measurement should be calculated from the standard deviation of the available flow measurement data plus evaluations of uncertainty of the individual quantities in the governing equation. In most cases, uncertainty components can be assumed to be independent and uncorrelated, but there are certain cases where correlated uncertainties are an issue (see para. 9.3).

Because eq. (4-3) is comprised of products, it is simplest to use normalized sensitivity coefficients and relative uncertainties expressed as percentages (the dimensional uncertainty divided by the average value of the respective component). In this way, the sensitivity coefficients for a function like eq. (4-3) are the exponents of the respective components. In the case where the uncertainty components are assumed to be independent and uncorrelated or when the respective correlated effects are negligible, a practical working formula for calculating the relative combined standard uncertainty by RSS is

$$u_c(\dot{m}) = \sqrt{[u_A(\dot{m})]^2 + [u_B(C_D)]^2 + [u_B(A^*)]^2 + [u_B(C_R^*)]^2 + [u_B(P_0)]^2 + \frac{1}{4} [u_B(R_u)]^2 + \frac{1}{4} [u_B(M)]^2 + \frac{1}{4} [u_B(T_0)]^2} \quad (9-2)$$

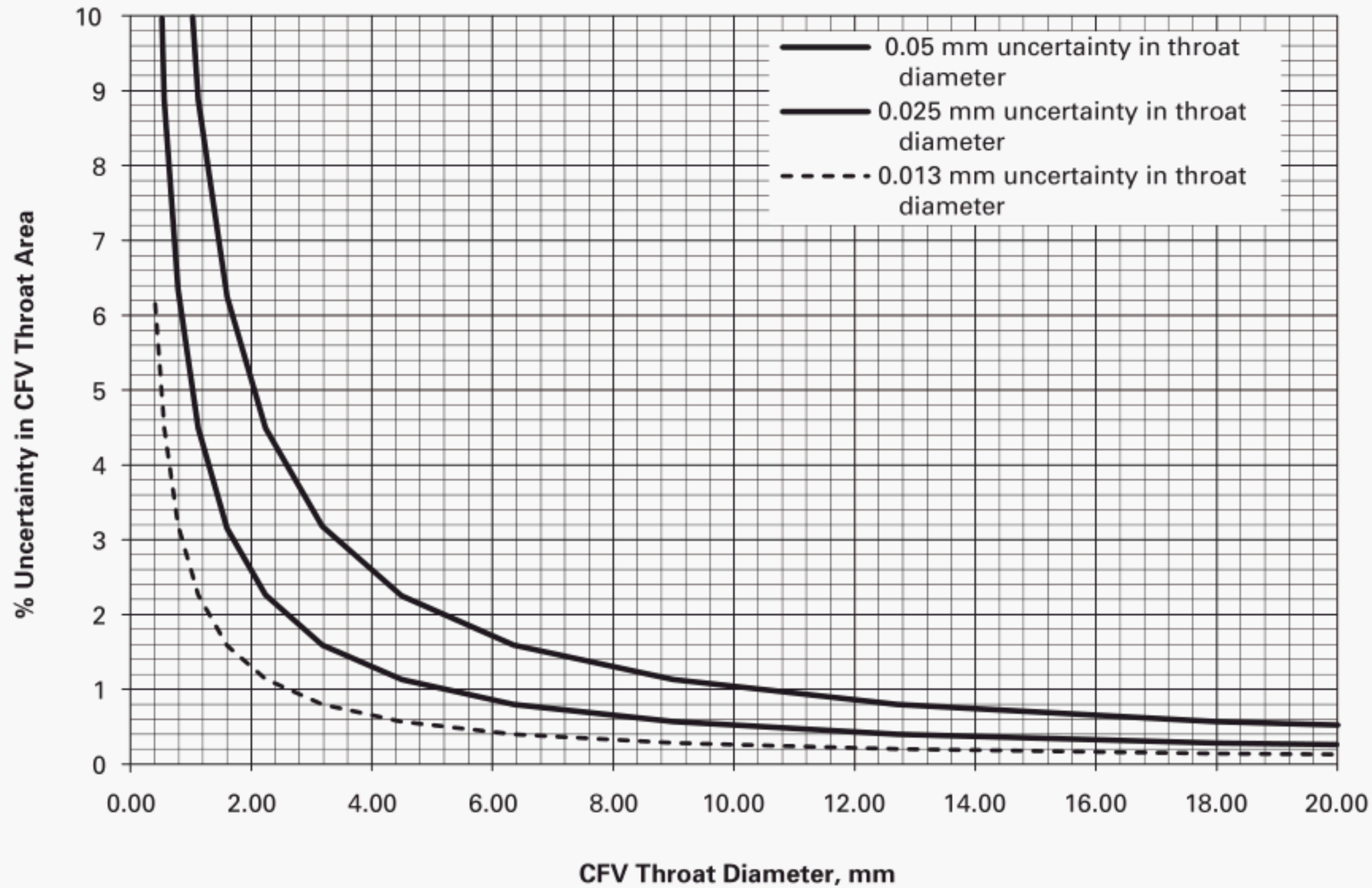
where the squares of the square-bracketed terms are variances.

The Type A relative uncertainty term, $u_A(\dot{m})$, can be calculated from the standard deviation of the available replicated measurement data.

The Type B relative uncertainty terms in eq. (9-2) can be calculated from the uncertainty of each factor with the absolute uncertainties of each component being divided by the magnitude of that component to determine the relative uncertainties. Then the relative uncertainty terms are squared and combined by the RSS relationship.

Each uncertainty component has its own subset of uncertainty sources. Some of the uncertainty components that should be considered are

- (a) long-term reproducibility (drift) of the discharge coefficient
- (b) pressure and temperature sensor calibrations
- (c) drift between periodic calibrations
- (d) temperature effects on the CFV mass flow (e.g., stem conduction)
- (e) sampling errors

Fig. 9.2-1 Percent Uncertainty in CFV Throat Area due to Uncertainty in Throat Diameter Measurement

- (f) thermal expansion of the throat
- (g) interference effects between CFVs in a plenum
- (h) species effects (calibration in one gas, usage in another)
- (i) leaks
- (j) contamination of CFV surfaces with dirt
- (k) pressure effects because real gas effects are not perfectly captured (e.g., errors in C_R^*)

An example of a subcomponent study is presented in Fig. 9.2-1, which shows the relationship between diameter uncertainties (of various magnitudes) and area uncertainties.

9.3 Correlated Uncertainty Components

In some measurement situations the components are not fully or predominately independent and the correlation of variables must be considered.

For the measurement cases where the terms in the governing equation cannot be assumed to be independent and the degree of correlation is significant, the computations become somewhat more complex because the respective relative correlation terms should be included. The correlated variable terms are computed or evaluated from data for the respective interacting terms.

For example, both C_R^* and M depend on the gas composition. When these terms are included, the combined relative uncertainty equation becomes

$$u_c(\dot{m}) = \sqrt{[u_A(\dot{m})]^2 + [u_B(C_D)]^2 + [u_B(A^*)]^2 + [u_B(C_R^*)]^2 + [u_B(P_0)]^2 + \frac{1}{4} [u_B(R_u)]^2 + \frac{1}{4} [u_B(M)]^2 + \frac{1}{4} [u_B(T_0)]^2 + \frac{1}{2} CV(M, gc)} \quad (9-3)$$