
**Measurement of gas flow by means of
critical flow nozzles**

Mesurage de débit de gaz au moyen de tuyères en régime critique

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

ISO 9300 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 2, *Pressure differential devices*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/SS F05, *Measuring instruments*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 9300:2005), which has been technically revised.

The main changes are as follows:

- the discharge coefficient curve is given by a single equation each for the toroidal- and cylindrical-throat critical flow nozzles (CFNs) that covers both the laminar and turbulent boundary layer regimes;
- the discharge coefficient curve of the cylindrical-throat CFN is updated based on the recent experimental and theoretical data;
- the quadrant CFN and detachable diffuser are introduced;
- the basic equations used to measure the discharge coefficient are listed;
- the premature unchoking phenomenon is explained to give attention to the unpredictable unchoking at low Reynolds numbers;
- REFPROP is introduced for the calculations of critical flow function and viscosity as well as their fitted curves are given for some pure gases and air;

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- the diameter correction method is introduced to fit the experimental discharge coefficient data to a reference curve;
- the detailed method to match the discharge coefficient curve on an experimental data set is described;
- the background of the specifications is given.

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Measurement of gas flow by means of critical flow nozzles

1 Scope

This document specifies the geometry and method of use (installation in a system and operating conditions) of critical flow nozzles (CFNs) used to determine the mass flow rate of a gas flowing through a system basically without the need to calibrate the CFN. It also gives the information necessary for calculating the flow rate and its associated uncertainty.

This document is applicable to nozzles in which the gas flow accelerates to the critical velocity at the minimum flowing section, and only where there is steady flow of single-phase gas. When the critical velocity is attained in the nozzle, the mass flow rate of the gas flowing through the nozzle is the maximum possible for the existing inlet condition, while the CFN can only be used within specified limits, e.g. the CFN throat to inlet diameter ratio and Reynolds number. This document deals with the toroidal- and cylindrical-throat CFNs for which direct calibration experiments have been made in sufficient number to enable the resulting coefficients to be used with certain predictable limits of uncertainty.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Pressure

3.1.1

static pressure

pressure of the flowing gas (see Annex J)

Note 1 to entry: The static pressure is measured through a *wall pressure tapping* (3.1.3).

3.1.2

stagnation pressure

pressure which would exist in a flowing gas stream if the stream were brought to rest by an isentropic process

3.1.3

wall pressure tapping

hole drilled in the wall of a conduit to measure the *static pressure* (3.1.1) of the flowing gas in the conduit

3.2 Temperature

3.2.1

static temperature

temperature of the flowing gas (see Annex J)

Note 1 to entry: The static temperature cannot be measured exactly by a temperature sensor fixed in the conduit.

3.2.2

stagnation temperature

temperature which would exist in a flowing gas stream if the stream were brought to rest by an isentropic process (see Annex J).

3.2.3

recovery temperature (wall temperature, measured temperature)

temperature of the gas touching the wall (see Annex J)

Note 1 to entry: The temperature sensor fixed on a conduit measures the recovery temperature.

3.3 Nozzle

3.3.1

contraction

portion of the *nozzle* (3.3.5) upstream of the *throat* (3.3.2) intended to accelerate the flow and attain the supposed flow field at the *critical point* (3.4.4).

3.3.2

throat

portion of the *nozzle* (3.3.5) where the cross section is minimum

Note 1 to entry: This document deals with nozzles with toroidal- and cylindrical-throats.

3.3.3

diffuser

divergent portion of the *nozzle* (3.3.5) behind the *throat* (3.3.2) intended to recover the pressure

3.3.4

traditional diffuser

frustum *diffuser* (3.3.3) machined as one piece

3.3.5

nozzle

device inserted in a system intended to use for measurement of the flow rate through system, which consists of *contraction* (3.3.1) and *throat* (3.3.2), or *contraction* (3.3.1), *throat* (3.3.2), and *diffuser* (3.3.3)

3.3.6

critical flow nozzle

CFN

nozzle (3.3.5) that attains the *critical flow* (3.4.2)

3.3.7**normal precision nozzle****NPN**

nozzle (3.3.5) machined by a lathe, with the surface polished to achieve the desired roughness

3.3.8**high precision nozzle****HPN**

nozzle (3.3.5) machined by a lathe that can achieve mirror finish without polishing the surface, thus it has the form exactly as designed

3.4 Flow**3.4.1****isentropic flow**

theoretical flow along which the thermodynamic process is adiabatic and reversible (see Annex J)

3.4.2**critical flow**

flow in a *nozzle* (3.3.5) that has attained the maximum flow rate of the *nozzle* (3.3.5) for a given set of inlet conditions (see Annex J)

3.4.3**choke**

attaining the *critical flow* (3.4.2) in a *nozzle* (3.3.5) (see Annex J)

3.4.4**critical point**

location in the *CFN* (3.3.6) where the flow attains the *critical velocity* (3.4.11)

3.4.5**critical pressure**

p^*

static pressure (3.1.1) at the *critical point* (3.4.4) (see Annex J)

3.4.6**critical pressure of perfect gas**

p_p^*

theoretical *static pressure* (3.1.1) at the *critical point* (3.4.4) assuming the *isentropic flow* (3.4.1) of *perfect gas* (3.6.1)

3.4.7**critical temperature**

T^*

static temperature (3.2.1) at the *critical point* (3.4.4)

3.4.8**critical temperature of perfect gas**

T_p^*

theoretical *static temperature* (3.2.1) at the *critical point* (3.4.4) assuming the *isentropic flow* (3.4.1) of *perfect gas* (3.6.1)

3.4.9

critical density

ρ^*

density at the *critical point* (3.4.4)

3.4.10

critical density of perfect gas

ρ_p^*

theoretical density at the *critical point* (3.4.4) assuming the *isentropic flow* (3.4.1) of *perfect gas* (3.6.1)

3.4.11

critical velocity

c^*

flow velocity at the *critical point* (3.4.4) (see Annex J)

3.4.12

critical velocity of perfect gas

c_p^*

theoretical flow velocity at the *critical point* (3.4.4) assuming the *isentropic flow* (3.4.1) of *perfect gas* (3.6.1)

3.5 Flow rate

3.5.1

mass flow rate

q_m

mass of the gas passing through the *CFN* (3.3.6) per unit time

Note 1 to entry: In this document, the term "mass flow rate" without any adjective always refers to the true mass flow rate through the *CFN*.

3.5.2

theoretical mass flow rate of perfect gas

$q_{th,P}$

theoretical mass flow rate through the *CFN* (3.3.6) assuming one-dimensional *isentropic flow* (3.4.1) of *perfect gas* (3.6.1)

3.5.3

theoretical mass flow rate of real gas

$q_{th,R}$

theoretical mass flow rate through the *CFN* (3.3.6) assuming one-dimensional *isentropic flow* (3.4.1) of *real gas* (3.6.1)

3.5.4

volume flow rate

q_V

volume of the gas passing through the conduit, in which the *CFN* (3.3.6) is installed, per unit time at a designated location (see Annex J)

Note 1 to entry: The volume flow rate at the designated location, where the density is ρ , is given by:

$$q_V = \frac{q_m}{\rho}$$

3.5.5**Reynolds number**

$$Re = \frac{4q_m}{\pi d \mu_0}$$

dimensionless parameter calculated from the throat diameter, *mass flow rate* (3.5.1), and gas dynamic viscosity at *CFN* (3.3.6) inlet stagnation condition (see Annex J)

3.5.6**discharge coefficient**

$$C_d = \frac{q_m}{q_{th,R}}$$

ratio of the *mass flow rate* (3.5.1) to theoretical one of *real gas* (3.6.1) at the same inlet stagnation condition

3.5.7**critical pressure ratio**

ratio of the *critical pressure* (3.4.5) of *perfect gas* (3.6.1) to the inlet *stagnation pressure* (3.1.2)

3.5.8**back-pressure ratio**

ratio of the *static pressure* (3.1.1) at the diffuser exit to the inlet *stagnation pressure* (3.1.2)

3.5.9**local Mach number**

$$M_a$$

ratio of the flow velocity to local acoustic one

3.5.10**Mach number in the upstream conduit**

$$M_{ac}$$

ratio of the mean axial flow velocity over the cross-section of upstream conduit to the acoustic velocity at the same location

Note to entry: It is not necessary for M_{ac} to be accurate and it may be approximated by:

$$M_{ac} = \frac{q_m}{\frac{\pi D^2}{4} \rho_0 \sqrt{\gamma \frac{R}{M} T_0}}$$

3.5.11**uncertainty**

parameter, associated with the results of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

3.6 Gas**3.6.1****perfect gas**

theoretical gas whose *isentropic exponent* (3.6.6) equals to the specific heat that is constant at any gas condition and also *compressibility factor* (3.6.3) is always unity

3.6.2

real gas

actual gas whose *isentropic exponent* (3.6.6) and *compressibility factor* (3.6.3) depend on its pressure and temperature

3.6.3

compressibility factor

Z

correction factor for the deviation of the real gas constant from the universal one (see Annex J)

3.6.4

critical flow function

C^*

dimensionless function that relates the thermodynamic properties of the gas at the throat of CFN (3.3.6) to its inlet stagnation condition assuming one-dimensional *isentropic flow* (3.4.1)

3.6.5

critical flow function for the flow rate equation using density

$$C^*_D = C^* \sqrt{Z_0}$$

alternative *critical flow function* (3.6.4) to be used in the equation of *mass flow rate* (3.5.1) that uses density

3.6.6

isentropic exponent

κ

ratio of the relative variation in pressure to the corresponding relative variation in density under isentropic process

4 Symbols and abbreviations

Symbol	Description	Dimension	SI unit
a, b, c, d, e, f, n	Coefficients for Formula (17)	Dimensionless	—
A	Flowing area	L^2	m^2
A^*	Flowing area at the critical point	L^2	m^2
A_2	Cross-sectional area of nozzle exit	L^2	m^2
A_{nt}	Cross-sectional area at the critical point at the operating CFN temperature	L^2	m^2
c	Local acoustic velocity	LT^{-1}	$m \cdot s^{-1}$
c^*	Local acoustic velocity at the critical point	LT^{-1}	$m \cdot s^{-1}$
c^*_p	Local acoustic velocity at the critical point of perfect gas	LT^{-1}	$m \cdot s^{-1}$
C_{c^*}	Parameter for the equation of C^*	Dimensionless	—
C_μ	Parameter for the equation of μ	Dimensionless	—
C_d	Discharge coefficient	Dimensionless	—
$C_{d^{target}}$	Target discharge coefficient obtained when applying the DCM	Dimensionless	—
$C_{d^{ISO}}$	Discharge coefficient calculated by using Formula (17)	Dimensionless	—
C^*	Critical flow function	Dimensionless	—
C^*_D	Critical flow function for the flow rate equation using density	Dimensionless	—
C^*_p	Critical flow function of perfect gas	Dimensionless	—
C^*_{DA}	Critical flow function of dry air	Dimensionless	—
C^*_{HA}	Critical flow function of humid air	Dimensionless	—

Symbol	Description	Dimension	SI unit
$C_{i,j}$	Coefficient to calculate C^*	b	b
c_v	Covariance	Dimensionless	—
D	Diameter of the inlet conduit	L	m
d_{DCM}	Throat diameter corrected by the DCM	L	m
d_{nt}	Throat diameter at the operating CFN temperature	L	m
d_{nt0}	Measured throat diameter (at temperature T_{nt0})	L	m
d_{ORI}	Throat diameter used at the calibration for the DCM	L	m
d_p	Diameter of the wall pressure tapping breakthrough into the conduit	L	m
H_R	Relative humidity	%	—
k	Coverage factor	Dimensionless	—
l	Diffuser length	L	m
l_1	Distance between Etoile straightener outlet and nozzle inlet plane	L	m
l_2	Length of Etoile straightener	L	m
M	Molar mass	M	kg mol ⁻¹
M_a	Local Mach number	Dimensionless	—
M_{a2}	Local Mach number at the CFN exit assuming the fully subsonic flow in the diffuser	Dimensionless	—
M_{aC}	Local Mach number at the location of the inlet pressure tapping	Dimensionless	—
p	Static pressure of the gas	ML ⁻¹ T ⁻²	Pa
p_0	Stagnation pressure of the gas at the CFN inlet	ML ⁻¹ T ⁻²	Pa
p_1	Static pressure of the gas measured through the upstream wall pressure tapping	ML ⁻¹ T ⁻²	Pa
p_2	Static pressure of the gas at the diffuser exit	ML ⁻¹ T ⁻²	Pa
p_{2i}	Theoretical static pressure of the gas at the diffuser exit when the nozzle is choked but the flow in the diffuser is fully subsonic	ML ⁻¹ T ⁻²	Pa
p_{den}	Static pressure in the gas at densitometer	ML ⁻¹ T ⁻²	Pa
P_r	The Prandtl number	Dimensionless	—
p^*	Static pressure at the critical point	ML ⁻¹ T ⁻²	Pa
p_p^*	Theoretical static pressure at the critical point of perfect gas	ML ⁻¹ T ⁻²	Pa
q_m	Mass flow rate (True mass flow rate)	MT ⁻¹	kg·s ⁻¹
$q_{th,P}$	Theoretical mass flow rate of perfect gas	MT ⁻¹	kg·s ⁻¹
$q_{th,R}$	Theoretical mass flow rate of real gas	MT ⁻¹	kg·s ⁻¹
q_V	Volume flow rate	MT ⁻¹	kg·s ⁻¹
R	Universal gas constant (8,314 5 J/(mol·K))	M L ² T ⁻² Θ ⁻¹	J·mol ⁻¹ K ⁻¹
R_a	Arithmetic average roughness	L	m
Re	Reynolds number	Dimensionless	—
Re^{ORI}	The Reynolds number at the calibration for the DCM	Dimensionless	—
R_f	Recovery factor	Dimensionless	—
r_c	Radius of inlet contraction	L	m
r_{CBP}	Critical back-pressure ratio	Dimensionless	—
r_{nt}	Radius in the vicinity of throat inlet in cylindrical-throat CFN	L	m
T	Static temperature of the gas	Θ	K
T_0	Stagnation temperature of the gas at the CFN inlet	Θ	K
T_1	Measured temperature of the gas at the CFN inlet	Θ	K
T_{den}	Static temperature at densitometer	Θ	K
T_m	Measured temperature	Θ	K

Symbol	Description	Dimension	SI unit
T_{nt0}	Temperature when throat diameter was measured	Θ	K
T^*	Static temperature at the critical point	Θ	K
T_p^*	Theoretical static temperature at the critical point of perfect gas	Θ	K
T_{c^*}	Parameter for the equation of C^*	Θ	K
T_μ	Parameter for the equation of μ	Θ	K
u	Standard uncertainty ($k = 1$)	b	—
u_c	Combined standard uncertainty ($k = 1$)	b	—
U	Expanded uncertainty (with specified coverage factor, k)	b	U
V_{ij}	Coefficient to calculate viscosity	b	U
U	Expanded uncertainty (with specified coverage factor, k)	b	U
x_i	Mole fraction of the i -th component	Dimensionless	—
Z	Compressibility factor	Dimensionless	—
Z_0	Compressibility factor at upstream stagnation condition	Dimensionless	—
Z_{den}	Compressibility factor at densitometer	Dimensionless	—
α	Linear expansion coefficient of the nozzle material	Θ^{-1}	K^{-1}
β	Diameter ratio of the throat and conduit (d_{nt}/D)	Dimensionless	—
δ	Absolute uncertainty	a	a
γ	Heat capacity ratio	Dimensionless	—
κ	Isentropic exponent	Dimensionless	—
μ_0	Dynamic viscosity of the gas at the inlet stagnation conditions	$ML^{-1}T^{-1}$	Pa·s
μ	Dynamic viscosity of the gas	$ML^{-1}T^{-1}$	Pa·s
θ	Angle of the frustum diffuser wall against the nozzle AOS	Dimensionless	rad
ρ	Density of the gas	ML^{-3}	kg
ρ_0	Gas density at the inlet stagnation conditions at nozzle inlet	ML^{-3}	$kg \cdot m^{-3}$
ρ_{den}	Gas density measured by a densitometer	ML^{-3}	$kg \cdot m^{-3}$
ρ^*	Theoretical density of the gas at the critical point	ML^{-3}	$kg \cdot m^{-3}$
ρ_p^*	Theoretical density of the gas at the critical point of perfect gas	ML^{-3}	$kg \cdot m^{-3}$
<p>M = mass L = length T = time Θ = temperature</p> <p>^a Same as the corresponding quantity. ^b Depending on each terms of the equation.</p>			

Abbreviation	Description
AOS	axis of symmetry
CFN	critical flow nozzle
CL	center line
DCM	diameter correction method
HPN	high precision nozzle
NPN	normal precision nozzle
IP	inlet plane
PUP	premature unchoking phenomenon
TLS	tangential line of surface

5 Basic equations

5.1 Gas behaviour

5.1.1 Isentropic process

The pressure, temperature, and density of gas in the isentropic process are related by Formulae (1) and (2);

$$\frac{p^{\gamma-1}}{T^{\gamma}} = \text{const.} \quad (1)$$

$$\frac{p}{\rho^{\gamma}} = \text{const.} \quad (2)$$

5.1.2 State equation

The behaviour of real gas is described by Formula (3);

$$\frac{p}{\rho} = \left(\frac{RZ}{M} \right) T \quad (3)$$

5.2 Isentropic flow of a perfect gas

5.2.1 Flowing area

The flowing area is related to the local Mach number by Formula (4);

$$A = \frac{1}{M_a} \left[\frac{(\gamma-1)M_a^2 + 2}{\gamma+1} \right]^{\frac{1}{2}} \frac{1}{M_a^{\frac{\gamma+1}{2}}} A_{nt} \quad (4)$$

5.2.2 Static pressure

The static pressure is related to the local Mach number by Formula (5);

$$p = \left(1 + \frac{\gamma-1}{2} M_a^2 \right)^{-\frac{\gamma}{\gamma-1}} p_0 \quad (5)$$

5.2.3 Static temperature

The static temperature is related to the local Mach number by Formula (6);

$$T = \frac{2}{2 + (\gamma - 1)M_a^2} T_0 \quad (6)$$

5.3 Theoretical variables at the critical point

5.3.1 General

The theoretical variables at the critical point are derived assuming the isentropic flow of perfect gas.

5.3.2 Critical pressure

The theoretical static pressure at the critical point is given by Formula (7);

$$p^*_P = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} p_0 \quad (7)$$

5.3.3 Critical temperature

The theoretical static temperature at the critical point is given by Formula (8);

$$T^*_P = \frac{2}{\gamma + 1} T_0 \quad (8)$$

5.3.4 Critical density

The theoretical density at the critical point is given by Formula (9);

$$\rho^*_P = \left(\frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \rho_0 \quad (9)$$

5.3.5 Critical velocity

The theoretical flow velocity at the critical point is given by Formula (10);

$$c^*_P = \sqrt{\gamma \frac{R}{M} T^*_P} \quad (10)$$

5.4 Theoretical mass flow rates

5.4.1 General

The theoretical mass flow rates are derived assuming one-dimensional isentropic flow of perfect or real gas.

5.4.2 Theoretical mass flow rate of a perfect gas

The theoretical mass flow rate of a perfect gas is defined by the product of flowing area, local acoustic velocity, and density at the critical point assuming one-dimensional isentropic flow of a perfect gas, i.e. $Z = 1$ and $k = \gamma$, which is given by Formula (11);

$$q_{th,P} \equiv A^* c^* \rho^* = A^* C^* \frac{p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}} \quad (11)$$

5.4.3 Theoretical mass flow rate of real gas

The theoretical mass flow rate of real gas is defined by the product of flowing area, local acoustic velocity, and density at the critical point assuming one-dimensional isentropic flow of real gas, which is given by Formula (12);

$$q_{th,R} \equiv A^* c^* \rho^* = A^* C^* \frac{p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}} \quad (12)$$

5.5 Mass flow rate

The mass flow rate of CFN is given by Formulae (13) or (14);

$$q_m = C_d q_{th,R} \quad (13)$$

or

$$q_m = C_d (A^* C^* \sqrt{p_0 \rho_0}) \quad (14)$$

6 General requirements

- a) The flow shall be steady-state and single-phase with no condensation to the critical point (throat).
- b) A sufficiently low back-pressure ratio shall be applied on the CFN to maintain the critical flow.

NOTE The typical pressure ratio required to operate the CFN with a sufficiently long diffuser can be about 0,8 at high Reynolds numbers, e.g., greater than 2×10^5 (corresponding to ca. 50 m³/h CFN at the atmospheric pressure); however, it is often necessary to keep the ratio lower than 0,5 at low Reynolds numbers or sometimes 0,25 at very low Reynolds numbers (see Clause 11 and Annex H).

- c) The thermodynamic properties of the gas, C^* and M (or c^*_D and ρ when a densitometer is used), are required at low uncertainties (see 10.4).

NOTE For a gas mixture, accurate gas composition is required to calculate C^* at sufficiently low uncertainty.

If the following requirements cannot be achieved, the CFN will have to be flow calibrated at the same condition as in its application.

- d) The gas should have no significant relaxation effect (see B.5).
- e) The temperatures of the gas and CFN should be stable (see Annex J).
- f) The form and surface in the contraction and throat should be accurately machined as specified in Clause 8 (see Annex G).
- g) The form of the CFN will be verified periodically, especially in the contraction and throat (see Annex G).

NOTE The contraction and throat can be deformed over time by the impact of any solids contained in the gas.

The contraction and throat shall retain their cleanliness and hence surface finish. If this cannot be guaranteed, the measurement shall not be claimed to conform to this document, and flow calibration is recommended.

7 Applications for which the method is suitable

Each application should be evaluated to determine whether a CFN or some other device is the most suitable.

The most common applications for CFNs are to act as working or reference standards to calibrate other flowmeters, as check or transfer standards to verify or compare calibration facilities, as controllers of flow rates, and so on.

Important considerations are:

- a) The mass and volume flow rates through the CFN are independent of the downstream condition.
- b) The volume flow rate through the conduit where the CFN is installed is almost constant at any upstream pressure if the temperature is stable.

NOTE Multiple CFNs installed in parallel (e.g. the chamber configuration) are required to vary the volume flow rate through the CFN system for a fixed upstream pressure (see 9.3 and Annex J).

Some other considerations are:

- c) Accurate measurements of the pressure and temperature (or density when using a densitometer) are required only at the upstream location of the CFN.
- d) The downstream pressure should be monitored or estimated to confirm that the CFN is choked.
- e) The mass flow rate measured by the CFN is proportional to the inlet stagnation pressure; accordingly, the maximum mass flow rate that can be achieved by the CFN is practically limited by the maximum inlet pressures. (see Annex J)

8 CFN

8.1 General requirements for both the standard CFN types

8.1.1 General

This section specifies the common requirements to the toroidal- and cylindrical-throat CFNs.

To perform the measurement of flow rate at the uncertainty specified in 10.3.2 by using the discharge coefficient specified in 10.3.1, the CFN shall comply with the specifications in 8.1.2 to 8.1.4 and 8.2.

Verification of the form and dimensions by CMM are mandatory, and if the manufacturing tolerances specified in this section including the roughness cannot be achieved or verified by inspections, flow calibration is recommended.

8.1.2 Materials

The CFN shall be made of material suitable for the intended application. Some considerations are that:

- a) it should be possible to finish or machine the surface to the conditions required in 8.1.3 and 8.2,

NOTE Some materials are unsuitable due to pits, voids and lack of homogeneity.

- b) the material, together with any surface treatment used, shall not be subject to corrosion in the intended service, and
- c) the material should be dimensionally stable and should have known and repeatable thermal expansion characteristics, so that the throat diameter correction in Formula (16) can be made.

8.1.3 Contraction and throat

The contraction and throat of the CFN shall be

- a) axisymmetric around the centreline (axis of symmetry, AOS) of the CFN,
- b) smoothly finished so that the surface roughness should be

for $d_{nt} > 13$ mm: $R_a = 15 \times 10^{-6} d_{nt}$ as a maximum requirement, and

for $d_{nt} \leq 13$ mm: $R_a = 200$ nm as a maximum requirement

- c) free from dirt or any other contaminants.

It is difficult to machine the contraction and throat as specified, on which the discharge coefficient directly depends, and also to measure the throat diameter accurately, particularly in small nozzles, thus great care should be taken.

Great care is also necessary when polishing the contraction and throat because it may result in significant deformation of the surface.

8.1.4 Diffuser

The only requirement on the diffuser is that it shall not disturb the flow at the throat; therefore, the form of diffuser is not specified.

Besides the traditional diffuser, the requirement allows no diffuser, detachable diffusers^[2], and steps exactly at the throat and/or in the diffuser^[12] (see Annex J).

The traditional diffuser should be integrated in the nozzle by being machined as one piece. It should be controlled such that any steps, discontinuities, irregularities, and lack of concentricity do not exceed 1% of the local diameter. The length should be not less than d_{nt} . If there is a diameter discontinuity in the diffuser, then the diameter should increase (not decrease) toward the downstream. The arithmetic average roughness of the conical divergent section should not exceed $10^{-4}d_{nt}$. In the specified Reynolds number range, the critical back-pressure ratio of a traditional diffuser may be estimated in accordance with Clause 11.

Some phenomenon (premature unchoking phenomenon, PUP, see Annex H) impacts diffuser performance in an unpredictable manner at low Reynolds numbers^{[4][12]}. If the critical back-pressure ratio is essential for the system operation at low Reynolds numbers, e.g., lower than 2×10^5 , the actual critical back-pressure ratio should be measured experimentally using the very CFN with its own conduit for the application because the phenomenon may depend significantly on a slight difference of the CFN form and/or quality as well as its installing condition^{[9][11]}.

It is recommended to make the diffuser as long as possible^[10], at least $4d_{nt}$, to reduce the risk of the occurrence of PUP. If the diffuser is detachable, it can be exchanged by a longer one if the need arises. Additional detachable diffusers may be attached behind the integrated diffuser without affecting the discharge coefficient (see Figure J.1).

The inlet of the diffuser, regardless of whether it is integrated or detachable, shall be machined very carefully not to damage or block the throat, so as when attaching the detachable diffuser.

8.2 Requirements for each standard type of CFN

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8.2.1 Toroidal-throat CFN

There are two forms of the standard CFNs:

- a) toroidal-throat CFN;
- b) cylindrical-throat CFN.

Besides the requirements in 8.1, the toroidal- and cylindrical-throat CFNs shall comply with 8.2.2 and 8.2.3, respectively.

8.2.2 Toroidal-throat CFN

8.2.2.1 Besides the requirements in 8.1, the toroidal-throat CFN shall comply with the specifications in 8.2.2.2 to 8.2.2.7. The requirements are summarized in Figure 1.

8.2.2.2 The inlet plane (IP) is defined as the physical or virtual plane perpendicular to the nozzle AOS intersecting the contraction at a diameter equal to $(2,5 \pm 0,1)d_{nt}$, regardless of the form upstream of the IP.

8.2.2.3 The contraction downstream of the IP (to the right of IP on Figure 1) shall be a portion of a torus. At the throat, the tangential line of surface (TLS) shall be parallel to the nozzle AOS. A short torus, in which the throat TLS is not parallel to the nozzle AOS, shall be avoided because it may result serious error even if the deficit is very small. To reduce the risk of throat being damaged in the application, the torus preferably extends over the throat into the diffuser portion for some extent, e.g., to ca. $0,1d_{nt}$ downstream of the throat, in which the TLS of the torus end is an angle of approximately 3° to the nozzle AOS.

8.2.2.4 If the diffuser is integrated in the nozzle as one piece, great care shall be taken when machining the diffuser beyond throat because even a slight backlash of the lathe may produce unexpected forms exactly at the throat that may effect on the discharge coefficient significantly. Careful inspection of the throat form should be performed after machining, and then if any irregularity is found at the throat, the CFN should be flow calibrated.

8.2.2.5 The form upstream of the IP is not specified provided it does not disturb the flow in contraction; however, it should be axisymmetric and its surface at each axial location should have a diameter greater than or equal to the extension of torus behind the IP.

8.2.2.6 The radius of the torus between the IP and throat may be constant or vary smoothly between $1,8d_{nt}$ and $2,2d_{nt}$ provided the varying radius does not disturb the flow at the throat. Examples of the torus with constant and variable radii are shown in Figure 1.

8.2.2.7 The half-angle of traditional diffuser should be between $3,0^\circ$ and $6,0^\circ$, which contacts with the torus end smoothly at the same TLS as in Figure 1.

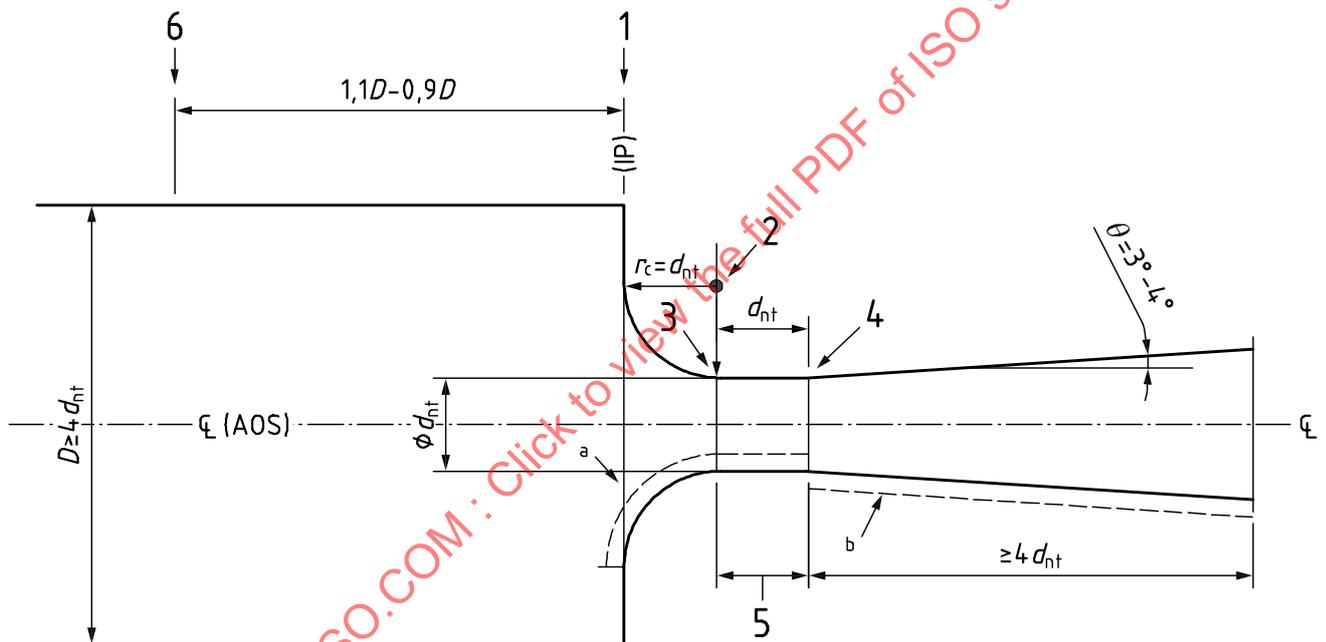
diameters on the cylindrical throat outlet. No diameter along the throat length shall deviate by more than $\pm 0,001 d_{nt}$ from the mean diameter.

8.2.3.7 The transition between contraction and throat should be inspected to verify that the local radius of surface r_c in the plane in which the nozzle AOS lies is never less than $0,5d_{nt}$ throughout the circumference formed by the contact plane of the contraction and throat. Figure 3 illustrates this requirement.

8.2.3.8 The length of the throat shall not deviate from d_{nt} by more than $0,05d_{nt}$. The connection between the throat and diffuser shall also be inspected to have no defect.

8.2.3.9 The surface of contraction and throat shall be properly polished so that the arithmetic average roughness height does not exceed $15 \times 10^{-6} d_{nt}$, where it can be measured.

8.2.3.10 The half-angle of traditional diffuser should be between 3° and 4° .

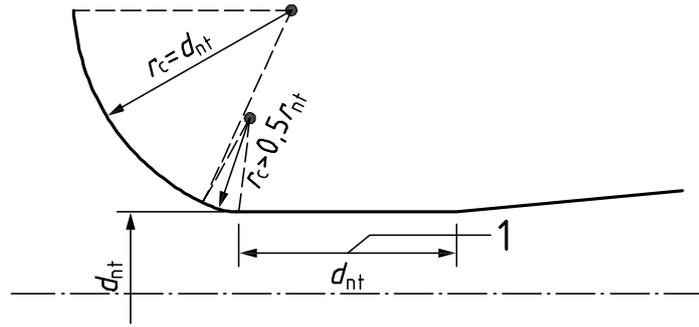


Key

- 1 inlet plane (physical plane)
- 2 centre of the inlet torus
- 3 throat inlet
- 4 throat exit
- 5 throat
- 6 location of pressure tapping

- a Cylindrical throat. In this portion, the arithmetic average roughness Ra shall not exceed $15 \times 10^{-6}d_{nt}$ and the contour shall not deviate from toroidal and cylindrical forms by more than $\pm 0,001d_{nt}$.
- b The length should be greater than d_{nt} but preferably than $4d_{nt}$.

Figure 2 — Cylindrical throat CFN



Key
1 throat

Figure 3 — Detail of connection between quarter of torus and cylindrical throat (transition region)

9 Installation requirements

9.1 General requirements for both the standard configurations

9.1.1 Standard configurations

The CFN shall be installed in either of

- a) the pipe configuration: a pipe of circular cross-section with $\beta \leq 0,25$, or
- b) the chamber configuration: a large volume (chamber or plenum) upstream the CFN such that β is effectively zero.

The pipe configuration shall contain only a single CFN and shall meet the requirements of 9.2 and 9.1.2 to 9.1.7.

The chamber configuration may contain multiple CFNs in a cluster and shall meet the requirements of 9.3 and 9.1.2 to 9.1.7.

9.1.2 Upstream pressure tapping

The upstream static pressure of CFN shall be measured through one or more wall pressure tapings drilled through the pipe or chamber wall upstream of the CFN.

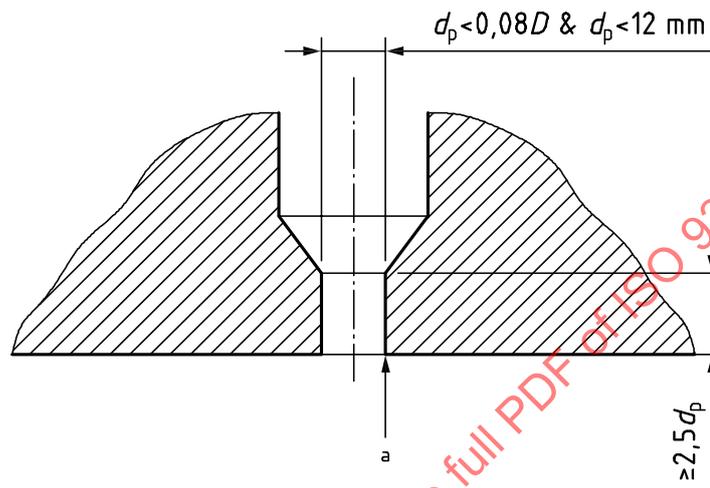
The wall pressure tapings may be located at upstream or downstream locations specified in 9.2.3 and 9.3.3 provided that they have been demonstrated that the measured pressure can be used reliably to give the upstream stagnation pressure (see Annex J).

If the flow over the pressure tapings cannot be approximated to be at rest, e.g., $\beta < 0,15$, the tapping hole shall meet the following requirements as summarized in Figure 4:

- a) the centreline shall be perpendicular to the nozzle AOS,
- b) the cross-section of breakthrough into the conduit shall be circular,

- c) the form in the wall shall be cylindrical with a minimum length of $2,5d_p$ from the breakthrough where d_p is the diameter of breakthrough,
- d) the edge of breakthrough shall be square or rounded to a radius not exceeding $0,1d_p$, and
- e) the edge of breakthrough shall be free from burrs.

Visual inspections shall confirm that these requirements are met.



Key

- ^a Edge of hole flush with internal surface of conduit, burr-free and square to a radius not exceeding $0,1d_p$.

Figure 4 — Detail of the wall pressure tapping

9.1.3 Downstream pressure tapping

The downstream pressure shall be measured through one or more wall pressure tapings, or estimated, in order to ensure that the nozzle is or all the nozzles are choked. The flow exhausted from the CFN exit should not directly impinge upon any of the pressure tapings.

In some applications, the outlet pressure can be determined without the use of a wall pressure tapping, for example, when the CFN discharges directly into a large space of known pressure, e.g. into atmosphere or large tank, the downstream pressure of the CFN may be represented by the pressure in the large space (see Annex J).

9.1.4 Temperature measurement

The upstream temperature shall be measured using one or more sensors located upstream of the CFN. There is no need to measure the downstream temperature.

The temperature sensor shall not disturb the upstream pressure measurement; to ensure this is the case, the sensor shall not be aligned with the upstream pressure tapping in the flow direction.

Particular care has to be exercised in the selection of the temperature sensor and the insulation of conduit if the stagnation temperature of the flowing gas differs significantly from that of the environment, e.g. by more than 5 K. In such cases, the sensor shall be insensitive to the effect of thermal radiation and the conduit shall be well lagged to minimize heat transfer between the flowing gas and environment (see Annex J). If the temperatures of the flowing gas and the conduit wall differ

significantly, it is extremely difficult to measure the gas temperature accurately. The heat conduction from the conduit to the sensor shield shall be minimized.

9.1.5 Density measurement

For some applications, it may be desirable to measure directly the gas density upstream of the nozzle; for example, when the molar mass of the gas is not known with sufficient accuracy. The densitometer shall be installed upstream of the inlet pressure and temperature tapings.

To achieve accurate measurement of the flow rate, particular attention shall be paid to:

- a) The densitometer shall not disturb the upstream static pressure and temperature measurements.
- b) If the densitometer is located in a bypass line from the upstream pipeline or chamber of CFNs, checks shall be carried out to ensure that the gas in the densitometer is the same as that flowing in the pipeline or chamber.
- c) The pressure and temperature at the densitometer should be as close as possible to those upstream of the CFN in order to minimize the corrections. The stagnation density of the CFN shall be calculated by Formula (15):

$$\rho_0 = \rho_{\text{den}} \frac{p_0}{p_{\text{den}}} \cdot \frac{T_{\text{den}}}{T_0} \cdot \frac{Z_{\text{den}}}{Z_0} \quad (15)$$

9.1.6 Drain hole

The pipe or chamber may be provided with drain holes to remove the condensate or other foreign substances that may collect in some applications. There shall be no flow through these drain holes while the measurement is in progress.

The drain holes shall be located upstream of the upstream wall pressure tapings in an axial plane different from that of the wall pressure tapping in order not to disturb the upstream static pressure measurement.

The drain holes should preferably follow the specifications of the pressure tapping shown in Figure 4. The axial distance from the drain hole to the plane of the inlet wall pressure tapping shall be greater than $1D$.

9.1.7 Downstream condition

There is no specification required on the downstream pipe and chamber provided it does not disturb the critical flow in the CFN or CFNs.

9.2 Pipe configuration

9.2.1 General

Besides 9.1, the pipe configuration shall conform to 9.2.2 to 9.2.4. The requirements are summarized in Figure 5.

9.2.2 Upstream pipe

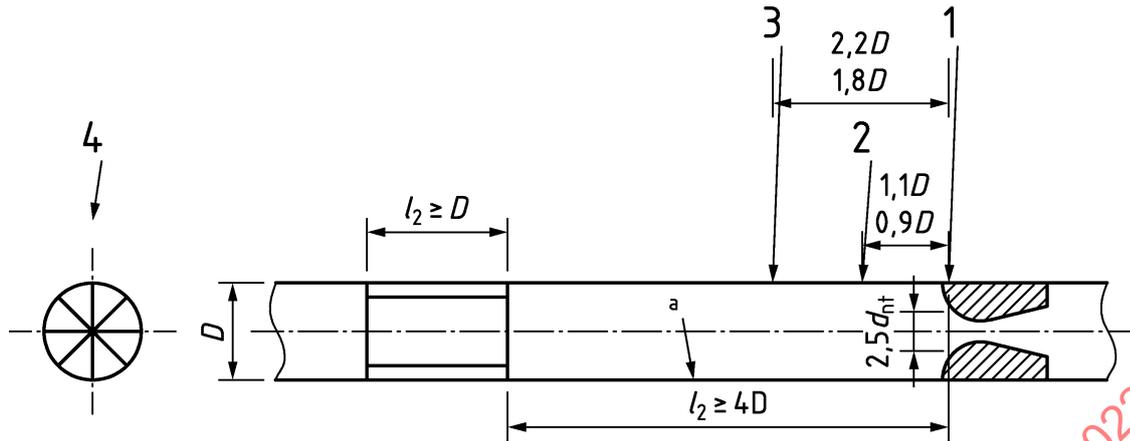
The upstream pipe shall:

- a) be straight,
- b) have a circular cross-section,
- c) be concentric around the nozzle AOS within $\pm 0,02D$,
- d) have a diameter of greater than $4d_{nt}$ ($\beta \leq 0,25$),
- e) not deviate from circularity by more than $0,01D$ for up to $3D$ upstream the IP, and
- f) have an arithmetic average roughness of smaller than $10^{-4}D$ for up to $3D$ upstream the IP.

If these requirements cannot be met, specific tests are recommended to investigate the influence of the installation conditions or to determine C_d by flow calibration using the same pipe.

In the case when $\beta > 0,25$, the mass flow rate calculated in accordance with Clause 10 may be corrected in accordance with Annex D; however, particular care shall be taken because the static pressure measurement of a high-speed flow may easily result a serious error depending on the location, form, and/or quality of the pressure tapping. Furthermore, the ambiguity of the recovery factor may affect significantly on the measurement and also the pressure drop between the upstream pressure tapping and IP may not be negligible (see Annex J).

Swirl shall not exist in the upstream pipe. If there is certain flow velocity existed in the upstream pipe, swirl-free conditions may be ensured by installing a flow straightener of the design shown in Figure 5 (Étoile straightener) at a distance $l_1 > 5D$ upstream of the IP. Other flow conditioners may be used according to ISO 5167-1 for the upstream installation^[1].



Key

- 1 IP (Inlet plane)
 - 2 location of pressure tapping
 - 3 location of temperature sensor
 - 4 Etoile straightener with vane thickness adequate to prevent buckling (if the flow velocity in conduit is not negligible)
- a In this portion, the surface roughness shall not exceed $10^{-4}D$.

Figure 5 — Installation requirements in a pipe

9.2.3 Pressure measurement

The location of the upstream pressure tapping should be at a distance between $0,9D$ and $1,1D$ upstream of the IP.

If there are multiple tapings, all of them shall be in a plane perpendicular to the nozzle AOS.

The downstream pressure may be measured through a pressure tapping located within $0,5D$ downstream of the diffuser exit. Locations further downstream can also be used provided there is no substantial pressure change. Other downstream tapping locations may be acceptable if an unchoking test (see H.4) is performed using that tapping location.

9.2.4 Temperature measurement

The upstream temperature may be measured at $1,8D$ to $2,2D$ upstream of the IP. The diameter of the sensor shall be not greater than $0,04D$.

If it is impracticable to use a sensor of diameter less than $0,04D$, the sensing element shall be so located that it can be demonstrated that it does not affect the upstream 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 nozzle inlet stagnation temperature. See Annex J.

9.3 Chamber configuration

9.3.1 General

Besides 9.1, the chamber configuration shall conform to 9.3.2 to 9.3.5.

9.3.2 Upstream chamber

The CFN can be assumed to be installed in a large volume (chamber) if its nozzle AOS is at least $5d_{nt}$ away from all the chamber walls.

If multiple CFNs are installed in a chamber in parallel, the minimum distance between the nozzle AOSs of any CFNs shall be greater than 6 times the largest throat diameter in order to avoid interference between CFNs^{[13] to [19]}. Testing is recommended to ensure that the performance is not degraded by the interferences between each CFNs and also between each CFNs and chamber walls.

9.3.3 Pressure measurement

The wall pressure tapping in the upstream chamber should preferably be located in a wall perpendicular to the IP and within a distance of $(10 \pm 1)d_{nt}$ from the IP.

9.3.4 Temperature measurement

The temperature sensor in the upstream chamber shall not be located where the flow is stagnated in order to ensure that the measured temperature represents the gas temperatures flowing into each CFN. Multiple sensors are recommended in a large chamber because of the high possibility of the stagnation of flow and/or temperature stratification.

9.3.5 Back-pressure ratio

If multiple CFNs are installed in a chamber, the back-pressure ratio across the chamber shall be smaller than the smallest value among the critical back-pressure ratios of all CFNs. See Annex H.

10 Calculations

10.1 General

If the CFN satisfies the requirements in Clauses 8 and 9, its mass flow rate should be calculated in accordance with 10.2 to 10.6.

It is noted again that the temperature of the CFN in operation is assumed to be in equilibrium with that of the gas because of the isentropic assumption (see Annex J); accordingly, the temperature of the CFN itself is represented by that of the gas in this document. If there is any significant temperature difference observed between the gas, CFN, conduit, and environment, the user should be consulted by an expert^[56] (see Annex J).

10.2 Calculation of mass flow rate, q_m

The mass flow rate through a CFN should be calculated by Formula (13) or (14) where A_{nt} should be the cross-section of throat when the CFN is measuring the flow rate, thus calculated by Formula (16);

$$A_{nt} = \frac{\pi d_{nt}^2}{4} = \frac{\pi d_{nt0}^2}{4} [1 + 2\alpha(T_1 - T_{nt,0})]^2 \tag{16}$$

It is noted that this equation is not for correcting the effect of non-isentropic flow caused by large temperature differences. See 10.1 and Annex J.

10.3 Calculation of discharge coefficient, C_d

10.3.1 The discharge coefficient of the CFN should be calculated by Formula (17);

$$C_d = (a - bRe^{-n}) - \frac{(c - dRe^{-n})}{1 + \exp\left(e - \frac{Re}{f}\right)} \tag{17}$$

The coefficients $a, b, c, d, e, f,$ and n are given in Table 1 for each type of CFN (see Annexes F and G). They are valid in each specified Reynolds number range.

Table 1 — Coefficients a, b, c, d, e, f and n

Toroidal-throat CFN	
$2,1 \times 10^4 < Re < 3,2 \times 10^7$	$a = 0,9990$ $b = 3,415$ $c = 0,0031$ $d = 0,690$ $e = 10$ $f = 120\,000$ $n = +0,5$
Cylindrical-throat CFN	
$1,5 \times 10^5 < Re < 1,2 \times 10^7$	$a = 1,0000$ $b = 6,341$ $c = 0,009$ for air $c = 0,008$ for natural gas $d = 3,000$ $e = 6$ $f = 170\,000$ $n = +0,5$

If the gas has the significant vibrational relaxation effect, e.g. CO₂ and SF₆, the discharge coefficient may cause more than 1 % if the steady state critical flow function (see 10.4) is used in small CFNs. See B.5.

For the purpose of calculation verification, the values of discharge coefficient are given in Annex A.

10.3.2 The relative uncertainty of the discharge coefficients calculated by using Formula (17) and Table 1 is 0,3 % at the 95 % confidence level.

10.4 Calculation of critical flow function, C^* or C^*_D

The value of critical flow function may be computed by any method of demonstrable accuracy. It is noted that most of the methods normally suppose that the state change of gas along the flow is in equilibrium, thus they cause serious errors if the gas cannot reach an equilibrium state owing to the rapid change in the fluid properties. See B.5.

Some examples of the applicable method to calculate C^* and C^*_D for natural gases are AGA Report No. 8^{[20][21]}, ISO 12213^{[22] to [24][31] to [35]}, and ISO 20765^{[25][26]} as the state equation. This approach ensures a relative uncertainty on C^* of 0,1 % at 95 % confidence level. Alternatively, any other state equation with comparable uncertainty can be used.

The REFPROP, thermodynamic database^[40], may be one of the most convenient and accurate ways to calculate C^* . It realizes the calculations based on all the state equations in the standards mentioned above. See B.3 and Annex J.

For some gases, the values of C^* shall be calculated in accordance with Annex C without using any specific software. The equations were obtained by curve fittings on the calculation results produced by REFPROP 10.0.

10.5 Conversion of measured pressure into stagnation pressure

The inlet stagnation pressure, p_0 , should be calculated by Formula (18):

$$p_0 = \left(1 + \frac{\kappa - 1}{2} M_a^2\right)^{\frac{\kappa}{\kappa - 1}} p_1 \quad (18)$$

If $\beta \leq 0,15$, the conversion is ignorable, thus p_0 is given by Formula (19):

$$p_0 = p_1 \quad (19)$$

10.6 Conversion of measured temperature into stagnation temperature

The inlet stagnation temperature, T_0 , should be calculated by Formula (20):

$$T_0 = \frac{2 + (\kappa - 1) M_a^2}{2 + R_f (\kappa - 1) M_a^2} T_1 \quad (20)$$

If $\beta \leq 0,25$, the effect is negligible, thus T_0 is given by Formula (21):

$$T_0 = T_1 \quad (21)$$

The recovery factor R_f may be calculated by any reliable method. If $\beta \leq 0,25$, it may be approximated by Formula (22):

$$R_f = \sqrt{P_r} \quad (22)$$

where P_r is the Prandtl number of the gas. See Annex J.

10.7 Calculation of viscosity

The value of viscosity may be computed by any method of demonstrable accuracy. The REFPROP may be one of the most convenient and accurate ways to calculate the viscosity.

For some gases, the value of viscosity may be calculated in accordance with Annex I without using any specific software. The equations were obtained by curve fits to the calculation results produced by REFPROP 10.0

11 Estimation of critical back-pressure ratio

11.1 For a traditional diffuser at Reynolds numbers higher than 2×10^5

The critical back-pressure ratio r_{CBP} for the traditional diffuser at Reynolds numbers higher than 2×10^5 may be estimated by Formula (23)^[3];

$$r_{CBP} = 0,8 \frac{p_{2i}}{p_0} + 0,2 \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa}{\kappa - 1}} \quad (23)$$

where p_{2i} is the theoretical static pressure at the diffuser exit when the nozzle attains the critical flow velocity but the flow in the diffuser is fully subsonic and fully attached, assuming one-dimensional isentropic flow. Formula (23) is graphed in Figure 6, by which the values of r_{CBP} may be estimated using A_2/A_{nt} or length of the frustum diffuser l at each wall half-angle θ . As seen in the figure, the pressure ratio r_{CBP} will not significantly become higher by lengthening the diffuser such that $A_2/A_{nt} > 4$, e.g., $l/d_{nt} > 7$ at $\theta = 4^\circ$.

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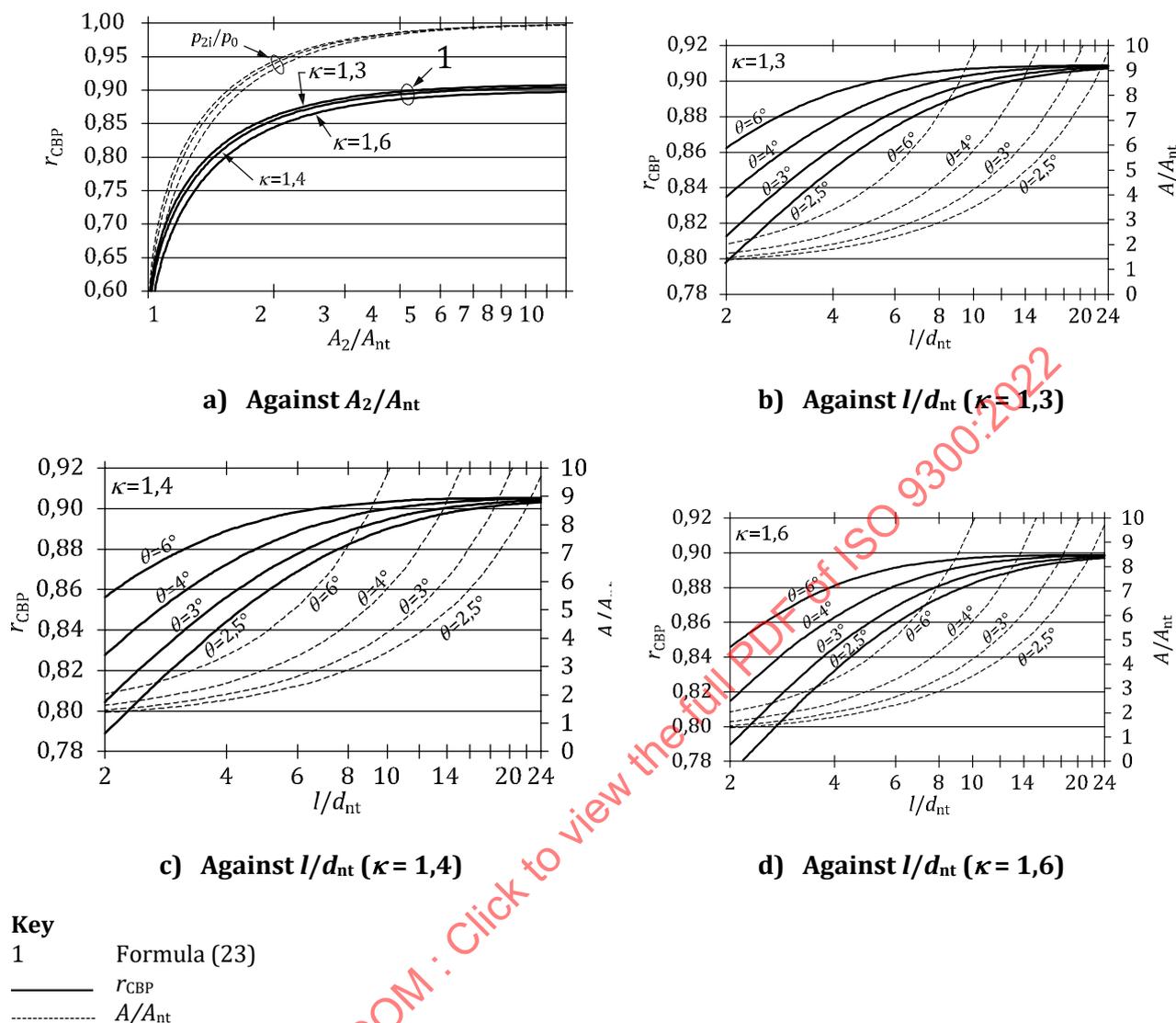


Figure 6 — Maximum permissible back-pressure ratio r_{CBP} calculated by Formula (23)

κ is not necessary to be accurate because the sensitivity on κ is not so high as seen in Figure 6 as well as Formula (23) gives only an estimation.

Higher back-pressure ratios may be used provided that it can be verified that the CFN chokes at those ratios. Pressure ratios of 0,9 may be achieved at high Reynolds numbers if the diffuser is sufficiently long and has an adequate form and quality.

11.2 For any diffuser at low Reynolds numbers

For any CFN with a diffuser, it is practically impossible to predict r_{CBP} at low Reynolds number, e.g. lower than 2×10^5 , because premature unchoking phenomenon (PUP) may occur that results in serious decrease in the discharge coefficient by an amount that is difficult to quantify. See 8.1.4 and Annex H. When the Reynolds number is lowered, the decrease of discharge coefficient caused by the PUP starts from an ignorable amount at a Reynolds number specific to each CFN and installing condition, and then, depending on the Reynolds number, it can reach several 10 % at the back-pressure ratios where the CFN should choke by the diffuser effect in theory (where the back-pressure ratio is greater than the critical pressure ratio). The amount of decrease at a specific back-pressure ratio at a specific Reynolds number is practically unpredictable.

If the Reynolds number is in the range where PUP is suspected, but is not sufficiently low to be of concern, most CFNs should choke at a back-pressure ratio slightly smaller than the critical pressure ratio (e.g. 0,5, see Figure H.1); however, if the Reynolds number approaches the lowest extreme of this document, it is recommended to keep the back-pressure ratio less than 0,25^[7] to ^[12].

If the exact critical back-pressure ratio is essential for the system operation, it is recommended to measure r_{CBP} using the given CFN with its own upstream and downstream conduits (see Annex J). The PUP may be very sensitive to the CFN form and also to its installing condition.

11.3 For CFNs without diffuser or with very short diffuser

For CFNs without a diffuser or with a very short diffuser such as $l = 0,1d_{nt}$, it is recommended to keep the back-pressure ratio always smaller than 0,35 regardless of the Reynolds number. If the difference of flow rate by 0,1 % is ignorable for the application, the critical back-pressure ratio of 0,5 (or slightly smaller ratio than the critical pressure ratio, see Figure H.5) may be applicable.

12 Uncertainties in the measurement of flow rate

12.1 General

The uncertainty associated with each measurement of mass flow rate is an essential consideration^{[41][44][46][48]} and shall be calculated and reported whenever a measurement is claimed to conform to this document. The uncertainty for a mass flow rate 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 rate. 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 rate as determined using Formula (13) 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 be performed in accordance with ISO/IEC Guide 98-1^{[42][43]}.

In general, the expanded uncertainty for a measurand can be calculated from the combined standard uncertainty, comprising the relative Type A uncertainty, which is obtained using statistics, and the relative Type B uncertainty, which is obtain using methods other than statistics. These are combined by root-sum-of-squares (RSS) as given by Formula (24);

$$U(y) = ku_c(y) = k \sqrt{u_A^2(y) + u_B^2(y)} \quad (24)$$

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 is the standard deviation, at 68 % confidence level, of the replicated measurements of mass flow rate from the repeatability and reproducibility test results. The relative Type B uncertainty is obtained from evaluations of the uncertainty of the components in the equation used to calculate the mass flow rate. 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 uncertainty is appropriate when the system has a large number of 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 formula^{[47][49]} 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. In most applications, $k = 2$ is an acceptable value to obtain 95 % confidence level uncertainties.

12.2 Practical computation of uncertainty

Substituting Formula (12) into Formula (13), the governing equation for mass flow rate, q_m , through a CFN is as given by Formula (25);

$$q_m = A * C_d C^* \frac{p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}} \quad (25)$$

The uncertainty of a flow rate 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 12.3).

Because Formula (24) 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 Formula (24) 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 given by Formula (26);

$$u_c(q_m) = \sqrt{u_A^2(q_m) + u_B^2(C_d) + u_B^2(A^*) + u_B^2(C^*) + u_B^2(p_0) + \frac{1}{4} [u_B^2(M) + u_B^2(T_0)]} \quad (26)$$

where the squares are variances.

The Type A relative uncertainty term, $u_A(q_m)$, can be calculated from the standard deviation of the available replicated measurement data. The Type B relative uncertainty terms in Formula (20) can be calculated from the uncertainty of each of the factors 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 of the Type B uncertainty components has its own subset of uncertainty sources. Uncertainty components that should be considered are

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

- g) interference effects between CFNs in a chamber,
- h) species effects (calibration in one gas, usage in another),
- i) leaks,
- j) contamination of CFN surfaces with dirt, and
- k) pressure effects e.g. errors in C^* because real gas effects are not perfectly captured (see Annex B).

An example of a sub-component study is presented in Figure 7, which shows the relationship between diameter uncertainties (of various magnitudes) and area uncertainties.

12.3 Correlated uncertainty components

In some measurement situations the components are not fully or predominately independent. If a component varies depending on the value of another component, they are not independent, and the correlation of variables shall 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^* and M depend on the gas composition. When these terms are included, the combined relative uncertainty equation becomes Formula (27);

$$u_c(q_m) = \sqrt{u_A^2(q_m) + u_B^2(C_d) + u_B^2(A^*) + u_B^2(C^*) + u_B^2(p_0) + \frac{1}{4}u_B^2(M) + \frac{1}{4}u_B^2(T_0) + \frac{1}{2}c_v(M, x_i)} \quad (27)$$

where $c_v(M, x_i)$ is the covariance of the molecular weight and gas composition, as evaluated using data and where other correlated uncertainty terms have been left out because they are either zero or negligible. For example, the deviation of the value used for the universal gas constant, R is so low, or if the same value of R is used during calibration and usage, that its uncertainty can be neglected.

For some gases at high pressure, the normalized sensitivity coefficients for the stagnation pressure and temperature can deviate from unity due to contributions from the critical flow function. For example, for natural gas at room temperature and 9 MPa the sensitivity coefficient for pressure increases from 1 to 1,03^[51]. In such cases, the upper value should be used to bound the effect.

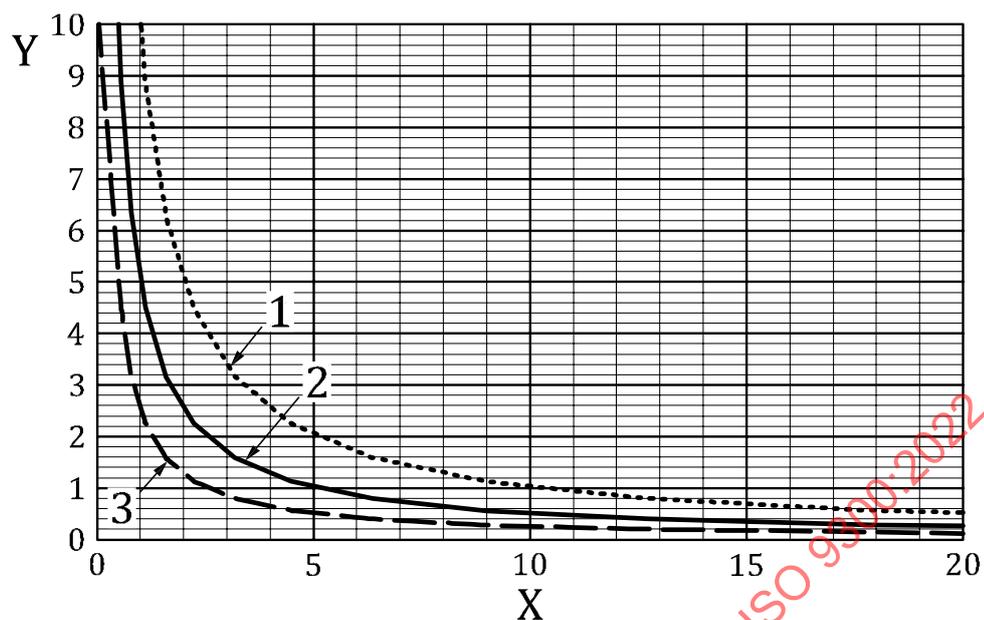
**Key**X d_{nt} (mm)Y uncertainty in A_{nt} (%)1 0,050 mm uncertainty in d_{nt} 2 0,025 mm uncertainty in d_{nt} 3 0,013 mm uncertainty in d_{nt}

Figure 7 — Percent uncertainty in CFN throat area due to uncertainty in throat diameter measurement

CFNs used in a plenum also have significant correlated uncertainty in pressure, temperature and C_d calibration.

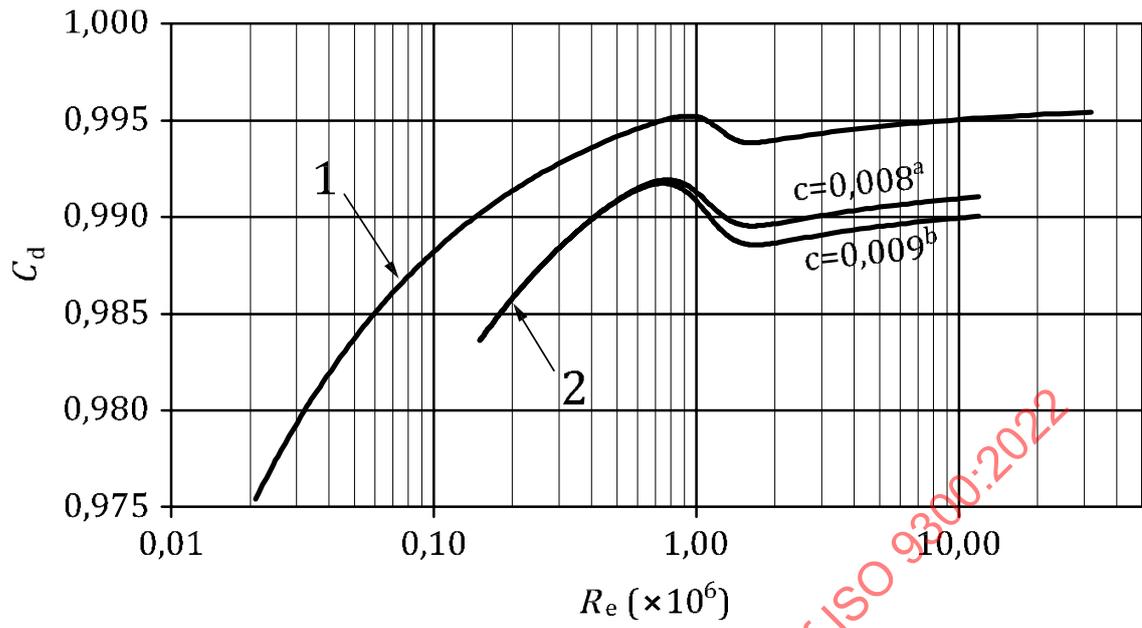
Annex A (informative)

Discharge coefficient values

For the purpose of calculation verification, Table A.1 gives the discharge coefficient values for a given set of Reynolds numbers calculated by Formula (17) with the coefficient in Table 1. The curves are graphed in Figure A.1.

Table A.1 — Discharge coefficients of CFNs

Toroidal throat		Cylindrical throat		
Reynolds number R_e	Discharge coefficient C_d	Reynolds number R_e	Discharge coefficient (air) C_d	Discharge coefficient (natural gas) C_d
$2,1 \times 10^4$	0,975 4	$1,5 \times 10^5$	0,983 6	0,983 6
3×10^4	0,979 3	2×10^5	0,985 8	0,985 8
5×10^4	0,983 7	3×10^5	0,988 4	0,988 4
1×10^5	0,988 2	5×10^5	0,990 9	0,990 8
3×10^5	0,992 8	7×10^5	0,991 8	0,991 7
5×10^5	0,994 2	1×10^6	0,991 3	0,990 8
1×10^6	0,995 2	$1,3 \times 10^6$	0,989 9	0,989 1
$1,5 \times 10^6$	0,993 9	2×10^6	0,989 7	0,998 7
3×10^6	0,994 3	3×10^6	0,990 1	0,989 1
5×10^6	0,994 7	5×10^6	0,990 5	0,989 5
1×10^7	0,995 0	$1,2 \times 10^7$	0,991 0	0,990 0
$3,2 \times 10^7$	0,995 4			

**Key**

- 1 toroidal-throat CFN
- 2 cylindrical-throat CFN
- ^a Natural gas.
- ^b Air.

Figure A.1 — Discharge coefficient curves

Annex B (informative)

Critical flow function

B.1 General

The mass flow rate of a CFN is at first approximated by the theoretical mass flow rate and then its deviation from the true value is corrected by the discharge coefficient. Since the theoretical mass flow rate is defined by the product of area, local acoustic velocity, and density at the critical point, the pressure and temperature that directly affect on the mass flow rate are those at the critical point.

However, when measuring the flow rate by using a CFN, the pressure and temperature are measured in the upstream conduit where the flow velocity is very low, and they are converted into those at the stagnation condition. This means that the equation of the theoretical flow rate contains a factor that converts the pressure and temperature at the stagnation condition into those at the critical point, which is the critical flow function.

The critical flow function is computed assuming one-dimensional isentropic flow from the stagnation to the critical points, and is a function of the stagnation condition and gas properties, i.e., compressibility factor and isentropic exponent^{[27] to [35]}.

B.2 Critical flow function of perfect gas

The compressibility factor of perfect gas is always unity regardless of the gas condition. Its isentropic exponent is also constant at any gas conditions and equals to the specific heat ratio. Under these conditions, the flow equations can be solved analytically and the basic equations listed in 5.2 are derived.

The theoretical flow rate is defined using the values at the critical point, but by using the basic equations in 5.2, it can be expressed by the temperature and pressure at the stagnation as Formula (B.1);

$$q_{th,l} \equiv A^* \rho^* c^* = A^* \left[\frac{\sqrt{\gamma}}{\sqrt{R}} \right] \left[\frac{p^*}{\sqrt{T^*}} \right] = A^* \left[\frac{\sqrt{\gamma}}{\sqrt{R}} \right] \left[\sqrt{\left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \frac{p_0}{\sqrt{T_0}}} \right] = A^* C^* \frac{p_0}{\sqrt{\frac{R}{M} T_0}} \quad (B.1)$$

The factor $\sqrt{\left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}$ converts $\frac{p_0}{\sqrt{T_0}}$ into $\frac{p^*}{\sqrt{T^*}}$. Including the remaining factor relating to the gas properties, $\sqrt{\gamma}$, the critical flow function is given by as Formula (B.2);

$$C^* = \sqrt{\gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (B.2)$$

If the upstream pressure is not high, e.g. lower than 1 MPa, Formula (B.2) may approximate C^* at low uncertainty. In this case, it is recommended to use the value of γ at the stagnation condition by referring a database.

B.3 Critical flow function of real gas

According to Formulas (7) and (8), the pressure and temperature at the critical point for $\gamma=1.4$ should be about 50 % and 80 % of the stagnation conditions, respectively. Under such large variations, the isentropic exponent and compressibility factor may vary significantly especially if the real gas effect is significant. The real gas critical flow function accounts for the variations of compressibility factor and isentropic factor that should occur during flowing from the stagnation to the critical point. In this case, it is not able to solve the flow equations analytically thus numerical calculations are required.

For specified stagnation conditions of p_0 and T_0 , the density and local acoustic velocity at the critical point, ρ^* and v^* , are calculated using a database of thermodynamic properties that accounts for real gas effects. Since the flow is isentropic and adiabatic, the values of entropy and enthalpy at the critical point are equal to those at the stagnation condition. The throat entropy and total enthalpy are independent thermodynamic variables, and therefore they determine the thermodynamic state at the critical point. The real gas critical flow function C^* is determined by finding the unique critical density and critical velocity corresponding to the thermodynamic state at the critical point. An iterative procedure is generally required to determine ρ^* and v^* from the known entropy and total enthalpy. The critical flow function is calculated by Formula (B.3);

$$C^* = \frac{\rho^* v^*}{p_0} \sqrt{\frac{R}{M} T_0} \quad (\text{B.3})$$

These computations can be easily performed by using the REFPROP, thermodynamic database^[42], which is maintained and kept up to date by the National Institute of Standards and Technology (NIST). It internally solves the one-dimensional isentropic flow model for C^* at the specified conditions of gas composition, the stagnation pressure, and stagnation temperature. It also provides subroutines that can be incorporated in EXCEL, Fortran, C++, VBI, LabVIEW, and so on, and it documents the uncertainty of experimentally measured properties, includes numerous gases (e.g. O₂, CO₂, N₂, H₂, Ar, C₂H₄, He), and provides flexibility to create user-defined gas mixtures (e.g. natural gas, dry air, and humid air).

B.4 Critical flow function to be used when CFN is flow calibrated

B.4.1 General

It is always recommended to use the exact value for C^* by referring an adequate database; however, if the CFN is to be flow calibrated against a reference standard, a simplified way may be acceptable to set the value of C^* as in B.4.2 and B.4.3.

B.4.2 Using in the same gas at the same stagnation condition

If the CFN is used in the same gas at the same stagnation pressure and temperature as per the calibration, then the critical flow function is not necessary to be accurate, e.g. a constant may be acceptable, and the same value shall be used both in calibration and application. In this case, the error of C^* included in the measured discharge coefficient is cancelled out when calculating the mass flow rate in the application, like the error in throat diameter.

B.4.3 Using in the same gas at the same range of stagnation condition

If the CFN is used in the same gas and in the same range of the stagnation conditions during calibration by matching the Reynolds number, then the equation for C^* is not necessary to be accurate at the required uncertainty but should reflect the tendency of true C^* at a reasonable accuracy, and the same equation shall be used both in the calibration and application.

If the combinations of the pressure and temperature in the application are almost the same as those in the calibration, a constant critical flow function for the whole range may be acceptable by the same reasoning as discussed in B.4.2, and the same constant shall be used in the application.

B.4.4 When accurate values are necessary

If the CFN is used in a different gas than that of the calibration, by matching the Reynolds numbers, then each c^* should be accurate in both cases. For example, if the nozzle is calibrated using air and used in oxygen, then c^* for air should be used in the calibration and that for oxygen in the application. The same may be required even if using the same gas if the Reynolds number range in the application is extrapolated beyond that of the calibration under the assumption that there is no boundary layer transition in the application.

B.5 Gases with significant vibrational relaxation effect

Some gases, such as SF₆ and CO₂, have significant energy in their vibrational modes. They may not keep the thermal equilibrium when passing through the contraction because of the rapid variations of temperature and pressure at this section; the internal energy stored in the vibrational modes of the gas molecules does not have sufficient time to reappportion to the molecules' translational and rotational modes and thus the critical flow function does not reach the steady state values, which the thermodynamic property database gives. The actual values for the critical flow function are partially "frozen" at the upstream value leading to a larger value than that of the steady state.

Consequently, the effect is more significant in smaller CFNs because of the shorter flowing time from the IP to throat. If the CFN is sufficiently large, the critical flow function given by the REFPROP thus Annex B may not cause significant error; however, for example, if a toroidal-throat CFN of a few mm throat diameter (typically at the Reynolds numbers below 10⁵) is used in CO₂, the mass flow rate using the steady state critical flow function may have an error larger than 1 %^{[5][6]}.

C.2 Nitrogen

The critical flow function values produced by the REFPROP are given in Table C.1. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Table C.2.

Table C.1 — C* values (nitrogen)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
200	0,685 61	0,703 67	0,724 97	0,748 45	0,773 43	0,798 56	0,822 04	0,842 30	0,858 42	0,870 23	0,878 09
220	0,685 38	0,698 67	0,713 60	0,729 28	0,745 30	0,761 09	0,775 99	0,789 38	0,800 81	0,810 06	0,817 10
240	0,685 22	0,695 21	0,706 08	0,717 14	0,728 16	0,738 84	0,748 89	0,758 03	0,766 04	0,772 80	0,778 25
260	0,685 10	0,692 72	0,700 83	0,708 90	0,716 79	0,724 34	0,731 40	0,737 82	0,743 52	0,748 40	0,752 44
280	0,685 00	0,690 88	0,697 02	0,703 03	0,708 82	0,714 30	0,719 38	0,723 99	0,728 08	0,731 60	0,734 55
300	0,684 92	0,689 48	0,694 17	0,698 70	0,703 00	0,707 03	0,710 74	0,714 08	0,717 03	0,719 56	0,721 68
320	0,684 85	0,688 39	0,691 98	0,695 40	0,698 62	0,701 60	0,704 31	0,706 73	0,708 85	0,710 65	0,712 13
340	0,684 78	0,687 52	0,690 26	0,692 85	0,695 24	0,697 44	0,699 41	0,701 14	0,702 63	0,703 87	0,704 86
360	0,684 70	0,686 81	0,688 89	0,690 82	0,692 58	0,694 17	0,695 58	0,696 79	0,697 80	0,698 61	0,699 22
380	0,684 62	0,686 21	0,687 76	0,689 18	0,690 45	0,691 57	0,692 53	0,693 33	0,693 97	0,694 44	0,694 75
400	0,684 52	0,685 70	0,686 82	0,687 83	0,688 71	0,689 45	0,690 07	0,690 54	0,690 88	0,691 09	0,691 16
420	0,684 41	0,685 25	0,686 03	0,686 70	0,687 26	0,687 71	0,688 04	0,688 26	0,688 36	0,688 35	0,688 24
440	0,684 28	0,684 84	0,685 33	0,685 73	0,686 04	0,686 24	0,686 35	0,686 36	0,686 27	0,686 09	0,685 82
460	0,684 13	0,684 45	0,684 71	0,684 89	0,684 98	0,684 99	0,684 91	0,684 75	0,684 51	0,684 19	0,683 79
480	0,683 95	0,684 09	0,684 15	0,684 15	0,684 07	0,683 91	0,683 68	0,683 38	0,683 01	0,682 58	0,682 07
500	0,683 76	0,683 73	0,683 64	0,683 48	0,683 25	0,682 96	0,682 61	0,682 20	0,681 72	0,681 19	0,680 60
520	0,683 55	0,683 38	0,683 15	0,682 86	0,682 52	0,682 12	0,681 66	0,681 15	0,680 59	0,679 98	0,679 32
540	0,683 31	0,683 03	0,682 69	0,682 29	0,681 85	0,681 35	0,680 81	0,680 22	0,679 59	0,678 92	0,678 20
560	0,683 05	0,682 68	0,682 24	0,681 75	0,681 22	0,680 65	0,680 04	0,679 39	0,678 70	0,677 97	0,677 21
580	0,682 78	0,682 32	0,681 80	0,681 24	0,680 64	0,680 01	0,679 34	0,678 63	0,677 89	0,677 12	0,676 32
600	0,682 49	0,681 96	0,681 38	0,680 75	0,680 10	0,679 41	0,678 68	0,677 93	0,677 15	0,676 35	0,675 51

Table C.2 — Coefficients $C_{i,j}$, range, and deviation (nitrogen)

j	i							
	0	1	2	3	4	5	6	7
0	6,433695661 1E-01	4,729607541 7E-04	3,125517934 2E-04	1,339652030 9E-04	3,794790755 1E-05	3,945716805 3E-06	1,681556058 0E-07	2,553129502 1E-09
1	5,572279564 3E+01	1,642512880 9E+00	5,749430594 7E-01	2,472244987 8E-01	7,105105406 6E-02	7,409989201 1E-03	3,157833885 8E-04	4,790483851 4E-06
2	3,010375779 8E+04	8,615455482 1E+02	4,123960910 7E+02	1,782979229 4E+02	5,199340169 8E+01	5,437137489 8E+00	2,316241134 6E-01	3,509840351 0E-03
3	8,112190581 2E+06	1,204021740 8E+05	1,437248741 4E+05	6,265088770 6E+04	1,857465214 1E+04	1,948138232 7E+03	8,294480849 0E+01	1,255149493 4E+00
4	1,087092166 9E+09	2,368537656 1E+07	2,548913585 8E+07	1,071782926 8E+07	3,239976819 0E+06	3,411095263 1E+05	1,451449689 9E+04	2,192823174 9E+02
5	5,784190846 3E+10	1,496684306 7E+09	1,930069178 2E+09	7,162704275 9E+08	2,208279754 9E+08	2,337908455 9E+07	9,944643008 7E+05	1,499699120 8E+04

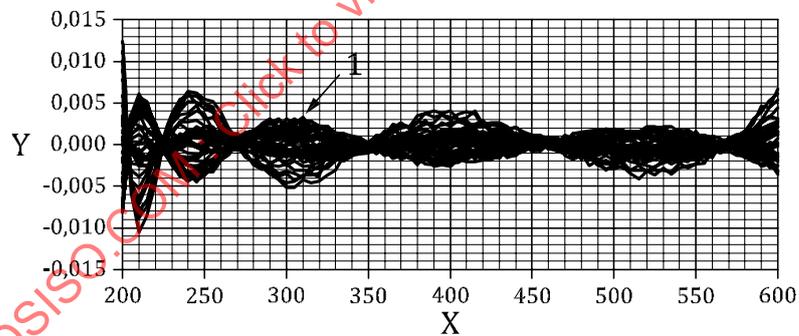
Paramete

$T_{c^*} = 0$
 $C_{c^*} = -1$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $200 \text{ K} \leq T \leq 600 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 600 \text{ K}$ with 5 K step

C.3 Argon

The critical flow function values produced by the REFPROP are given in Table C.3. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Table C.4.

Table C.3 — C* values (argon)

T (K)	p (MPa)										
	0,1	2	4	6	8	10	12	14	16	18	20
220	0,727 19	0,747 57	0,771 78	0,799 09	0,829 52	0,862 52	0,896 81	0,930 34	0,960 91	0,986 85	1,007 40
240	0,726 98	0,742 74	0,760 74	0,780 17	0,800 86	0,822 48	0,844 48	0,866 12	0,886 59	0,905 16	0,921 29
260	0,726 82	0,739 26	0,753 08	0,767 56	0,782 57	0,797 88	0,813 21	0,828 21	0,842 54	0,855 84	0,867 84
280	0,726 70	0,736 66	0,747 51	0,758 66	0,769 98	0,781 36	0,792 61	0,803 56	0,814 02	0,823 82	0,832 82
300	0,726 60	0,734 68	0,743 35	0,752 11	0,760 90	0,769 61	0,778 16	0,786 43	0,794 32	0,801 74	0,808 60
320	0,726 53	0,733 14	0,740 14	0,747 15	0,754 09	0,760 92	0,767 57	0,773 97	0,780 06	0,785 79	0,791 11
340	0,726 47	0,731 92	0,737 63	0,743 29	0,748 86	0,754 30	0,759 55	0,764 59	0,769 37	0,773 87	0,778 04
360	0,726 42	0,730 93	0,735 63	0,740 25	0,744 75	0,749 12	0,753 33	0,757 34	0,761 14	0,764 70	0,768 01
380	0,726 38	0,730 13	0,734 01	0,737 80	0,741 47	0,745 01	0,748 40	0,751 63	0,754 66	0,757 50	0,760 14
400	0,726 35	0,729 48	0,732 69	0,735 81	0,738 81	0,741 70	0,744 44	0,747 04	0,749 48	0,751 75	0,753 85
420	0,726 32	0,728 93	0,731 60	0,734 16	0,736 63	0,738 98	0,741 21	0,743 31	0,745 27	0,747 09	0,748 76
440	0,726 30	0,728 47	0,730 68	0,732 80	0,734 82	0,736 74	0,738 55	0,740 24	0,741 81	0,743 26	0,744 58
460	0,726 28	0,728 09	0,729 92	0,731 66	0,733 31	0,734 87	0,736 33	0,737 69	0,738 94	0,740 08	0,741 12
480	0,726 27	0,727 76	0,729 27	0,730 70	0,732 04	0,733 30	0,734 47	0,735 55	0,736 53	0,737 43	0,738 23
500	0,726 25	0,727 49	0,728 72	0,729 88	0,730 96	0,731 97	0,732 89	0,733 74	0,734 50	0,735 19	0,735 79
520	0,726 24	0,727 25	0,728 25	0,729 18	0,730 04	0,730 83	0,731 55	0,732 20	0,732 78	0,733 28	0,733 72
540	0,726 23	0,727 04	0,727 84	0,728 58	0,729 25	0,729 86	0,730 41	0,730 89	0,731 31	0,731 66	0,731 95
560	0,726 22	0,726 86	0,727 49	0,728 06	0,728 57	0,729 02	0,729 42	0,729 76	0,730 04	0,730 27	0,730 43
580	0,726 21	0,726 71	0,727 19	0,727 61	0,727 98	0,728 30	0,728 57	0,728 79	0,728 95	0,729 06	0,729 13
600	0,726 21	0,726 58	0,726 92	0,727 22	0,727 47	0,727 67	0,727 83	0,727 94	0,728 01	0,728 02	0,728 00

Table C.4 — Coefficients $C_{i,j}$, range, and deviation (argon)

j	i							
	0	1	2	3	4	5	6	7
0	7,261081671 1E-01	2,042474432 2E-04	3,709231249 9E-04	1,368723865 3E-04	2,397324295 1E-05	2,065954816 4E-06	8,393193083 4E-08	1,282665977 3E-09
1	9,567215480 2E-02	1,023026172 5E+00	4,563491931 3E-01	1,639150157 5E-01	2,840991278 3E-02	2,429891070 5E-03	9,811811472 3E-05	1,491886151 1E-06
2	4,459311758 9E+01	6,630621000 2E+02	2,116906566 8E+02	7,346252591 4E+01	1,258135189 1E+01	1,066701111 0E+00	4,275745148 3E-02	6,460403526 0E-04
3	9,721259944 4E+03	9,446421676 1E+04	4,506032155 8E+04	1,546589355 0E+04	2,614356224 8E+03	2,193525104 7E+02	8,712487773 0E+00	1,305885444 8E-01
4	1,000120072 5E+06	7,207680598 6E+06	4,411115375 6E+06	1,537498230 8E+06	2,570636491 9E+05	2,130360062 4E+04	8,363603082 1E+02	1,240535958 7E+01
5	3,931065245 5E+07	2,350267362 1E+08	1,663274171 3E+08	5,824148148 4E+07	9,670364213 1E+06	7,908152312 7E+05	3,058299920 5E+04	4,472335683 7E+02

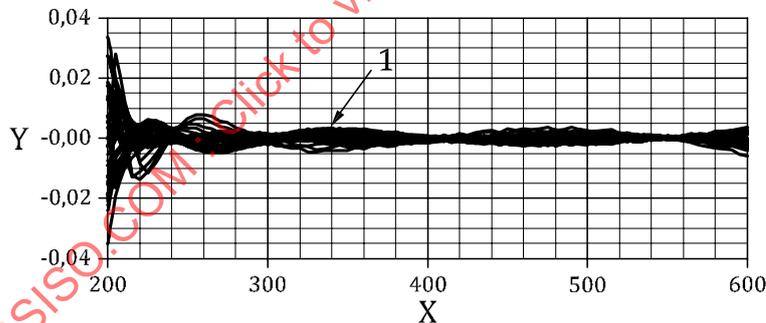
Parameters:

$T_{c^*} = 0$
 $C_{c^*} = -1$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $200 \text{ K} \leq T \leq 600 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 600 \text{ K}$ with 5 K step

C.4 Dry air with carbon dioxide (CIPM 2007 composition+CO₂/0,04 %)

The critical flow function values produced by the REFPROP are given in Table C.5. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Table C.6.

Each mole fraction in the CIPM 2007 composition is multiplied by a constant in order to include CO₂ of 0,04 % mole fraction and make the total summation

Table C.5 — C* values (dry air with CO₂/0,04 %)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
200	0,685 89	0,705 01	0,727 98	0,753 97	0,782 50	0,812 14	0,840 68	0,865 83	0,886 12	0,901 18	0,911 37
220	0,685 66	0,699 77	0,715 88	0,733 13	0,751 16	0,769 37	0,786 99	0,803 21	0,817 37	0,829 09	0,838 26
240	0,685 48	0,696 14	0,707 91	0,720 08	0,732 43	0,744 65	0,756 40	0,767 33	0,777 14	0,785 63	0,792 69
260	0,685 33	0,693 53	0,702 35	0,711 27	0,720 13	0,728 76	0,737 00	0,744 67	0,751 62	0,757 75	0,762 99
280	0,685 20	0,691 57	0,698 30	0,704 99	0,711 53	0,717 83	0,723 80	0,729 33	0,734 35	0,738 82	0,742 68
300	0,685 08	0,690 07	0,695 26	0,700 35	0,705 26	0,709 95	0,714 35	0,718 41	0,722 09	0,725 36	0,728 20
320	0,684 96	0,688 88	0,692 91	0,696 80	0,700 53	0,704 05	0,707 33	0,710 34	0,713 05	0,715 44	0,717 51
340	0,684 83	0,687 91	0,691 04	0,694 03	0,696 87	0,699 52	0,701 97	0,704 19	0,706 18	0,707 92	0,709 40
360	0,684 69	0,687 10	0,689 52	0,691 82	0,693 96	0,695 95	0,697 76	0,699 39	0,700 83	0,702 06	0,703 10
380	0,684 54	0,686 40	0,688 26	0,690 00	0,691 61	0,693 08	0,694 40	0,695 57	0,696 58	0,697 42	0,698 10
400	0,684 36	0,685 79	0,687 20	0,688 50	0,689 68	0,690 74	0,691 67	0,692 47	0,693 14	0,693 67	0,694 07
420	0,684 17	0,685 24	0,686 28	0,687 21	0,688 05	0,688 78	0,689 40	0,689 91	0,690 31	0,690 60	0,690 77
440	0,683 96	0,684 73	0,685 46	0,686 11	0,686 66	0,687 13	0,687 49	0,687 77	0,687 95	0,688 03	0,688 03
460	0,683 72	0,684 25	0,684 73	0,685 14	0,685 46	0,685 70	0,685 87	0,685 95	0,685 95	0,685 87	0,685 71
480	0,683 47	0,683 79	0,684 06	0,684 27	0,684 40	0,684 47	0,684 46	0,684 38	0,684 24	0,684 03	0,683 75
500	0,683 20	0,683 35	0,683 45	0,683 48	0,683 46	0,683 37	0,683 23	0,683 02	0,682 75	0,682 43	0,682 05
520	0,682 91	0,682 91	0,682 86	0,682 76	0,682 60	0,682 39	0,682 13	0,681 82	0,681 45	0,681 03	0,680 57
540	0,682 61	0,682 49	0,682 31	0,682 09	0,681 82	0,681 51	0,681 15	0,680 74	0,680 29	0,679 80	0,679 27
560	0,682 29	0,682 06	0,681 79	0,681 47	0,681 10	0,680 70	0,680 26	0,679 78	0,679 26	0,678 70	0,678 11
580	0,681 96	0,681 64	0,681 28	0,680 87	0,680 43	0,679 96	0,679 45	0,678 90	0,678 33	0,677 72	0,677 07
600	0,681 62	0,681 23	0,680 79	0,680 31	0,679 81	0,679 27	0,678 70	0,678 10	0,677 48	0,676 82	0,676 14
Component mole fractions (CIPM 2007 composition):											
Nitrogen	0,780 848 0		Methane		0,000 001 5						
Oxygen	0,209 390 0		Krypton		0,000 001 1						
Argon	0,009 332 0		Hydrogen (normal)		0,000 000 5						
Carbon dioxide	0,000 400 0		Nitrous oxide		0,000 000 3						
Neon	0,000 018 2		Carbon monoxide		0,000 000 2						
Helium	0,000 005 2		Xenon		0,000 000 1						

Table C.6 — Coefficients C_{ij} , range, and deviation (dry air with CO₂/0,04 %)

j	i							
	0	1	2	3	4	5	6	7
0	6,563295910 6E-01	2,641231313 8E-04	2,069877649 1E-04	9,027433400 3E-05	1,809363631 4E-05	1,636430763 6E-06	6,649487208 5E-08	9,972521737 1E-10
1	2,752516456 3E+01	1,193391522 4E+00	3,060999740 9E-01	1,329803031 2E-01	2,677802838 9E-02	2,424361393 3E-03	9,842280247 6E-05	1,473676015 1E-06
2	1,071811824 8E+04	6,175486543 2E+02	1,735669108 9E+02	7,568840569 9E+01	1,529191523 2E+01	1,384228208 7E+00	5,609032176 5E-02	8,378029425 7E-04
3	2,085858750 9E+06	6,914648540 2E+04	4,571392370 7E+04	2,077271853 4E+04	4,215625199 6E+03	3,812656349 7E+02	1,540555647 4E+01	2,293474221 6E-01
4	2,013451764 9E+08	5,987298974 2E+06	5,787239267 1E+06	2,743699842 8E+06	5,619197623 4E+05	5,079696626 4E+04	2,045191856 9E+03	3,031774864 6E+01
5	7,681225627 1E+09	2,695989180 7E+08	3,033457392 7E+08	1,400132897 0E+08	2,904411715 0E+07	2,630286366 2E+06	1,055020373 5E+05	1,555811504 3E+03

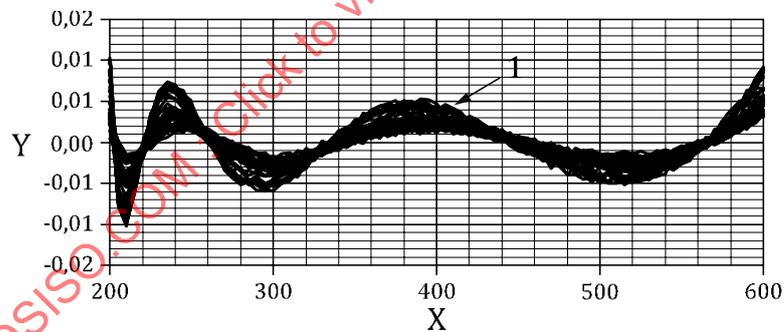
Parameters:

$T_{c^*} = 65$
 $C_{c^*} = -1$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $200 \text{ K} \leq T \leq 600 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 600 \text{ K}$ with 5 K step

C.5 Dry air without carbon dioxide (CIPM 2007 composition /no CO₂)

The critical flow function values produced by the REFPROP are given in Table C.7. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Table C.8.

Each mole fraction in the CIPM 2007 composition is multiplied by a constant to make the total summation unity.

NOTE In CIPM 2007 composition, the summation of all the mole fractions is not unity.

Table C.7 — C* values (dry air without CO₂)

T (K)	p (MPa)										
	0,1	2	4	6	8	10	12	14	16	18	20
200	0,685 90	0,704 99	0,727 93	0,753 88	0,782 34	0,811 92	0,840 40	0,865 49	0,885 75	0,900 78	0,910 97
220	0,685 66	0,699 76	0,715 84	0,733 07	0,751 07	0,769 25	0,786 83	0,803 02	0,817 15	0,828 85	0,838 00
240	0,685 48	0,696 13	0,707 89	0,720 04	0,732 37	0,744 57	0,756 30	0,767 20	0,777 00	0,785 47	0,792 52
260	0,685 34	0,693 52	0,702 34	0,711 24	0,720 09	0,728 71	0,736 93	0,744 58	0,751 52	0,757 64	0,762 87
280	0,685 21	0,691 57	0,698 30	0,704 97	0,711 50	0,717 79	0,723 75	0,729 27	0,734 28	0,738 74	0,742 60
300	0,685 09	0,690 07	0,695 26	0,700 33	0,705 24	0,709 92	0,714 31	0,718 37	0,722 04	0,725 30	0,728 14
320	0,684 97	0,688 88	0,692 90	0,696 80	0,700 52	0,704 03	0,707 31	0,710 31	0,713 01	0,715 40	0,717 46
340	0,684 84	0,687 91	0,691 04	0,694 03	0,696 86	0,699 51	0,701 95	0,704 17	0,706 15	0,707 88	0,709 37
360	0,684 70	0,687 11	0,689 53	0,691 82	0,693 96	0,695 94	0,697 75	0,699 38	0,700 81	0,702 04	0,703 07
380	0,684 55	0,686 41	0,688 27	0,690 01	0,691 61	0,693 08	0,694 40	0,695 56	0,696 56	0,697 40	0,698 08
400	0,684 38	0,685 80	0,687 21	0,688 50	0,689 68	0,690 73	0,691 66	0,692 46	0,693 13	0,693 66	0,694 06
420	0,684 19	0,685 25	0,686 29	0,687 22	0,688 05	0,688 78	0,689 40	0,689 91	0,690 30	0,690 59	0,690 76
440	0,683 97	0,684 74	0,685 47	0,686 12	0,686 67	0,687 13	0,687 50	0,687 77	0,687 95	0,688 03	0,688 02
460	0,683 74	0,684 27	0,684 74	0,685 15	0,685 47	0,685 71	0,685 87	0,685 95	0,685 95	0,685 87	0,685 71
480	0,683 49	0,683 81	0,684 08	0,684 28	0,684 41	0,684 47	0,684 47	0,684 39	0,684 24	0,684 03	0,683 75
500	0,683 22	0,683 36	0,683 46	0,683 49	0,683 47	0,683 38	0,683 23	0,683 03	0,682 76	0,682 43	0,682 05
520	0,682 93	0,682 93	0,682 88	0,682 77	0,682 62	0,682 40	0,682 14	0,681 82	0,681 46	0,681 04	0,680 57
540	0,682 62	0,682 50	0,682 33	0,682 11	0,681 84	0,681 52	0,681 16	0,680 75	0,680 30	0,679 81	0,679 27
560	0,682 31	0,682 08	0,681 80	0,681 48	0,681 12	0,680 72	0,680 27	0,679 79	0,679 27	0,678 71	0,678 12
580	0,681 98	0,681 66	0,681 29	0,680 89	0,680 45	0,679 97	0,679 46	0,678 92	0,678 34	0,677 73	0,677 08
600	0,681 63	0,681 25	0,680 80	0,680 33	0,679 82	0,679 28	0,678 71	0,678 12	0,677 49	0,676 83	0,676 15
Component mole fractions (CIPM composition - CO ₂):											
Nitrogen	0,781 162 7				Methane	0,000 001 5					
Oxygen	0,209 474 4				Krypton	0,000 001 1					
Argon	0,009 335 8				Hydrogen (normal)	0,000 000 5					
Carbon dioxide	0				Nitrous oxide	0,000 000 3					
Neon	0,000 018 2				Carbon monoxide	0,000 000 2					
Helium	0,000 005 2				Xenon	0,000 000 1					

Table C.8 — Coefficients C_{ij} , range, and deviation (dry air without CO₂)

j	i							
	0	1	2	3	4	5	6	7
0	6,5924300386 E-01	3,4234066969 E-04	2,0954051829 E-04	7,1150684529 E-05	1,2461892868 E-05	1,0679784439 E-06	4,2659753578 E-08	6,3861871635 E-10
1	2,3014475252 E+01	1,2812135058 E+00	2,9371545472 E-01	9,9339975043 E-02	1,7475562154 E-02	1,4993712527 E-03	5,9853180824 E-05	8,9484113100 E-07
2	8,3050638713 E+03	6,6182890885 E+02	1,5488602225 E+02	5,2695676886 E+01	9,3239379114 E+00	8,0107371049 E-01	3,1945775977 E-02	4,7670086671 E-04
3	1,4904164229 E+06	8,5926517878 E+04	3,7203094083 E+04	1,3294637918 E+04	2,3736570885 E+03	2,0424718497 E+02	8,1312613476 E+00	1,2099043993 E-01
4	1,3202707497 E+08	7,0930301542 E+06	4,1919752798 E+06	1,5982320288 E+06	2,9002281935 E+05	2,5020962991 E+04	9,9370844451 E+02	1,4726663588 E+01
5	4,6019572554 E+09	2,7151693882 E+08	1,9084668646 E+08	7,3785979970 E+07	1,3688804271 E+07	1,1879467068 E+06	4,7059347813 E+04	6,9373458601 E+02

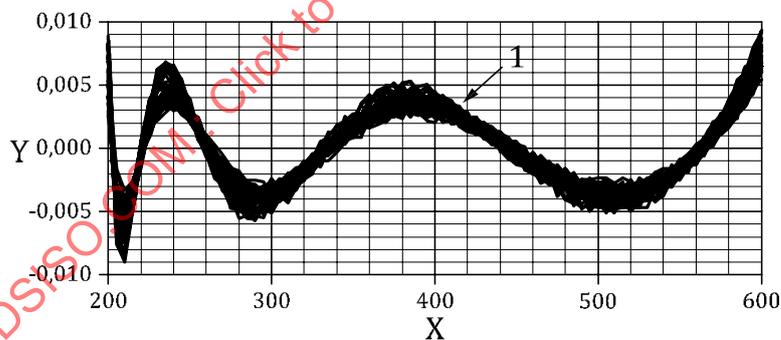
Parameters:

$T_{c^*} = 80$
 $C_{c^*} = -1$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $200 \text{ K} \leq T \leq 600 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%) 1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 600 \text{ K}$ with 5 K step

C.6 Humidity correction for air of a typical composition

The humidity correction may be estimated at a practical accuracy by Formula (C.2);

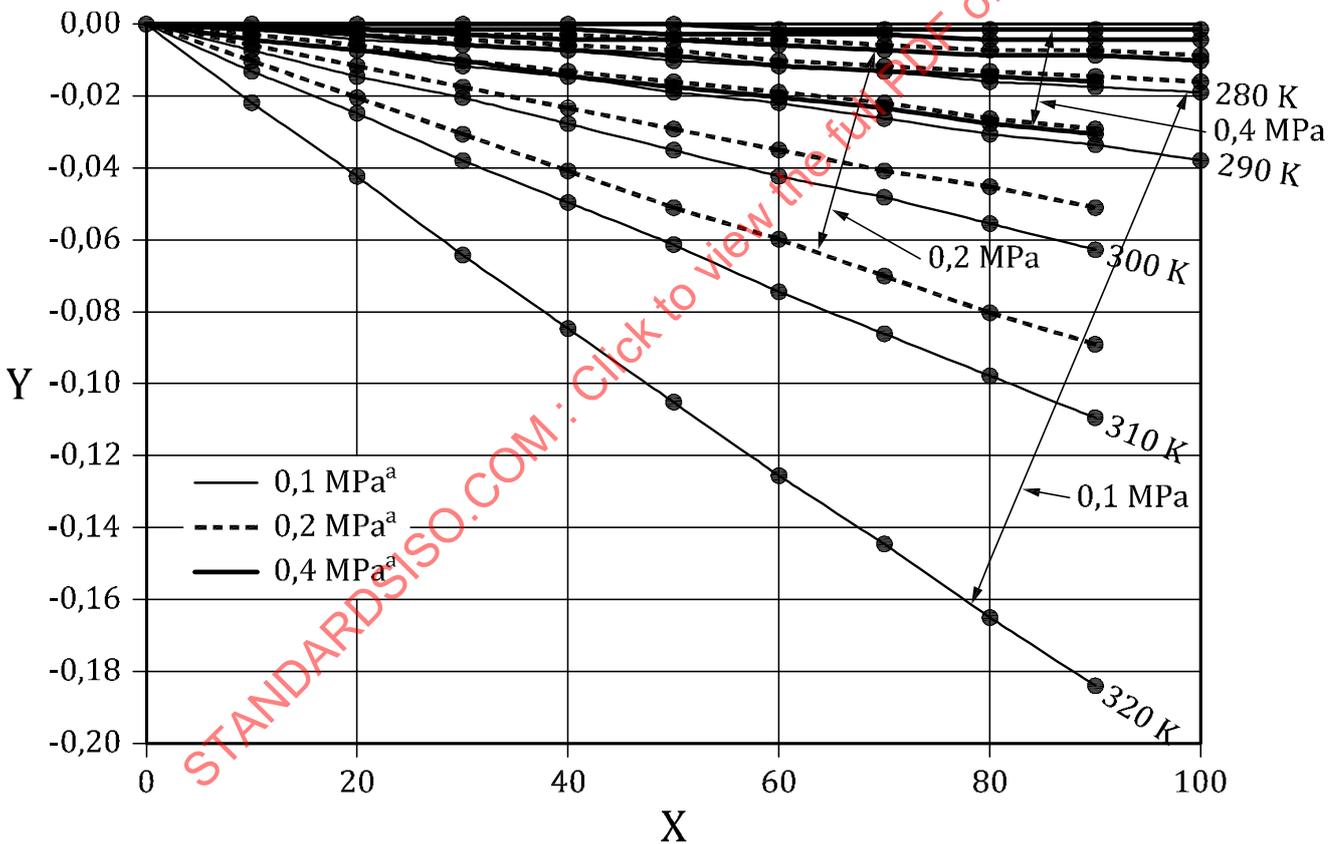
$$C^{*HA} = C^{*DA} \left[1 + \left\{ \left(7,894 - \frac{12,571}{p} \right) \frac{T^2}{100\,000} - \left(4,473 - \frac{7,056\,3}{p} \right) \frac{T}{100} + \left(6,366\,5 - \frac{9,926\,6}{p} \right) \right\} \frac{H_R}{100\,000} \right] \quad (C.2)$$

NOTE As far as confirmed for air with typical compositions, the deviations of the correction from the REFPROP values were smaller than 0,005 %.

This formula is valid in the ranges:

- 0,1 MPa ≤ p ≤ 0,5 MPa
- 280 K ≤ T ≤ 310 K
- 0 % ≤ H_R ≤ 90 %

As seen in Figure C.2, the deviation caused by the humidity may be negligible at high pressure. The REFPROP does not produce C* where there is no data point in the figure.



Key
 X humidity (%)
 Y deviation (%) of C* from that of dry air
 a Each at 280 K, 290 K, 300 K, 310 K and 320 K.

Figure C.2 — Differences of C*^{DA} with humidity from that of dry air in percent

C.7 Methane

The critical flow function values produced by the REFPROP are given in Table C.9. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Tables C.9 to C.12 for each range.

Table C.9 — C^* values (methane)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
200	0,674 80	0,721 09	0,811 78	—	—	—	—	—	—	—	—
220	0,674 04	0,707 10	0,757 33	0,840 96	0,992 20	1,163 40	1,265 20	1,309 70	1,322 80	1,318 90	1,305 90
240	0,673 23	0,697 96	0,731 18	0,775 54	0,835 85	0,912 11	0,989 36	1,049 30	1,088 00	1,109 70	1,119 50
260	0,672 29	0,691 35	0,715 15	0,743 81	0,778 22	0,818 18	0,861 09	0,902 06	0,936 53	0,962 60	0,980 60
280	0,671 19	0,686 19	0,704 03	0,724 26	0,747 02	0,772 03	0,798 39	0,824 59	0,848 87	0,869 83	0,886 78
300	0,669 92	0,681 89	0,695 66	0,710 68	0,726 91	0,744 13	0,761 92	0,779 64	0,796 56	0,812 00	0,825 46
320	0,668 50	0,678 15	0,688 98	0,700 49	0,712 59	0,725 13	0,737 88	0,750 51	0,762 68	0,774 03	0,784 30
340	0,666 96	0,674 80	0,683 44	0,692 43	0,701 72	0,711 18	0,720 67	0,730 02	0,739 04	0,747 54	0,755 35
360	0,665 32	0,671 73	0,678 69	0,685 82	0,693 08	0,700 39	0,707 64	0,714 75	0,721 59	0,728 06	0,734 06
380	0,663 63	0,668 89	0,674 54	0,680 25	0,686 00	0,691 73	0,697 37	0,702 87	0,708 14	0,713 14	0,717 79
400	0,661 93	0,666 26	0,670 85	0,675 46	0,680 05	0,684 59	0,689 03	0,693 33	0,697 45	0,701 34	0,704 97
420	0,660 25	0,663 81	0,667 56	0,671 29	0,674 97	0,678 59	0,682 11	0,685 50	0,688 73	0,691 78	0,694 63
440	0,658 60	0,661 53	0,664 59	0,667 61	0,670 58	0,673 47	0,676 27	0,678 95	0,681 49	0,683 89	0,686 11
460	0,657 00	0,659 40	0,661 90	0,664 35	0,666 73	0,669 05	0,671 27	0,673 39	0,675 39	0,677 27	0,679 00
480	0,655 47	0,657 43	0,659 46	0,661 44	0,663 35	0,665 19	0,666 95	0,668 62	0,670 18	0,671 64	0,672 98
500	0,654 01	0,655 61	0,657 24	0,658 82	0,660 35	0,661 80	0,663 18	0,664 49	0,665 70	0,666 82	0,667 84
520	0,652 62	0,653 91	0,655 21	0,656 47	0,657 67	0,658 81	0,659 88	0,660 88	0,661 80	0,662 64	0,663 39
540	0,651 31	0,652 33	0,653 36	0,654 34	0,655 27	0,656 14	0,656 96	0,657 70	0,658 39	0,659 00	0,659 53
560	0,650 07	0,650 87	0,651 66	0,652 41	0,653 11	0,653 76	0,654 36	0,654 90	0,655 38	0,655 80	0,656 15
580	0,648 91	0,649 51	0,650 10	0,650 65	0,651 16	0,651 63	0,652 04	0,652 40	0,652 71	0,652 97	0,653 18
600	0,647 80	0,648 24	0,648 66	0,649 05	0,649 39	0,649 70	0,649 96	0,650 17	0,650 34	0,650 46	0,650 54

Table C.10 — Coefficients C_{ij} , range, and deviation (methane/high temperature)

j	i							
	0	1	2	3	4	5	6	7
0	6,263640749 6E-01	- 6,142086968 1E-04	9,819183463 5E-06	- 9,795174480 1E-07	4,027749234 6E-08	1,218851539 8E-09	- 7,326340807 6E-11	6,263640749 6E-01
1	1,090426326 4E+03	1,496349335 6E+01	- 9,237198005 0E-01	9,226174522 1E-02	- 2,904124099 0E-03	- 1,804114893 3E-04	8,245591343 8E-06	1,090426326 4E+03
2	- 1,294075765 6E+07	8,123161898 2E+05	1,443834380 5E+04	- 2,621707593 0E+03	3,219097491 4E+01	9,985200670 8E+00	- 3,546186002 4E-01	- 1,294075765 6E+07
3	8,917793085 5E+10	- 7,462034485 3E+09	- 1,583460869 1E+07	2,199428820 2E+07	1,098003305 4E+06	- 2,371357434 5E+05	7,035417844 2E+03	8,917793085 5E+10
4	- 3,360159860 2E+14	3,227269030 2E+13	4,672315345 6E+10	1,272988532 7E+10	- 2,628563806 0E+10	2,583030127 4E+09	- 6,612531615 3E+07	- 3,360159860 2E+14
5	5,321656190 6E+17	- 5,604976573 4E+16	5,837009518 0E+14	- 5,224073288 0E+14	1,441478498 3E+14	- 1,106682957 5E+13	2,534730534 8E+11	5,321656190 6E+17

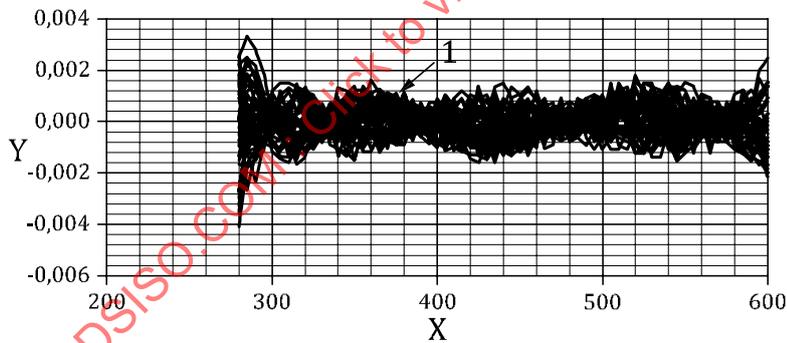
Parameters:

$T_{c^*} = 110$
 $C_{c^*} = -1,7$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $280 \text{ K} \leq T \leq 600 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 280 \text{ K} \sim 600 \text{ K}$ with 5 K step

Table C.11 — Coefficients C_{ij} , range, and deviation (methane/low pressure)

j	i							
	0	1	2	3	4	5	6	7
0	6,25605 59279E- 01	- 5,956392371 5E-04	- 1,242193433 3E-04	7,666112059 7E-05	- 2,356178324 6E-05	3,969684135 6E-06	- 3,025458313 0E-07	6,840671026 5E-09
1	1,22428 40792E+ 03	1,188678806 6E+01	8,394860954 5E+00	- 5,174242921 4E+00	1,584648571 3E+00	- 2,651151275 7E-01	1,893225893 4E-02	- 3,158903348 7E-04
2	- 1,48818 17391E+ 07	1,164801983 3E+06	- 2,242041315 3E+05	1,321641680 2E+05	- 4,272682225 9E+04	7,516638651 7E+03	- 5,441978969 5E+02	8,526860572 8E+00
3	1,02628 08655E+ 11	- 1,043782046 0E+10	3,136287008 8E+09	- 1,877167006 7E+09	6,725353580 5E+08	- 1,284098784 7E+08	1,014983108 8E+07	- 2,137694702 8E+05
4	- 4,07700 51666E+ 14	5,066067945 3E+13	- 2,212162374 2E+13	1,546953277 2E+13	- 5,987030080 4E+12	1,189718461 6E+12	- 9,805785979 3E+10	2,367255921 6E+09
5	8,65598 80822E+ 17	- 1,309881655 2E+17	8,138759946 6E+16	- 6,268291276 1E+16	2,507455337 9E+16	- 4,934045960 9E+15	3,919485960 8E+14	- 8,763280054 9E+12
6	- 7,58379 02117E+ 20	1,401086040 1E+20	- 1,153337978 4E+20	9,237521152 3E+19	- 3,654835794 4E+19	6,806593961 8E+18	- 4,616725083 5E+17	5,539596076 7E+15

Parameters:

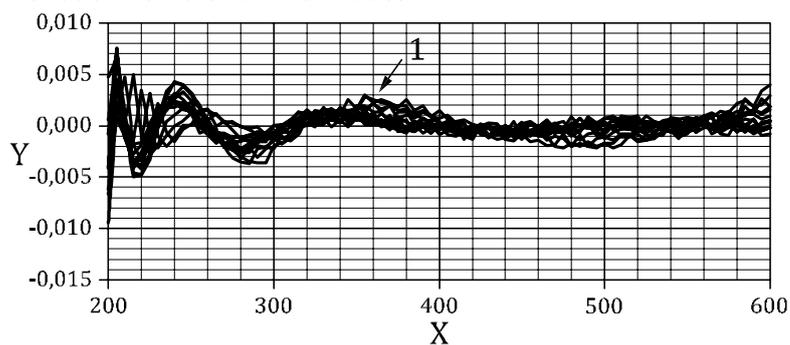
$T_{c^*} = 80$
 $C_{c^*} = -1,7$

Range:

$0,1 \text{ MPa} \leq p \leq 6,5 \text{ MPa}$
 Temperature range as below.

p MPa	Min. T K	Max. T K
0,1 ~ 4	200	600
4,5	205	
5	210	
5,5	215	
6	220	
6,5	225	

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 6,5 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 600 \text{ K}$ with 5 K step

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Table C.12 — Coefficients $C_{i,j}$, range, and deviation (methane/high pressure)

j	i							
	0	1	2	3	4	5	6	7
0	- 1,69772 65267E+ 00	- 1,152085760 7E+00	- 2,231734452 9E-01	- 2,121649863 2E-02	- 9,928890684 6E-04	- 1,663798479 6E-05	- 2,428748414 4E-07	- 8,681346709 5E-09
1	- 3,29858 61490E+ 05	- 1,588799060 0E+05	- 2,965220007 6E+04	- 2,627909625 9E+03	- 1,027564323 9E+02	- 2,797042991 8E-01	- 9,345603855 0E-02	- 1,912148535 8E-03
2	- 1,61831 07265E+ 10	- 7,542634661 1E+09	- 1,316640018 7E+09	- 1,006609476 5E+08	- 2,118843477 5E+06	- 1,492459924 1E+05	- 9,269166474 4E+03	- 1,483517249 8E+02
3	- 3,53205 85319E+ 14	- 1,544894865 9E+14	- 2,358396283 7E+13	- 1,161465546 0E+12	- 5,981195185 1E+10	- 9,136212696 5E+09	- 3,705794881 3E+08	- 5,191305752 0E+06
4	- 3,56511 04301E+ 18	- 1,372523009 4E+18	- 1,440380129 1E+17	- 7,066024966 4E+15	- 2,521589128 6E+15	- 1,982754319 0E+14	- 6,771163693 7E+12	- 8,753920254 6E+10
5	- 1,50088 49666E+ 22	- 4,072878023 8E+21	- 2,483411354 1E+20	- 2,001342273 1E+20	- 2,797281528 9E+19	- 1,793276932 8E+18	- 5,587510372 9E+16	- 6,857344403 0E+14
6	- 1,66779 25014E+ 25	- 2,045971848 8E+24	- 3,563232122 1E+24	- 8,767610434 5E+23	- 9,769324883 6E+22	- 5,670408794 1E+21	- 1,671069252 9E+20	- 1,979459267 0E+18

Parameters:

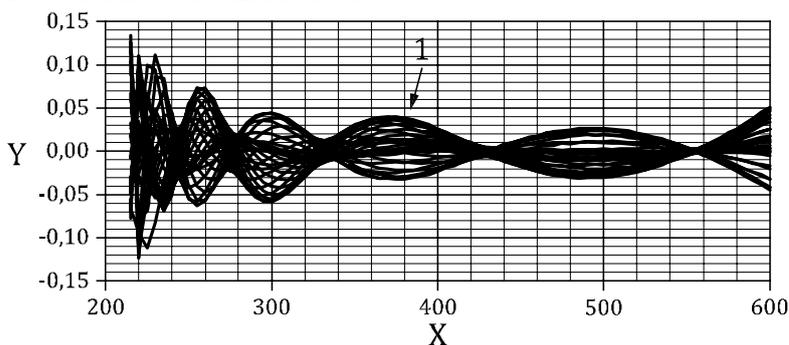
$T_{c^*} = 80$
 $C_{c^*} = -1,8$

Range:

$6,5 \text{ MPa} \leq p \leq 20 \text{ MPa}$
Temperature range as below.

p MPa	Min. T K	Max. T K
6,5 ~ 7	215	600
7,5 ~ 8,5	220	
9 ~ 19	215	
19,5 ~ 20	220	

Deviation from the REFPROP values:



Key

- X temperature (kelvin)
- Y deviation (%)
- 1 $p = 6,5 \text{ MPa} \sim 20 \text{ MPa}$ with 0,5 MPa step, and $T = 215 \text{ K} \sim 600 \text{ K}/5 \text{ K}$ step

C.8 Carbon dioxide

The critical flow function values produced by the REFPROP are given in Table C.13. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Tables C.14 and C.15 for each range.

NOTE Carbon dioxide may have a significant vibrational relaxation effects and the effect becomes stronger in small nozzles. See B.5.

Table C.13 — C* values (carbon dioxide)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
260	—	0,736 59	—	—	—	—	—	—	—	—	—
280	—	0,715 19	0,808 20	—	—	—	—	—	—	—	—
300	—	0,701 88	0,755 14	0,866 04	—	—	—	—	—	—	—
320	0,666 46	0,692 45	0,729 20	0,784 19	0,884 86	—	—	v	—	—	—
340	0,664 70	0,685 39	0,712 56	0,748 21	0,797 97	0,872 74	0,986 59	1,120 50	1,228 30	1,298 50	1,340 00
360	0,663 13	0,679 89	0,700 83	0,726 33	0,758 13	0,798 64	0,850 46	0,913 90	0,982 71	1,045 90	1,096 30
380	0,661 71	0,675 50	0,692 09	0,711 34	0,733 88	0,760 41	0,791 55	0,827 36	0,866 73	0,907 11	0,945 22
400	0,660 42	0,671 89	0,685 32	0,700 38	0,717 29	0,736 31	0,757 56	0,780 99	0,806 20	0,832 39	0,858 44
420	0,659 26	0,668 89	0,679 93	0,691 99	0,705 18	0,719 54	0,735 11	0,751 79	0,769 39	0,787 55	0,805 80
440	0,658 19	0,666 34	0,675 53	0,685 38	0,695 92	0,707 16	0,719 08	0,731 60	0,744 61	0,757 91	0,771 28
460	0,657 21	0,664 16	0,671 88	0,680 03	0,688 62	0,697 63	0,707 03	0,716 77	0,726 77	0,736 92	0,747 08
480	0,656 31	0,662 26	0,668 80	0,675 62	0,682 72	0,690 07	0,697 65	0,705 42	0,713 32	0,721 28	0,729 22
500	0,655 48	0,660 60	0,666 18	0,671 93	0,677 86	0,683 94	0,690 15	0,696 45	0,702 82	0,709 20	0,715 54
520	0,654 71	0,659 13	0,663 91	0,668 80	0,673 79	0,678 87	0,684 02	0,689 21	0,694 42	0,699 61	0,704 75
540	0,653 99	0,657 82	0,661 93	0,666 11	0,670 34	0,674 62	0,678 92	0,683 24	0,687 55	0,691 83	0,696 05
560	0,653 32	0,656 65	0,660 19	0,663 77	0,667 38	0,671 00	0,674 63	0,678 25	0,681 85	0,685 40	0,688 90
580	0,652 69	0,655 58	0,658 65	0,661 73	0,664 82	0,667 90	0,670 97	0,674 02	0,677 04	0,680 01	0,682 93
600	0,652 10	0,654 62	0,657 28	0,659 93	0,662 58	0,665 21	0,667 82	0,670 40	0,672 95	0,675 45	0,677 89

Table C.14 — Coefficients $C_{i,j}$, range, and deviation (carbon dioxide/low temperature and low pressure)

j	i						
	0	1	2	3	4	5	6
0	- 7,2651017647E +02	- 7,4282410458 E+03	- 1,8178414177E +04	- 1,8366764887 E+04	- 8,8398754707E +03	- 2,0093181655 E+03	- 1,7393995859 E+02
1	- 9,9523245358E +03	- 1,0144544029 E+05	- 2,4786025589E +05	- 2,5017382440 E+05	- 1,2033270592E +05	- 2,7342096481 E+04	- 2,3665929299 E+03
2	- 5,4476152343E +04	- 5,5403801369 E+05	- 1,3514635095E +06	- 1,3626602981 E+06	- 6,5501414597E +05	- 1,4877822819 E+05	- 1,2875660370 E+04
3	- 1,4906557209E +05	- 1,5125824719 E+06	- 3,6834931977E +06	- 3,7100625626 E+06	- 1,7822079229E +06	- 4,0465276783 E+05	- 3,5014523641 E+04
4	- 2,0390474043E +05	- 2,0642995508 E+06	- 5,0185149477E +06	- 5,0492187611 E+06	- 2,4238629669E +06	- 5,5012626003 E+05	- 4,7594939416 E+04
5	- 1,1154329978E +05	- 1,1266558320 E+06	- 2,7342748454E +06	- 2,7479445070 E+06	- 1,3182298545E +06	- 2,9906817856 E+05	- 2,5870114020 E+04

Parameters:

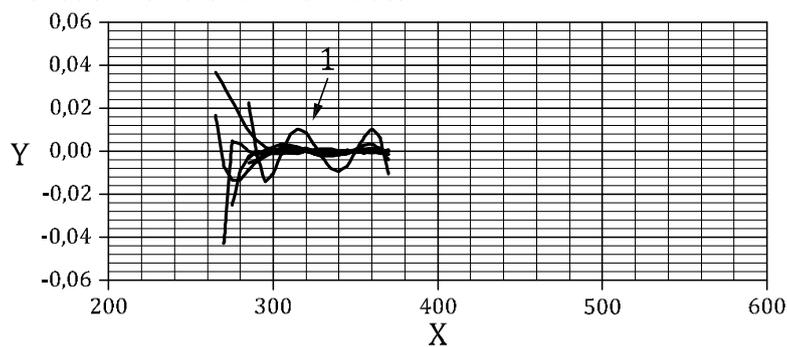
$T_{c^*} = 175$
 $C_{c^*} = -0,2$

Range:

$0,1 \text{ MPa} \leq p \leq 4 \text{ MPa}$
 Temperature range a below.

p MPa	Min. T K	Max. T K
0,1	305	370
0,5		
1	265	
1,5		
2	275	
2,5	285	
3	270	
3,5	280	
4		

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 4 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 265 \text{ K} \sim 370 \text{ K}$ with 5 K step

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Table C.15 — Coefficients C_{ij} , range, and deviation (carbon dioxide/high temperature and low pressure)

j	i							
	0	1	2	3	4	5	6	7
0	6,37569 79939E- 01	- 2,421770841 5E-03	9,841030616 1E-04	- 5,858764685 5E-04	1,832225395 9E-04	- 2,932490992 3E-05	2,304712041 3E-06	- 7,054949253 4E-08
1	3,74909 85095E+ 00	7,040191399 6E-01	- 3,894896491 6E-01	2,277406627 9E-01	- 7,098538903 7E-02	1,136389005 2E-02	- 8,941256440 3E-04	2,742299236 4E-05
2	- 2,56785 60824E+ 02	- 5,765703226 9E+00	5,497456116 5E+01	- 3,219639397 6E+01	9,981941963 9E+00	- 1,597646619 4E+00	1,258960569 8E-01	- 3,872667995 9E-03
3	9,90669 59359E+ 03	- 9,855986072 2E+01	- 3,381080281 0E+03	2,063687706 4E+03	- 6,362925893 4E+02	1,018018742 7E+02	- 8,043730151 1E+00	2,487331396 5E-01
4	- 1,98122 88906E+ 05	- 3,649526270 0E+03	9,587751864 1E+04	- 5,974307939 2E+04	1,838390560 6E+04	- 2,939945450 1E+03	2,333901485 9E+02	- 7,287512883 4E+00
5	1,58994 67523E+ 06	1,094674221 6E+05	- 9,896342802 7E+05	6,218726303 5E+05	- 1,911490346 2E+05	3,059606696 9E+04	- 2,447406459 9E+03	7,781555475 8E+01
6	6,37569 79939E- 01	- 2,421770841 5E-03	9,841030616 1E-04	5,858764685 5E-04	1,832225395 9E-04	- 2,932490992 3E-05	2,304712041 3E-06	- 7,054949253 4E-08

Parameters:

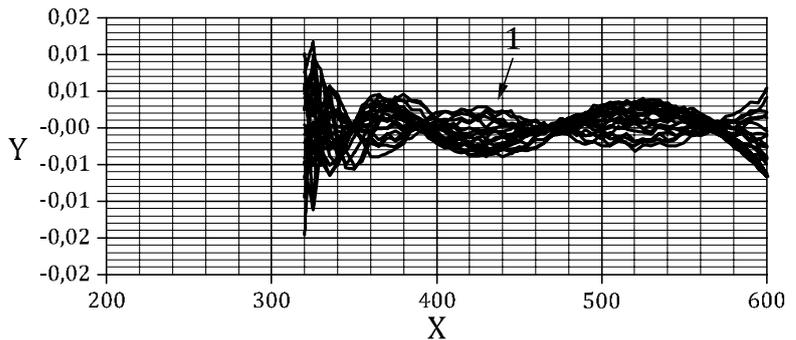
$T_{c^*} = 280$
 $C_{c^*} = -0,9$

Range:

$0,1 \text{ MPa} \leq p \leq 10 \text{ MPa}$
 Temperature range as below.

p	Min. T	Max. T
MPa	K	K
0,1 ~ 9	320	600
9,5	325	
10	330	

Deviation from the REFPROP values:



Key

X temperature (kelvin)
 Y deviation (%)
 1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 10 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 320 \text{ K} \sim 600 \text{ K}/5 \text{ K}$ step

C.9 Oxygen

The critical flow function values produced by the REFPROP are given in Table C.16. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Tables C.17 and C.18 for each range.

Table C.16— C^* values (oxygen)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
200	0,685 75	0,708 23	0,737 08	0,773 15	0,818 54	0,873 94	0,935 16	0,992 78	1,038 80	1,071 20	1,091 90
220	0,685 47	0,702 20	0,722 30	0,745 33	0,771 55	0,800 77	0,832 08	0,863 71	0,893 42	0,919 31	0,940 38
240	0,685 23	0,698 04	0,712 79	0,728 88	0,746 27	0,764 76	0,783 95	0,803 25	0,821 94	0,839 32	0,854 81
260	0,685 01	0,695 01	0,706 19	0,718 02	0,730 40	0,743 20	0,756 21	0,769 15	0,781 73	0,793 65	0,804 63
280	0,684 77	0,692 69	0,701 36	0,710 34	0,719 54	0,728 88	0,738 22	0,747 43	0,756 37	0,764 87	0,772 81
300	0,684 51	0,690 85	0,697 68	0,704 64	0,711 67	0,718 70	0,725 67	0,732 49	0,739 07	0,745 34	0,751 22
320	0,684 22	0,689 32	0,694 77	0,700 24	0,705 71	0,711 13	0,716 45	0,721 62	0,726 60	0,731 33	0,735 77
340	0,683 88	0,688 02	0,692 39	0,696 74	0,701 05	0,705 28	0,709 41	0,713 40	0,717 22	0,720 85	0,724 25
360	0,683 51	0,686 87	0,690 39	0,693 87	0,697 29	0,700 63	0,703 86	0,706 98	0,709 94	0,712 75	0,715 38
380	0,683 09	0,685 83	0,688 67	0,691 46	0,694 19	0,696 84	0,699 38	0,701 82	0,704 14	0,706 32	0,708 36
400	0,682 64	0,684 87	0,687 16	0,689 40	0,691 58	0,693 67	0,695 68	0,697 60	0,699 41	0,701 10	0,702 68

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Table C.17 — Coefficients C_{ij} , range, and deviation (oxygen/whole range)

j	i							
	0	1	2	3	4	5	6	7
0	6,9665724146 E-01	4,610600444 5E-02	4,7567358141 E-02	1,5912009266 E-02	2,49445918 28E-03	1,90544879 65E-04	6,88816958 09E-06	9,47117711 71E-08
1	1,1823468498 E-02	6,059241858 0E-02	4,7907181508 E-02	1,6546338204 E-02	2,59483926 50E-03	2,00613771 86E-04	7,38548710 21E-06	1,03518282 35E-07
2	4,6203639956 E-03	2,481480225 6E-02	1,9375891973 E-02	6,8114246732 E-03	1,06977934 99E-03	8,36223947 51E-05	3,12611401 31E-06	4,45063748 42E-08
3	9,0080321451 E-04	4,759318359 8E-03	3,9094413907 E-03	1,3874477853 E-03	2,18390913 13E-04	1,72408598 12E-05	6,52936630 56E-07	9,41581987 20E-09
4	8,9420595571 E-05	4,488347576 6E-04	3,9212518072 E-04	1,3985989771 E-04	2,20723016 41E-05	1,75791955 12E-06	6,73114025 45E-08	9,81064518 96E-10
5	3,8560932735 E-06	1,689581455 8E-05	1,5613068340 E-05	5,5829691326 E-06	8,83552019 17E-07	7,09212305 60E-08	2,74120325 75E-09	4,03108668 91E-11

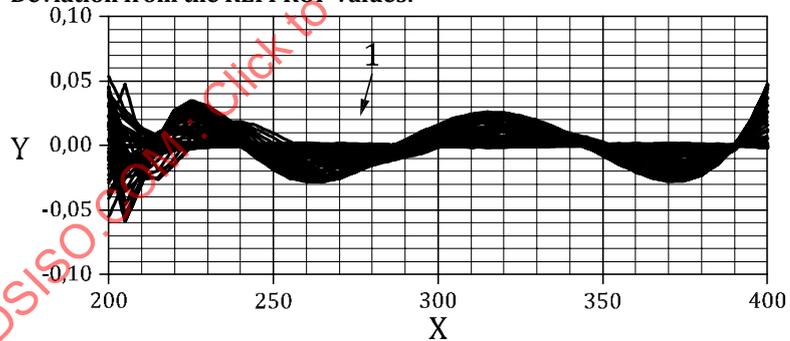
Parameters:

$T_{c^*} = 190$
 $C_{c^*} = 0,35$

Range:

$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$
 $200 \text{ K} \leq T \leq 400 \text{ K}$

Deviation from the REFPROP values:



Key

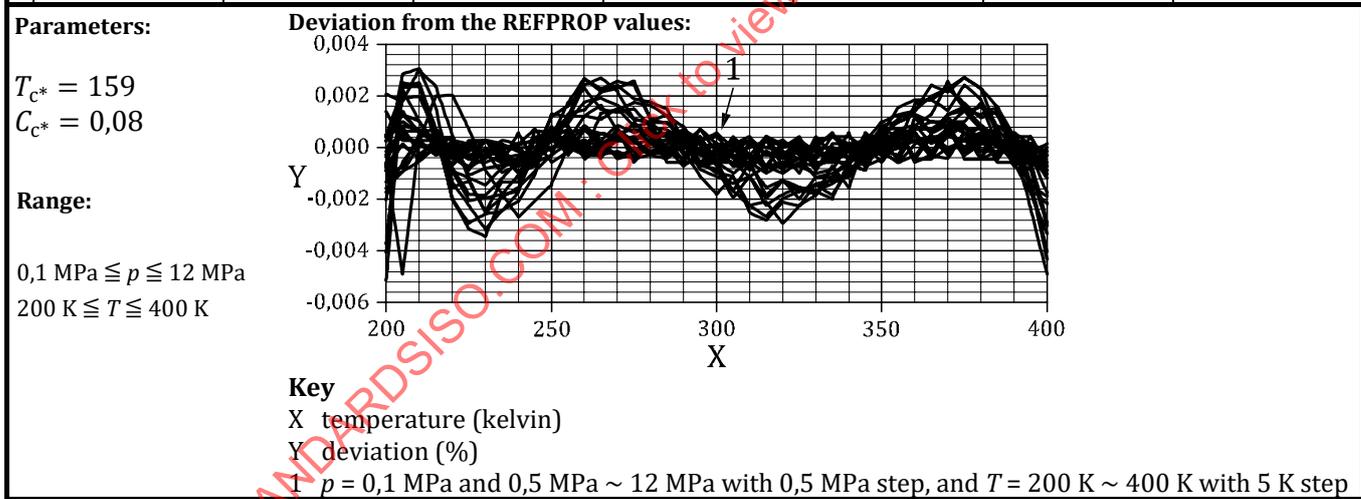
X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 20 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 200 \text{ K} \sim 400 \text{ K}$ with 5 K step

Table C.18 — Coefficients C_{ij} , range, and deviation (oxygen/ high accuracy at low pressures)

i	0	1	2	j 3	4	5	6
0	3,2625615758E+00	2,6411737361E+01	2,6559289469E+01	1,0232345111E+01	2,5629438653E+00	3,2547928464E-01	-1,3404136153E-02
1	1,3152444836E+01	9,5505818766E+01	9,1604337015E+01	3,5191511384E+01	8,8106593730E+00	1,1131181383E+00	4,5719814041E-02
2	2,4602540776E+01	1,3778565194E+02	1,2617984292E+02	4,8392763470E+01	1,2108120896E+01	1,5220462857E+00	-6,2355399023E-02
3	2,1860112941E+01	9,8978831449E+01	8,6781773466E+01	3,3258876728E+01	8,3149169582E+00	1,0401463574E+00	4,2506703474E-02
4	9,3897436213E+00	3,5377731086E+01	2,9805713869E+01	1,1423914120E+01	2,8533539229E+00	3,5525673308E-01	-1,4482861353E-02
5	1,5754181469E+00	5,0323240705E+00	4,0902565392E+00	1,5688761261E+00	3,9143853918E-01	-4,8513512511E-02	1,9731258821E-03



C.10 Steam (single-phase gas)

The critical flow function values produced by the REFPROP are given in Table C.19. The coefficients for Formula (C.1), their valid ranges, and deviations from the REFPROP values are given in Tables C.20 and C.21 for each range.

Table C.19 — C^* values (steam)

T K	p MPa										
	0,1	2	4	6	8	10	12	14	16	18	20
420	0,673 37	—	—	—	—	—	—	—	—	—	—
440	0,672 72	—	—	—	—	—	—	—	—	—	—
460	0,672 08	—	—	—	—	—	—	—	—	—	—
480	0,671 48	—	—	—	—	—	—	—	—	—	—
500	0,670 90	0,696 57	—	—	—	—	—	—	—	—	—
520	0,670 35	0,693 59	—	—	—	—	—	—	—	—	—
540	0,669 81	0,689 76	0,715 39	—	—	—	—	—	—	—	—
560	0,669 29	0,686 40	0,708 86	0,735 98	—	—	—	—	—	—	—
580	0,668 78	0,683 58	0,702 46	0,725 79	0,754 68	—	—	—	—	—	—
600	0,668 29	0,681 18	0,697 14	0,716 38	0,740 04	0,769 86	0,811 34	—	—	—	—
620	0,667 81	0,679 12	0,692 78	0,708 74	0,727 77	0,751 01	0,780 30	0,819 82	—	—	—
640	0,667 33	0,677 32	0,689 13	0,702 60	0,718 16	0,736 48	0,758 52	0,785 85	0,821 42	0,872 52	—
660	0,666 87	0,675 72	0,686 04	0,697 56	0,710 56	0,725 40	0,742 59	0,762 87	0,787 37	0,817 97	0,858 17
680	0,666 41	0,674 30	0,683 37	0,693 35	0,704 40	0,716 72	0,730 61	0,746 41	0,764 66	0,786 08	0,811 77
700	0,665 96	0,673 02	0,681 04	0,689 76	0,699 28	0,709 71	0,721 23	0,734 02	0,748 34	0,764 52	0,783 02
720	0,665 52	0,671 85	0,678 99	0,686 67	0,694 95	0,703 91	0,713 65	0,724 27	0,735 92	0,748 76	0,763 00
740	0,665 08	0,670 78	0,677 16	0,683 97	0,691 23	0,699 02	0,707 37	0,716 37	0,726 08	0,736 60	0,748 04
760	0,664 64	0,669 80	0,675 52	0,681 58	0,688 01	0,694 83	0,702 08	0,709 81	0,718 06	0,726 88	0,736 33
780	0,664 22	0,668 88	0,674 04	0,679 47	0,685 18	0,691 20	0,697 55	0,704 27	0,711 37	0,718 88	0,726 85
800	0,663 79	0,668 03	0,672 69	0,677 57	0,682 67	0,688 02	0,693 63	0,699 52	0,705 70	0,712 19	0,719 01
820	0,663 37	0,667 23	0,671 46	0,675 85	0,680 44	0,685 21	0,690 20	0,695 39	0,700 82	0,706 49	0,712 40
840	0,662 96	0,666 48	0,670 32	0,674 30	0,678 43	0,682 71	0,687 16	0,691 78	0,696 58	0,701 57	0,706 74
860	0,662 55	0,665 76	0,669 26	0,672 87	0,676 61	0,680 47	0,684 46	0,688 59	0,692 86	0,697 28	0,701 85
880	0,662 14	0,665 09	0,668 28	0,671 57	0,674 95	0,678 45	0,682 04	0,685 75	0,689 57	0,693 51	0,697 56
900	0,661 74	0,664 44	0,667 36	0,670 36	0,673 44	0,676 61	0,679 86	0,683 20	0,686 64	0,690 16	0,693 78
920	0,661 34	0,663 82	0,666 50	0,669 24	0,672 05	0,674 93	0,677 88	0,680 91	0,684 00	0,687 17	0,690 42
940	0,660 95	0,663 23	0,665 69	0,668 20	0,670 77	0,673 39	0,676 08	0,678 82	0,681 63	0,684 49	0,687 42
960	0,660 56	0,662 67	0,664 92	0,667 23	0,669 58	0,671 98	0,674 42	0,676 92	0,679 47	0,682 06	0,684 71
980	0,660 18	0,662 12	0,664 20	0,666 31	0,668 47	0,670 67	0,672 90	0,675 18	0,677 50	0,679 86	0,682 26
1 000	0,659 81	0,661 59	0,663 51	0,665 46	0,667 44	0,669 45	0,671 50	0,673 58	0,675 70	0,677 85	0,680 03

Table C.20 — Coefficients C_{ij} , range, and deviation (steam/low temperature)

j	i					
	0	1	2	3	4	5
0	7,6383628636E-01	-1,3948809459E+00	-9,4682604528E-03	-1,6324349951E-02	-4,8136125911E-04	2,7472738708E-04
1	-2,5022686945E+02	3,0698113874E+03	2,5438748520E+02	-1,9835926887E+01	1,0308868889E+01	-1,2180337513E+00
2	2,2309865728E+05	-2,5007340159E+06	-4,3319430117E+05	6,8529295310E+04	-1,7185358070E+04	1,5839639878E+03
3	-8,3375219628E+07	8,9290286975E+08	2,5143120800E+08	-4,6235981182E+07	9,8380474046E+06	-8,1916664054E+05
4	1,1296847136E+10	-1,1698415314E+11	-4,8602570794E+10	9,4769242935E+09	-1,8812765934E+09	1,4882150791E+08

Parameters:

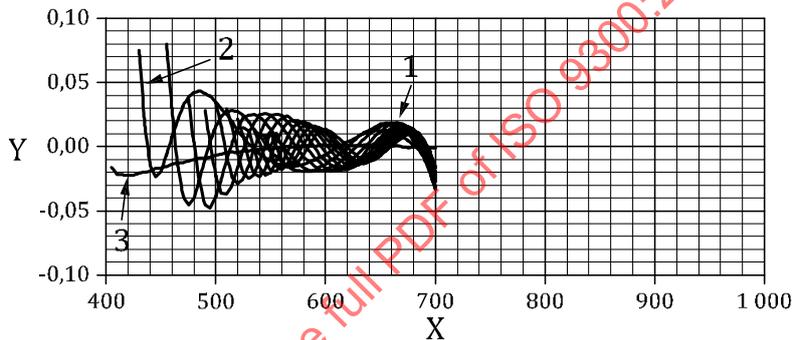
$T_{c^*} = 0$
 $C_{c^*} = -1$

Range:

$0,1 \text{ MPa} \leq p \leq 6 \text{ MPa}$
 Temperature range as below.

p MPa	Min. T K	Max. T K
0,1	405	700
0,5	430	
1	455	
1,5	475	
2	490	
2,5	500	
3	510	
3,5	520	
4	525	
4.5	535	
5	540	
5,5	545	
6	550	

Deviation from the REFPROP values:



Key

- X temperature (kelvin)
- Y deviation (%)
- 1 $p = 0,1 \text{ MPa}$ and $0,5 \text{ MPa} \sim 6 \text{ MPa}$ with $0,5 \text{ MPa}$ step, and $T = 405 \text{ K} \sim 700 \text{ K}$ with 5 K step
- 2 $0,1 \text{ MPa}$
- 3 $0,5 \text{ MPa}$

Table C.21 — Coefficients C_{ij} , range, and deviation (steam/high temperature)

j	i					
	0	1	2	3	4	5
0	6,0538184067E-01	4,4451919734E-03	-1,0552950714E-03	2,6192602318E-04	-3,0734451594E-05	1,6713260277E-06
1	2,5168685232E+00	-3,5787620199E-01	7,0538988170E-02	-1,7254081463E-02	2,0412362614E-03	-1,1177534079E-04
2	-4,5170447476E+01	1,0172762225E+01	-1,8680420538E+00	4,4732366508E-01	-5,3361463859E-02	2,9464670782E-03
3	4,2758519902E+02	-1,1602332503E+02	2,4357667835E+01	-5,7162905587E+00	6,8716465501E-01	-3,8321292332E-02
4	-2,0807195140E+03	6,3131772787E+02	-1,5405400890E+02	3,6119701698E+01	-4,3706355366E+00	2,4653199971E-01
5	4,1081046567E+03	-1,3597740602E+03	3,8149828437E+02	-9,0450567417E+01	1,1028054833E+01	-6,2965180441E-01

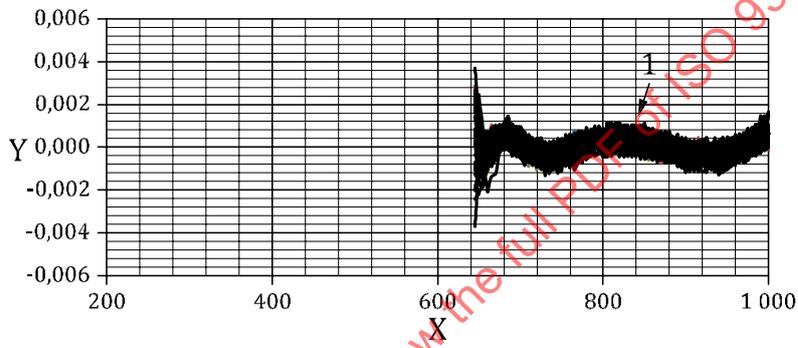
Parameters:

$T_{c^*} = 583$
 $C_{c^*} = -0,5$

Range:

$0,1 \text{ MPa} \leq p \leq 6 \text{ MPa}$
 $645 \text{ K} \leq T \leq 1000 \text{ K}$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}, 0,5 \text{ MPa} \sim 17 \text{ MPa}/0,5 \text{ MPa step}$, and $T = 645 \text{ K} \sim 1000 \text{ K}/5 \text{ K step}$

Annex D (informative)

Computation of critical mass flux for critical flow nozzles with high nozzle throat to upstream pipe diameter ratio, $\beta > 0,25$

D.1 General

A pressure tapping is used to measure the static pressure, i.e. the pressure of the moving gas; however, a temperature sensor fixed on the pipe measures the temperature of the gas when it is in rest owing to the viscosity of the gas, recording a temperature, T_m , that is neither the stagnation temperature T_0 nor the static temperature T . The relationship between the temperatures is given by the recovery factor depending on the gas, probe form, and flow Formula (D.1);

$$R_f = \frac{T_m - T}{T_0 - T} \quad (\text{D.1})$$

For R_f , a value of zero means that the probe is measuring the static temperature T , whilst a value of 1 means it is the stagnation temperature T_0 being measured. $R_f=0$ and 1 correspond to the temperature boundary layers whose thicknesses are infinite and equal to that of the velocity boundary layer thickness, respectively. In practice, R_f is generally in the range 0,5 to 0,9, which implies that the measured temperature is closer to the stagnation temperature than the static temperature.

D.2 Correction factors

IMPORTANT — At the time of drafting this Annex, the correction factors for natural gas mixtures had not been established. See References [36] to [39]. If a correction factor for a natural gas mixture is required, then that for methane is a reasonable estimate and should be used.

NOTE It is not recommended to measure flow rate using CFNs if the flow velocity in the upstream pipe is high because there will be significant error in the static pressure measurement, and also the error caused by the ambiguity of the correction factors (see Annex J) will be significant. This annex should only be applied only to estimate the flow rate when the diameter of the upstream pipe is unavoidably small.

The following correction factor is applicable to nitrogen, argon, dry CO₂-free air and methane. The valid temperature and pressure range is 250 K – 600 K (270 K – 600 K for methane) and up to 20 MPa. The correction is valid for β values from 0,25 to 0,5.

The mass flow through a nozzle with a high β (0,15 to 0,5), $q_{m,\beta}$, for a given inlet measured temperature, T_m (K), and pressure p_m (MPa), can be calculated from Formula (D.2);

$$q_{m,\beta} = q_{m,\text{stag}} [(1 - R_f)F_0 + R_f F_1] \quad (\text{D.2})$$

where

$q_{m,\text{stag}}$ is the mass flow rate as calculated using Annex C;

R_f is the temperature probe recovery factor.

The correction factors, F_0 and F_1 take the form Formula (D.3);

$$F_i = 1 + B \cdot C_i \tag{D.3}$$

where

$$B = 25,879 \beta^6 - 32,693 \beta^5 + 34,276 \beta^4 - 6,019 \beta^3 + 1,115 \beta^2 - 0,112 \beta + 0,004 \tag{D.4}$$

and

$$C_i = \sum_k n_{i,k} \pi^{p_{i,k}} \tau^{t_{i,k}} \tag{D.5}$$

The coefficients for Formula (D.5) are given in Tables D.1 to D.4. For the critical parameters required to obtain the reduced pressure and temperature, π and τ .

See Reference [41].

Table D.1 — Coefficients for Formula (D.5) for nitrogen

i	k	$n_{i,k}$	$p_{i,k}$	$t_{i,k}$
0	1	$1,304\ 619 \times 10^{-2}$	0	0
	2	$-3,666\ 323 \times 10^{-5}$	0	1
	3	$-3,668\ 820 \times 10^{-3}$	0,5	-5
	4	$5,024\ 075 \times 10^{-4}$	1	-1
	5	$2,846\ 962 \times 10^{-3}$	2	-6
	6	$-7,569\ 285 \times 10^{-4}$	3	-8
1	1	$1,516\ 890 \times 10^{-2}$	0	0
	2	$-2,433\ 804 \times 10^{-5}$	0	1
	3	$-3,755\ 322 \times 10^{-3}$	1	-3
	4	$4,068\ 331 \times 10^{-3}$	1	-2
	5	$9,540\ 179 \times 10^{-3}$	1,5	-6
	6	$-4,828\ 687 \times 10^{-6}$	5	-6

Table D.2 — Coefficients for Formula (D.5) for argon

<i>i</i>	<i>k</i>	$n_{i,k}$	$p_{i,k}$	$t_{i,k}$
0	1	$1,359\ 113 \times 10^{-2}$	0	0
	2	$5,072\ 601 \times 10^{-4}$	1	-1
	3	$5,776\ 326 \times 10^{-4}$	2	-4
	4	$4,625\ 040 \times 10^{-4}$	3	-10
	5	$-3,001\ 709 \times 10^{-7}$	6	-4
1	1	$1,702\ 515 \times 10^{-2}$	0	0
	2	$3,255\ 007 \times 10^{-3}$	1	-2
	3	$2,029\ 543 \times 10^{-4}$	1	-1
	4	$6,931\ 127 \times 10^{-3}$	2	-6
	5	$-1,846\ 055 \times 10^{-4}$	4	-6

Table D.3 — Coefficients for Formula (D.5) for dry CO₂-free air

<i>i</i>	<i>k</i>	$n_{i,k}$	$p_{i,k}$	$t_{i,k}$
0	1	$1,307\ 864 \times 10^{-2}$	0	0
	2	$-4,752\ 544 \times 10^{-5}$	0	1
	3	$1,760\ 268 \times 10^{-2}$	0,5	-6
	4	$-1,340\ 098 \times 10^{-2}$	0,5	-5
	5	$4,672\ 622 \times 10^{-4}$	1	-1
	6	$1,294\ 203 \times 10^{-3}$	1,5	-4
1	1	$1,522\ 775 \times 10^{-2}$	0	0
	2	$-4,726\ 879 \times 10^{-5}$	0	1
	3	$-5,958\ 875 \times 10^{-3}$	1	-4
	4	$3,445\ 387 \times 10^{-3}$	1	-2
	5	$1,256\ 916 \times 10^{-2}$	1,5	-6
	6	$-4,775\ 091 \times 10^{-5}$	4	-6

Table D.4 — Coefficients for Formula (D.5) for methane

<i>i</i>	<i>k</i>	$n_{i,k}$	$p_{i,k}$	$t_{i,k}$
0	1	$1,068\,826 \times 10^{-3}$	0	-1
	2	$1,199\,593 \times 10^{-2}$	0	0
	3	$-1,482\,920 \times 10^{-3}$	0,5	-6
	4	$2,764\,799 \times 10^{-4}$	1	-1
	5	$7,920\,711 \times 10^{-5}$	2	-2
	6	$1,111\,278 \times 10^{-3}$	3	-8
	7	$-6,815\,626 \times 10^{-5}$	5	-10
	8	$3,862\,490 \times 10^{-8}$	10	-18
1	1	$-3,463\,148 \times 10^{-3}$	0	-3
	2	$5,286\,029 \times 10^{-3}$	0	-1
	3	$1,195\,016 \times 10^{-2}$	0	0
	4	$1,664\,232 \times 10^{-3}$	1	-2
	5	$1,159\,371 \times 10^{-3}$	1,5	-4
	6	$7,260\,461 \times 10^{-3}$	3	-10
	7	$-7,541\,933 \times 10^{-4}$	5	-12
	8	$2,613\,967 \times 10^{-7}$	10	-15

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Annex E (informative)

Diameter correction method

E.1 General

The diameter correction method (DCM) is to put the discharge coefficient curve in a convenient range or to match it on a reference/target curve based on a calibration result at a single Reynolds number. It modifies the throat diameter without affecting on the calculation result of mass flow rate. For example, a CFN complying with this document should have the discharge coefficient curve expressed by Formula (17) with the coefficients in Table 1; however, a flow calibration of the CFN sometimes results in a discharge coefficient curve that is significantly deviated from the equation, which is mostly caused by the error in throat diameter and the DCM corrects it. It is noted that some tiny structure formed at the throat - such as a small projection immersed in the boundary layer - may not have any effect on the flow field, but it may have an effect on the throat diameter measurement; as a result, the flow calibration may result in a significantly large offset of discharge coefficient curve if the CFN is small.

Since the DCM replaces the role of throat diameter by a calibration result, the value of throat diameter to be used at the calibration is no longer necessary to be accurate, thus a nominal value or even a visually assessed value can be used during the calibration.

Although the throat diameter appears in the equation of mass flow rate superficially, it actually does not have any effect on the calculation result of mass flow rate if the discharge coefficient curve was obtained by flow calibration. That is because the curve implicitly contains the inverse of square of throat diameter that is cancelled out when calculating the mass flow rate, therefore, the only thing that is important for the throat diameter is to use the same value at both the calibration and application. Consequently, when calibrating the CFN, the discharge coefficient curve can be shifted to anywhere on the Y-axis by modifying the throat diameter.

It is noted that the throat diameter is still one of the most important parameters if the flow rate measurement is based on dry calibration, which is the main purpose of this document.

Except for applying on pooled historical data, the DCM should be applied at the beginning of calibration and, from that point onwards, the calibration shall use the corrected throat diameter, d_{DCM}

E.2 Procedures

E.2.1 Overview

There are three ways to apply the DCM. If possible, the visual procedure is recommended because it automatically contains all the corrections necessary for the DCM and, thus, can achieve the highest accuracy, although the procedure is very simple.

The calibration Reynolds number for the DCM shall not be in, or in the vicinity of, the transition regime because the behaviour of CFN in it may be unstable.

E.2.2 Visual procedure

If the calibration software can be modified to include a routine to calculate the target discharge coefficient, and if all the calculation results can immediately respond to the change of throat diameter, the visual procedure is recommended.

- a) Make the calibration software calculate the target discharge coefficient at the calibration condition.
- b) Make the calibration software display the deviation of discharge coefficient obtained by the calibration from the reference curve.
- c) Make the calibration software recalculate all the results if the throat diameter is changed.
- d) Continue changing the throat diameter until the resultant discharge coefficient reaches the reference curve. Denote the final value of throat diameter by d_{DCM} .
- e) Continue the calibration using d_{DCM} .
- f) In the application, use d_{DCM} .

This procedure can be applied also to the pooled historical calibration data set obtained in the past if all of the calculations are active.

E.2.3 Coarse procedure

If it is not necessary for the shifted discharge coefficient curve to pass exactly through the target value, the coarse procedure is applicable. Although the Reynolds number is shifted by the correction of throat diameter, this procedure does not compensate for it; therefore, the shifted discharge coefficient curve does not pass through the target, but near it. The procedure is suitable to locate the curve in the convenient range.

It is not recommended to perform the calibration for DCM at low Reynolds number because of the high sensitivity of discharge with the Reynolds number, which may result in a significant shift of the curve from the target even by a slight correction in the throat diameter.

Denote the target value of discharge coefficient at the calibration Reynolds number by C_d^{target} .

- a) Calibrate the CFN at the Reynolds number using the given throat diameter d_{ORI} . Denote the resultant discharge coefficient by C_d^{ORI} .
- b) Calculate the coarsely corrected throat diameter d_{DCM} by Formula (E.1);

$$d_{\text{DCM}} = d_{\text{ORI}} \sqrt{\frac{C_d^{\text{ORI}}}{C_d^{\text{target}}}} \quad (\text{E.1})$$

- c) Continue the calibration using d_{DCM} .
- d) In the application, use d_{DCM} .

E.2.4 Fine procedure

This procedure compensates for the effect of shifted Reynolds number by the correction of throat diameter based on the supposed Reynolds number dependence. It requires iterative calculation, but if

the sensitivity of discharge coefficient curve against the Reynolds number is similar to or smaller than that of Formula (17), with the coefficients in Table 1, a single iteration should be sufficient in most cases (see Figure E.1).

Several hundred percent error in the given throat diameter does not affect significantly on the resultant discharge coefficient curves even by the single iteration. However, it is recommended not to perform the calibration for DCM at low Reynolds number by the same reason as in E.2.3.

Suppose that the target discharge coefficient curve is expressed by a function f , as given by Formula (E.2);

$$C_d^{\text{target}} = f(Re) \quad (\text{E.2})$$

If the CFN is complying with this document, f should be Formula (17) with the coefficients in Table 1.

- a) Calibrate the CFN at a Reynolds number Re^{ORI} using the given throat diameter d_{ORI} . Denote the measured discharge coefficient by C_d^{ORI} . C_d^{ORI} and Re^{ORI} should be calculated in accordance with this document using d_{ORI} thus by Formulae (E.3) and (E.4);

$$C_d^{\text{ORI}} = \frac{q_m}{\left(\frac{\pi d_{\text{ORI}}^2}{4}\right) C^* \frac{p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}}} \quad (\text{E.3})$$

$$Re^{\text{ORI}} = \frac{4q_m}{\pi \mu_0} \frac{1}{d_{\text{ORI}}} \quad (\text{E.4})$$

where q_m is the mass flow rate of CFN measured by the calibration facility.

- b) Calculate the base target discharge coefficient C_d^{target0} at Re^{ORI} by Formula (E.5);

$$C_d^{\text{target0}} = f(Re^{\text{ORI}}) \quad (\text{E.5})$$

- c) Calculated the base corrected throat diameter d_{DCM0} by Formula (E.6);

$$d_{\text{DCM0}} = d_{\text{ORI}} \sqrt{\frac{C_d^{\text{ORI}}}{C_d^{\text{target0}}}} \quad (\text{E.6})$$

- d) Calculate the corrected Reynolds number Re^{target} by Formula (E.7);

$$Re^{\text{target}} = Re^{\text{ORI}} \frac{d_{\text{ORI}}}{d_{\text{DCM0}}} \quad (\text{E.7})$$

- e) Calculate the target discharge coefficient C_d^{target} at Re^{target} by Formula (E.8);

$$C_d^{\text{target}} = f(Re^{\text{target}}) \quad (\text{E.8})$$

f) Calculate the corrected throat diameter d_{DCM} by Formula (E.9) or (E.10);

$$d_{DCM} = d_{ORI} \sqrt{\frac{C_d^{ORI}}{C_d^{target}}} \tag{E.9}$$

or

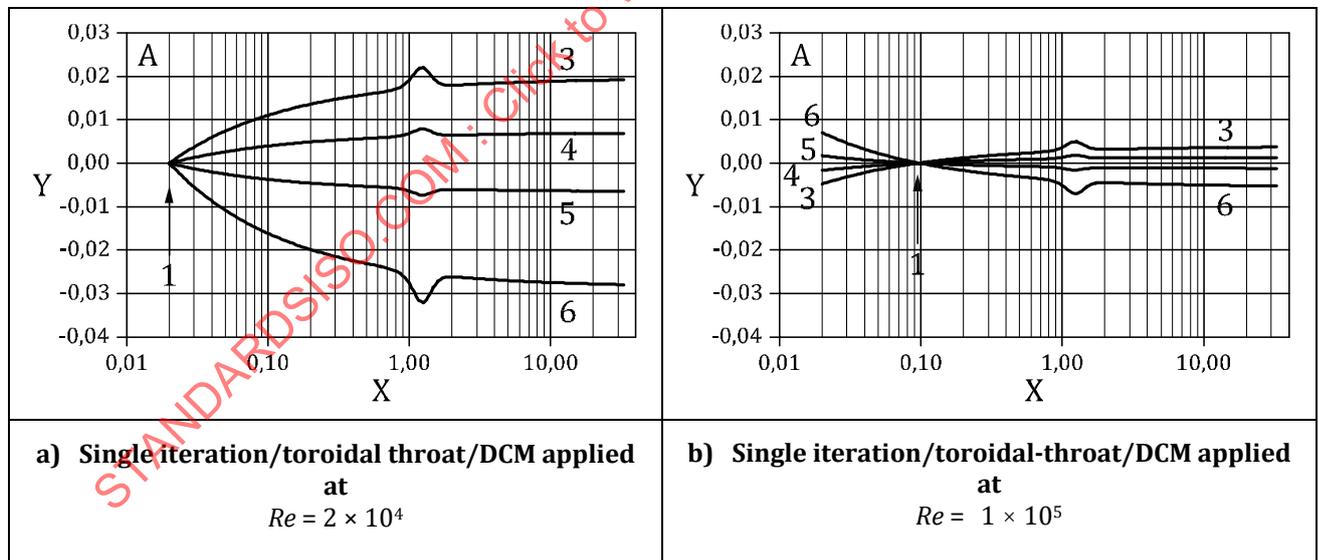
$$d_{DCM} = d_{DMCO} \sqrt{\frac{C_d^{target0}}{C_d^{target}}} \tag{E.10}$$

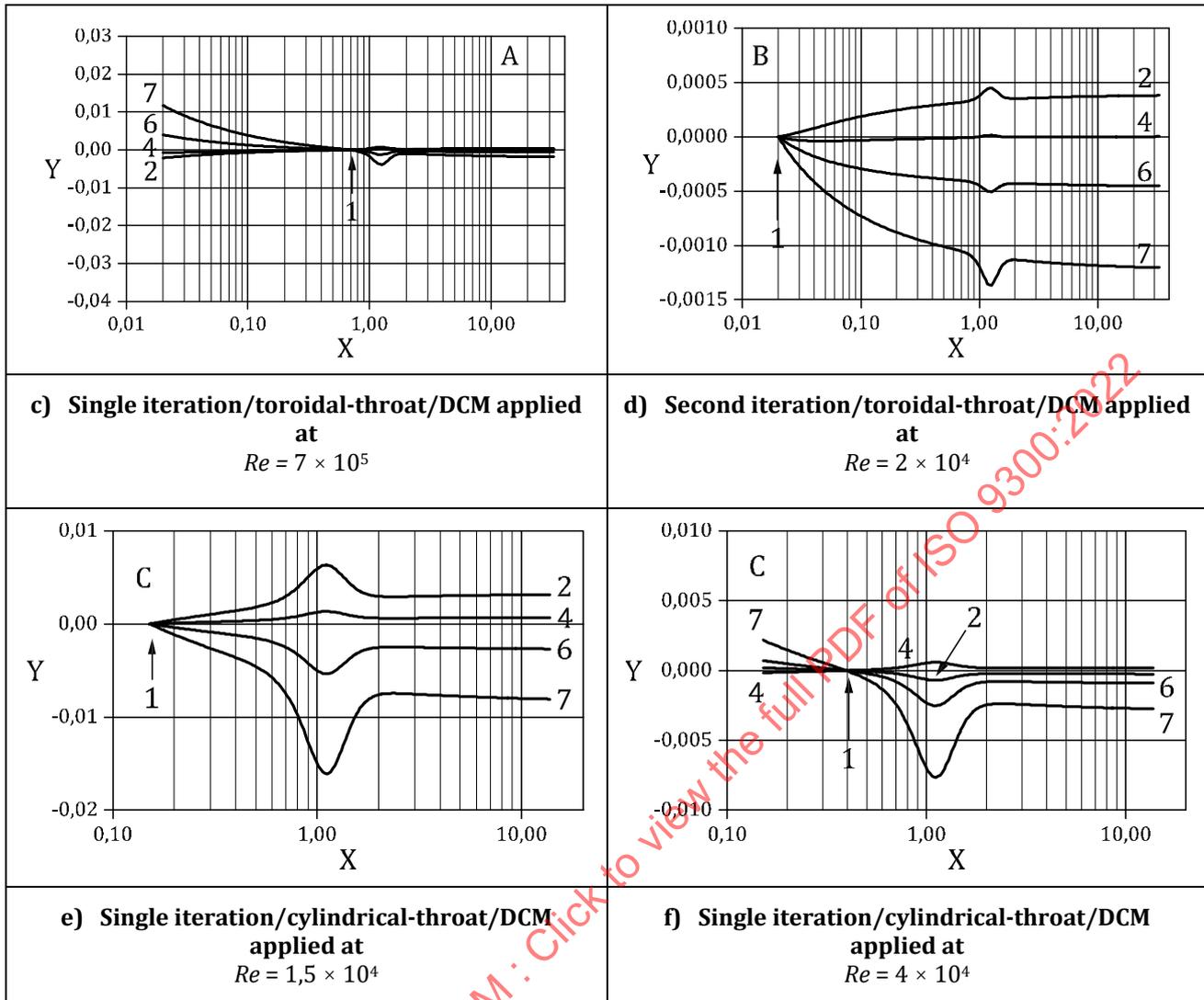
g) Continue the flow calibration using d_{DCM} .

h) In the application, use $f(Re)$ and d_{DCM} .

Further iteration is possible by substituting Re^{target} for Re^{ORI} Formula (E.5); however, the single iteration, i.e., Formula (E.9) or (E.10), should be sufficiently accurate in most cases if the sensitivity of discharge coefficient against the Reynolds number is similar to or smaller than Formula (17), with the coefficients in Table 1.

Examples of the deviations of resultant curves from the target one are shown in Figure E.1, provided that the CFN complies with this document and the target curve is expressed by Formula (17) with the coefficients in Table 1.





Key

- X Reynolds number, $Re (\times 10^6)$
- Y deviation (%) from Formula (17)
- 1 DCM applied point
- 2 -80 % error in d_{nt}
- 3 -50 % error in d_{nt}
- 4 -20 % error in d_{nt}
- 5 +20 % error in d_{nt}
- 6 +100 % error in d_{nt}
- 7 +400 % error in d_{nt}

Figure E.1 — Error in the fine procedure applied on the CFN complying with this document

Annex F (informative)

Adjustment of discharge coefficient curve on a data set

F.1 General

Formula (17) can be fitted on any of data sets of discharge coefficients of typical CFNs regardless of the type. This Annex describes a way to fit the curve on a data set.

The coefficients in Formula (17) are to be adjusted using Formula (F.1), which has an extra parameter g . It transforms into Formula (17) by Formulae (F.2) and (F.3);

$$C_d = (a - bRe^{-n}) \frac{g(c_{adj} - d_{adj}Re^{-n})}{1 + \exp\left(e - \frac{Re}{f}\right)} \quad (F.1)$$

$$c = gc_{adj} \quad (F.2)$$

$$d = gd_{adj} \quad (F.3)$$

The effects of each coefficient in Formula (F.1) are summarized in Table F.1.

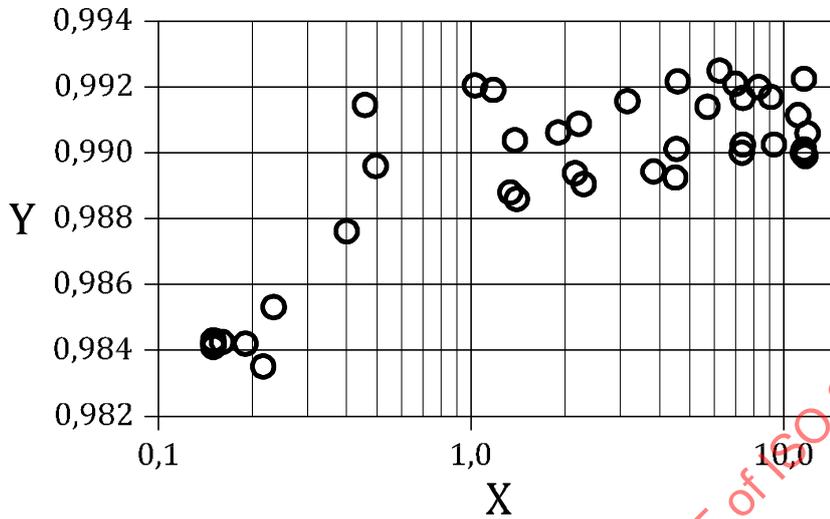
Table F.1 — Effects of coefficients in Formula (F.1)

Coefficient	Effect	Explanation
a, b	Shape of the laminar curve.	$(a - bRe^{-n})$ defines the laminar curve, thus a is for the core flow distribution and b is for the laminar boundary layer.
c_{adj}, d_{adj}	Tendency in the turbulent regime.	$(c_{adj} - d_{adj}Re^{-n})$ defines the tendency of the deviation of the turbulent curve from the laminar one.
g	Jump height at the transition	Larger g makes the jump larger.
e	Jump steepness.	Larger e makes the jump steeper.
f	Jump location.	Larger f makes the transition at higher Reynolds number.
n	Tendency of the curve.	Larger n makes the curve steeper.

n can be set at individual values, e.g., 0,5 and 0,2 for the laminar and turbulent regimes, respectively; however, 0,5 should work fine for the whole range as shown below.

F.2 Fitting procedure

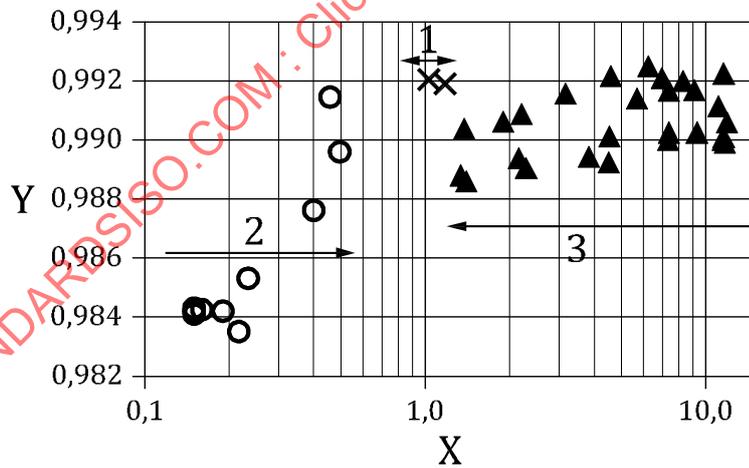
a) Figure F.1 is a sample data set from a toroidal throat CFN, on which the curve is to be fitted.



Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient

Figure F.1 — Typical data set on which the curve is fitted

b) The data points in Figure F.1 are visually categorized into the laminar and turbulent regions. If necessary, the transition region can be considered as in the figure.



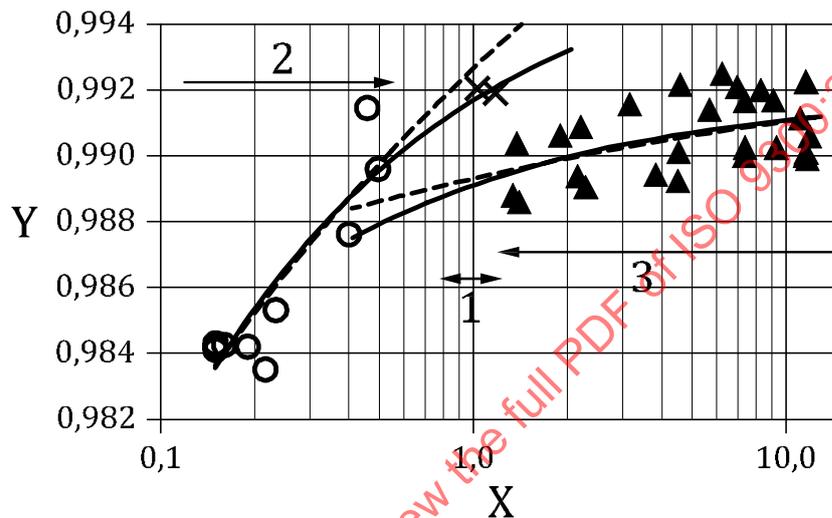
Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient
 1 transition region
 2 laminar region
 3 turbulent region

Figure F.2 — Visual categorization into the laminar, transition, and turbulent regimes

- c) As shown in Figure F.3, the data in the laminar and turbulent regions are individually fitted by the traditional equation for C_d expressed by Formula (F.1);

$$C_d = a_{\text{trad}} - b_{\text{trad}} Re^{-n} \quad (\text{F.1})$$

using a preferred n , that may be theoretically 0,5 and 0,2 in the laminar and turbulent regions, respectively. However, they will produce insignificant differences in the turbulent regime whereas significant ones at higher Reynolds numbers in the laminar regimes as seen in the figure, therefore, 0,5 is recommended to use for the whole range of the Reynolds number for simplicity. This Annex uses $n = 0,5$ in the whole range.

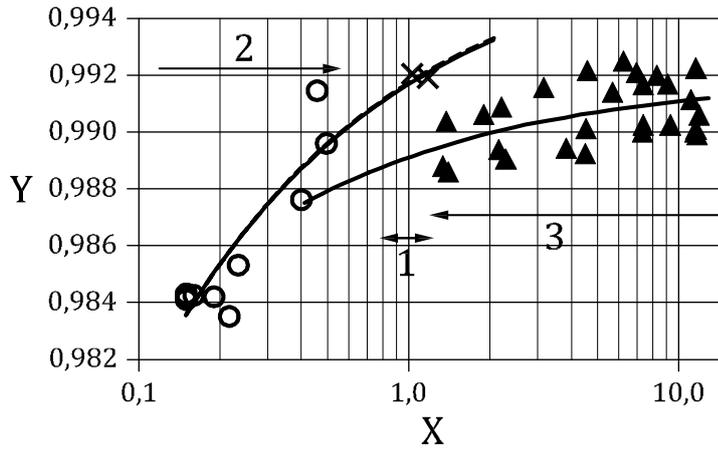


Key

- X Reynolds number, Re ($\times 10^6$)
- Y discharge coefficient
- 1 transition region
- 2 laminar region
- 3 turbulent region
- $n = 0,2$ fit
- $n = 0,5$ fit

Figure F.3 — Fittings on the traditional C_d equation individually in the laminar and turbulent regimes

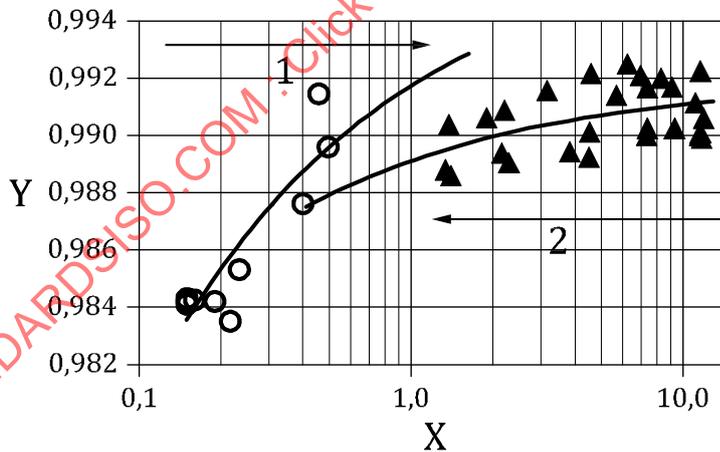
Choosing $n = 0,5$, the curve in the laminar regime is almost identical even when the transition data are included as seen in Figure F.4, thus it was not necessary in this data set to exclude the transition data from the laminar data.



- Key**
- X Reynolds number, $Re (\times 10^6)$
 - Y discharge coefficient
 - 1 transition region
 - 2 laminar region
 - 3 turbulent region
 - including transition data ($n = 0,5$ fit)
 - excluding transition data ($n = 0,5$ fit)

Figure F.4 — Fittings on the traditional C_d equation with $n=0,5$

Finally, the two curves pertaining to each regime, on which Formula (F.1) is to be adjusted, are obtained as in Figure F.5. The values of the coefficients for the laminar curve are shown in Table F.2. Those for the turbulent curve are not used in the following, but its curve is referred to when adjusting the equation.



- Key**
- X Reynolds number, $Re (\times 10^6)$
 - Y discharge coefficient
 - 1 laminar region ($n = 0,5$ fit)
 - 2 turbulent region ($n = 0,5$ fit)

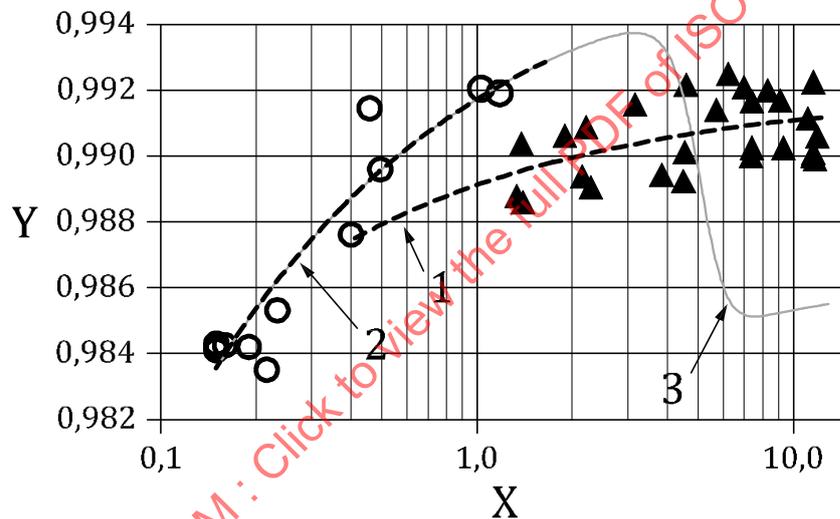
Figure F.5 — Two curves acting as basis of the adjustment bases

Table F.2 — Coefficients a_{trad} and b_{trad} for the laminar curve in Figure F.5

Coefficient	Laminar regime
a_{trad}	0,9969
b_{trad}	5,163

- d) Substitute a_{trad} and b_{trad} for a and b of Formula (F.1), and also for c_{adj} and d_{adj} , respectively. Put the typical values into g , e , and f , e.g., 0,01, 10, and 5×10^5 , respectively. The equation is now expressed by Formula (F.4) and shown in Figure F.6.

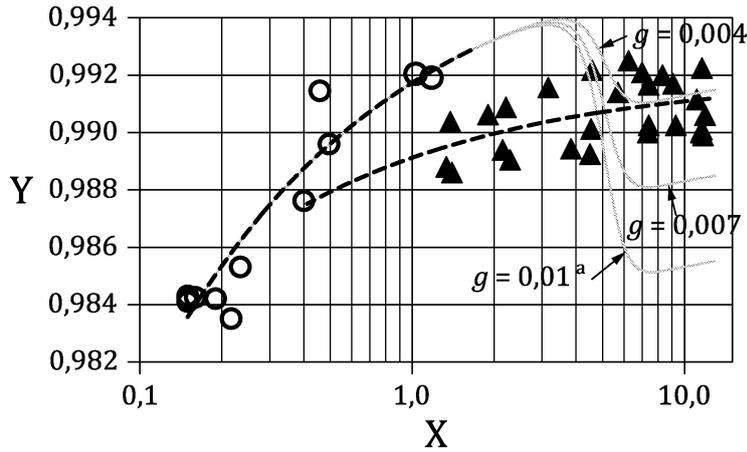
$$C_d = \left(0,9969 - \frac{5,163}{\sqrt{Re}}\right) \frac{0,01 \left(0,9969 - \frac{5,163}{\sqrt{Re}}\right)}{1 + \exp\left(10 - \frac{Re}{5 \times 10^5}\right)} \quad (\text{F.4})$$

**Key**

- X Reynolds number, Re ($\times 10^6$)
Y discharge coefficient
1 turbulent curve
2 laminar curve
3 curve by Formula (F.4)

Figure F.6 — Initial curve using the coefficients for the laminar curve and typical values for the other coefficients

- e) Adjust g to match the curve in the turbulent regime on the turbulent curve as in Figure F.7. Fine adjustment is not necessary here because the following adjustments will change the tendency slightly, therefore, g is re-adjusted later. $g = 0,004$ is fine in this stage. The adjusted equation is now expressed by Formula (F.5).

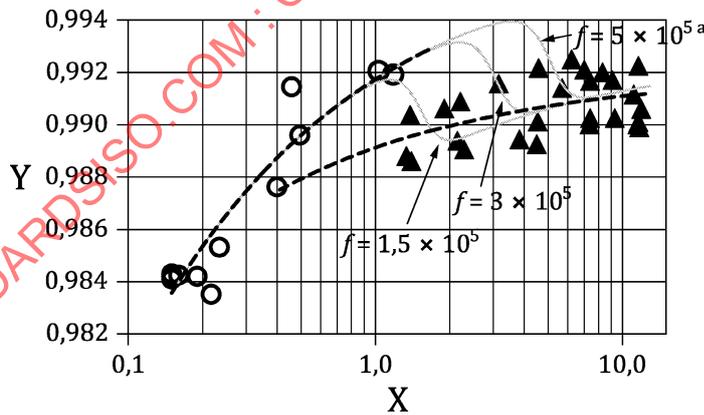


Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient
^a Base line.

Figure F.7 — Adjustment of the jump height

$$C_d = \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right) - \frac{0,004 \left(0,9969 - \frac{5,162}{\sqrt{Re}} \right)}{1 + \exp \left(10 - \frac{Re}{5 \times 10^5} \right)} \tag{F.5}$$

f) Adjust f to locate the jump location around the supposed transition Reynolds number as in Figure F.8. f is re-adjusted later, therefore, $f = 1,5 \times 10^5$ is fine at this stage. The adjusted equation is now expressed by Formula (F.6).

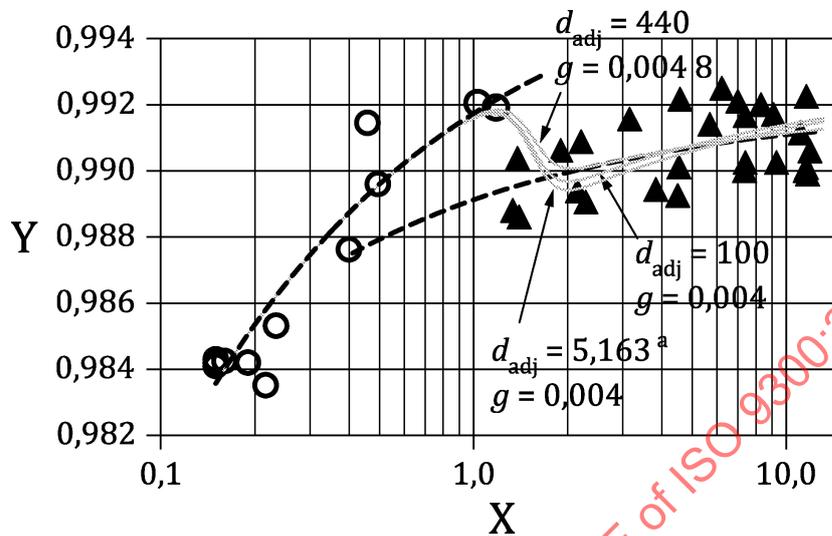


Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient
^a Base line.

Figure F.8 — Adjustment of the transition Reynolds number

$$C_d = \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right) - \frac{0,01 \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right)}{1 + \exp \left(10 - \frac{Re}{1,5 \times 10^5} \right)} \tag{F.6}$$

- g) Adjust both d and g to let the curve in the turbulent regime match on the turbulent curve as in Figure F.9. $d_{adj} = 440$ and $g = 0,0048$ are fine in this stage. The adjusted equation is now expressed by Formula (F.7).



Key

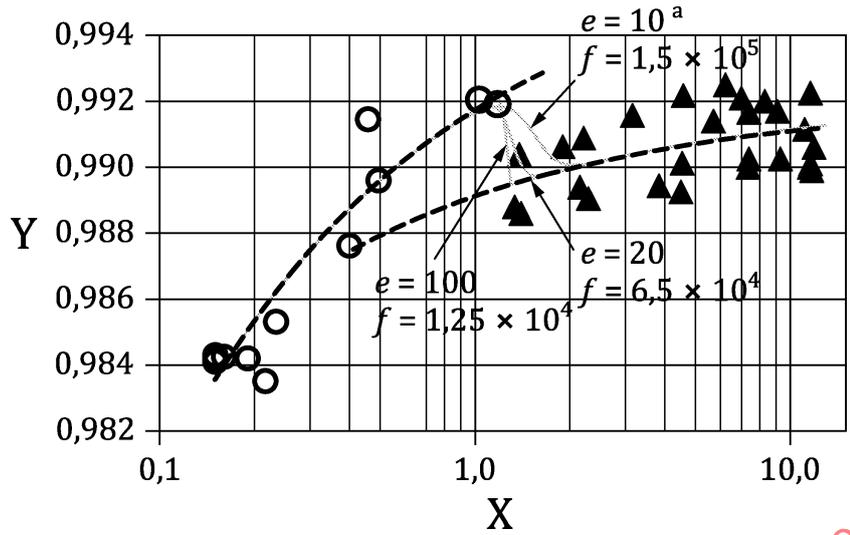
- X Reynolds number, Re ($\times 10^6$)
- Y discharge coefficient
- ^a Base line.

Figure F.9 — Adjustment of the tendency in the turbulent regime

$$C_d = \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right) - \frac{0,0048 \left(0,9969 - \frac{440}{\sqrt{Re}} \right)}{1 + \exp \left(10 - \frac{Re}{1,5 \times 10^5} \right)} \quad (F.7)$$

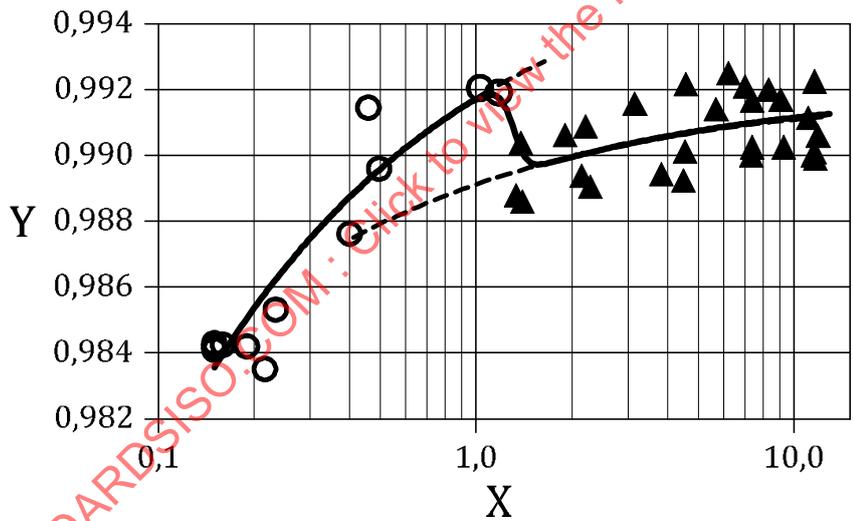
- h) Finally, adjust both e and f so that the jump occurs at the supposed location at the supposed steepness. Examples of some adjustments are shown in Figure F.10. The adjusted equation, e.g. using $e = 20$ and $f = 6,5 \times 10^4$ is now expressed by Formula (F.8) and shown in Figure F.11.

$$C_d = \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right) - \frac{0,0048 \left(0,9969 - \frac{440}{\sqrt{Re}} \right)}{1 + \exp \left(10 - \frac{Re}{6,5 \times 10^4} \right)} = \left(0,9969 - \frac{5,163}{\sqrt{Re}} \right) - \frac{\left(0,0048 - \frac{2,11}{\sqrt{Re}} \right)}{1 + \exp \left(10 - \frac{Re}{6,5 \times 10^4} \right)} \quad (F.8)$$



Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient
^a Base line.

Figure F.10 — Adjustment of the jump steepness



Key
 X Reynolds number, $Re (\times 10^6)$
 Y discharge coefficient

Figure F.11 — Curve by Formula (F.8)

Annex G (informative)

Discharge coefficient

G.1 General

Discharge coefficient compensates for the effect of distortion of flow field at the critical point from the flat distribution, which the theoretical flow rate assumes. In the flat distribution, it is assumed that the flow direction over the cross section is parallel to the AOS of the CFN exactly from wall-to-wall and the flow velocity is constant and equal to the critical velocity^{[55] to [89]}.

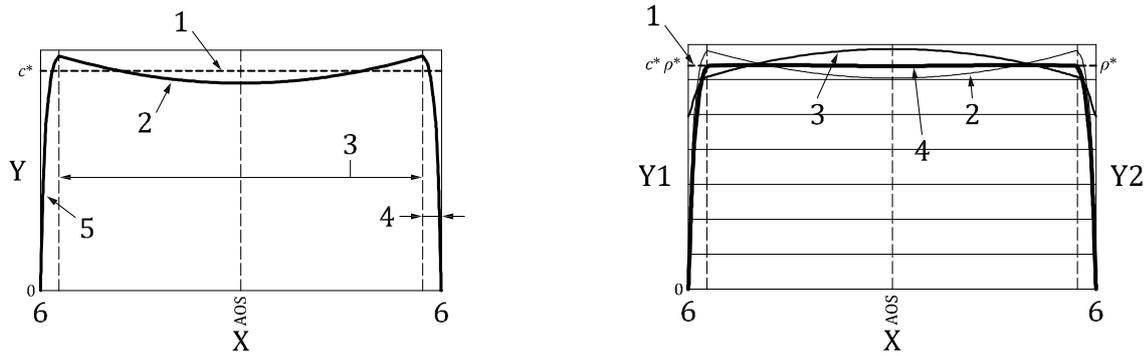
G.2 Flow field distribution along a diameter at the critical point

The distortion in the flow field at the critical point is caused by the momentum of flow and also by the viscosity of gas - even in an ideal CFN that complies completely with the specifications in Clause 8.

The momentum of flow makes the flow faster near the wall and slower in the centre because the acceleration is produced by the curved wall; thus, the nearer to the wall the flow is, the more it is accelerated.

On the other hand, the viscosity of gas decelerates the flow in the vicinity of the wall. In the range of gas conditions this document covers, the gas molecules touching a wall should adhere to it; therefore, the flow velocity at wall is zero and the flow along a diameter at the critical point increases very rapidly from zero to typically over 300 m/s at the edge of the boundary layer, whose thickness is typically in the order of several tens micrometres.

The portion where the flow is decelerated by the effect of viscosity is referred to as the "boundary layer", whereas the remaining portion - where the viscous effect is negligible - is the "core flow". The core flow can be dealt with as the isentropic flow. Being combined these distortions, the flow velocity distribution at the critical point along a diameter is as depicted in Figure G.1 a).



Key

- X position on a diameter at the critical point
- Y velocity
- 1 flat (1 D isentropic flow)
- 2 distortion by momentum
- 3 core flow
- 4 boundary layer
- 5 distortion by boundary layer

a) Velocity distribution

Key

- X position on a diameter at the critical point
- Y1 velocity × density
- Y2 density
- 1 flat (1 D isentropic flow)
- 2 velocity
- 3 density
- 4 velocity × density

b) Density and mass flux distributions

Figure G.1 — Flow velocity distribution along a diameter at the critical point

Since a faster velocity is accompanied with a lower pressure thus a higher density in the isentropic flow (see Formula (2)), the density distribution in the core is curved in the opposite sense compared with the velocity distribution as in Figure G.1 b). According to the boundary layer theory, the pressure in the boundary layer is kept constant in the direction perpendicular to the wall, thus the density distribution in it becomes as depicted in the figure. Finally, the mass flux, i.e., the product of flow velocity and density, by which the mass flow rate is calculated as its integral over the throat area, becomes almost flat in the core and rapidly decreases toward zero in the boundary layer as seen in the figure. Since the flow is axisymmetric, the distributions over the critical point are actually given by the surfaces formed when rotating the distributions in the figure about the AOS. The ratio of the volumes surrounded by the surfaces formed by the thick line in Figure G.1 b) to that by the flat broken line is the discharge coefficient.

The discharge coefficients specified in this document are valid only when the assumed distributions as in Figure G.1 are generated at the critical point. Since the distributions are effected by how the flow is accelerated and how large the surface friction is in the contraction (and also in the throat if it is cylindrical), the specifications in Clause 7 are required.

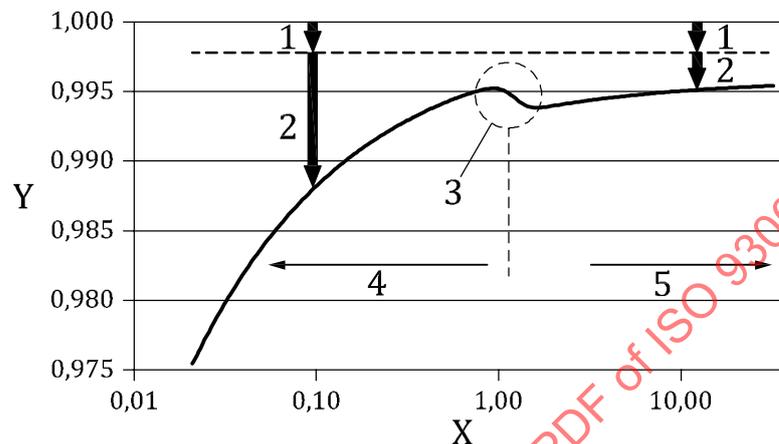
G.3 Reynolds number dependence of discharge coefficient

Momentum distortion: Because the cause of momentum distortion is the curved wall, it is inherent to the form of CFN from somewhere in the contraction to the critical point for each gas. The acceleration in the contraction is so quick that the histories of the flow impressed while flowing in the upstream conduit and inlet of contraction are almost gone, therefore, only the form in the vicinity of throat has an effect on the distortion. The location of the IP of the toroidal-throat CFN had been historically defined, and it was confirmed later that there was no effect observed on the mass flow rate depending on its upstream form^[73]. Since the acceleration caused by the pressure gradient depends on the isentropic exponent of the gas, the distortion also depends on the gas species. Generally speaking, the distortion in a specific gas does not depend on the Reynolds number.

Viscous distortion: The viscous distortion also depends on the CFN form because of the dependence of boundary layer growth on the surface form. It has a significant Reynolds number dependence because of that of the boundary layer thickness. Generally speaking, the larger the Reynolds number is, the

thinner the boundary layer is. The dependence on the Reynolds number is smaller in the turbulent boundary layer than in it is the laminar one.

Total distortion: Combined these two effects, the Reynolds number dependence is as depicted in Figure G.2. The boundary layer at the critical point becomes laminar or turbulent depending on the gas condition at the upstream stagnation. Because of the difference in the thicknesses between the laminar and turbulent boundary layers, a small jump is observed at the transition Reynolds number.



Key

- X Reynolds number, Re ($\times 10^6$)
- Y discharge coefficient
- 1 decrease by the momentum effect
- 2 decrease by the viscous effect
- 3 transition
- 4 laminar boundary layer
- 5 turbulent boundary layer

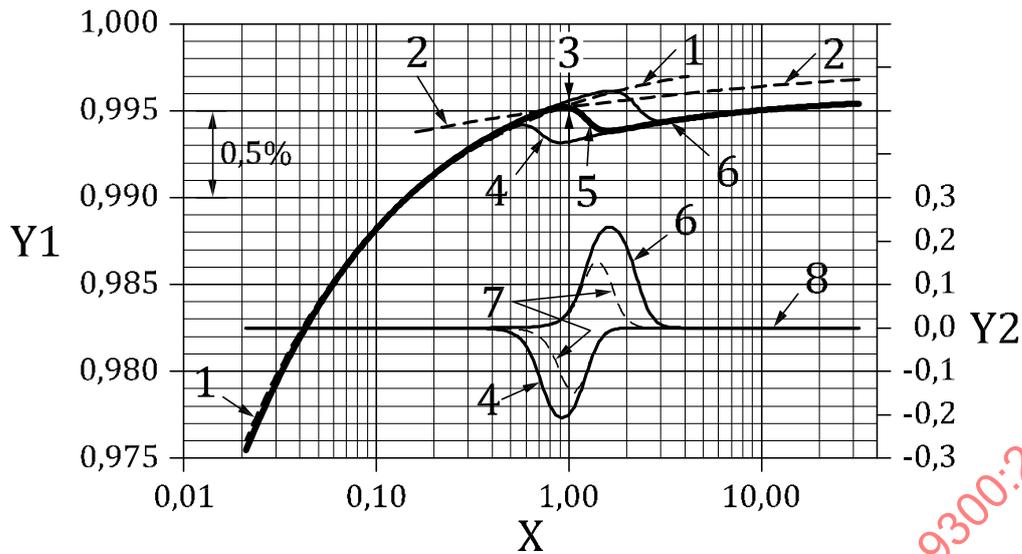
Figure G.2 — The Reynolds number dependence of discharge coefficient

G.4 Boundary layer transition

The transition from one to the other boundary layer takes place around a Reynolds number that may be specific to each CFN, but it is typically around 10^6 for the CFNs complying with this document.

The standard form of the toroidal-throat CFN, which has the inlet curvature of $r_c = 2d_{nt}$, was originally designed by Stratford^[60] to make the jump negligible. This was achieved by choosing the contraction curvature with which the theoretical boundary layer thicknesses at the expected transition Reynolds number (10^6) were almost identical as shown by the broken lines in Figure G.3. However, the actual turbulent curve is somewhat lower than expected by Stratford, so the jump in the standard CFN is normally from a higher to lower values across the transition when the Reynolds number is increased.

The transition Reynolds number may strongly depend on the CFN quality; for example, a rough surface and/or defects in the contraction may result in a low transition Reynolds number. In some CFNs, the transition may occur at 2×10^6 for unknown reasons, which should be however very rare. Furthermore, the transition Reynolds number may vary over time - even in a specific CFN, in which the variation may be caused by contamination on the contraction surface; however, the transition should be repeatable if the surface condition is kept the same. Even if the transition Reynolds number in a specific CFN varies for some reason, the discharge coefficient may trace the laminar or turbulent curve as shown in Figure G.3^[81].



- Key**
- X Reynolds number, $Re (\times 10^6)$
 - Y1 discharge coefficient
 - Y2 deviation (%) from Formula (17)
 - 1 Stratford laminar curve
 - 2 Stratford turbulent curve
 - 3 theoretically expected jump
 - 4 low Re jump
 - 5 curve by Formula (17)
 - 6 high Re jump
 - 7 middle Re jump
 - 8 deviation (%)

Figure G.3 — Typical boundary layer transitions in the toroidal-throat CFNs and theoretical curves by Stratford

As shown in Figure G.3, the difference of the transition Reynolds number may result in deviations beyond 0,2 % from Formula (17) with the coefficients in Table 1; accordingly, it is recommended not to use the CFNs in the transition regime, which may be from $0,5 \times 10^6$ to 3×10^6 including some safe margin, especially if periodic surface inspections together with prior transition measurements are not available.

To avoid the Reynolds numbers in the transition regime, multiple CFNs connected in parallel, e.g., the chamber configuration and parallel connection of multiple pipe configurations, may be used (as discussed in Annex J). It can achieve the required flow rate in total by summing all the flows through each CFNs that are kept at low Reynolds numbers.

G.5 Discharge coefficient curves

The coefficients in Table 1 were derived by the method in Annex F using the experimental and theoretical data reviewed in Reference [71] as well as the experimental data from References [72] to [80] for the toroidal-throat CFN, and References [87] to [90] for the cylindrical-throat CFN.

The laminar and turbulent curves in Formula (17) with the coefficients in Table 1 for the toroidal-throat CFN are identical to the curves for accurately machined nozzle (HPN) and normally machined nozzle (NPN) in the former version of this document, respectively.

The toroidal-throat CFN was originally proposed to make it possible to calculate the flow rate analytically at high accuracy in the era when no calibration facility existed and no effective numerical

calculation had been established. Consequently, it is possible to calculate the discharge coefficient curve of toroidal-throat CFNs analytically and it agrees very well with the laminar boundary layer curve in Formula (17) with the coefficients in Table 1^{[59]-[61][70][101][102]}. The theoretical verifications were also performed and the curve was re-confirmed by numerical calculations^[68].

The discharge coefficients obtained by flow calibrations of HPNs showed that their discharge coefficients distributed around Formula (17) mostly within $\pm 0,05$ %, as well as the NPNs if the DCM was applied, provided the throat was toroidal. Their transition curves also followed the path given by Formula (17); the transition mostly started and ended between $0,8 \times 10^6$ and $1,5 \times 10^6$. There was only one HPN found that traced the high transition path in Figure G.3. Putting artificial roughness on the contraction resulted in paths between the low and typical transitions in Figure G.3^[81].

It was confirmed that the form downstream of the critical point does not have any effect on the discharge coefficient even in the transition regime^[80]: that is, the quadrant CFNs and also CFNs with very short diffuser of about $0,3 \cdot 1d_{nt}$ length both with and without a detachable diffuser (see Figure J.2) followed the trend given by Formula (17).

G.6 Obtaining discharge coefficient curve

If the CFN complies with the specifications in Clause 8, and the throat diameter is given at low uncertainty, its discharge coefficients should be given by Formula (17) with the coefficients in Table 1 at low uncertainty.

If the CFN complies with the specifications in Clause 8, but the throat diameter may have a significant uncertainty, its discharge coefficient should be given by Formula (17) with the coefficients in Table 1 at low uncertainty by applying the DCM.

If the CFN may not comply with the specifications in Clause 8 or the gas may have a significant vibrational relaxation effect, the CFN should be flow calibrated.

If the value of throat diameter has a large error, the calibration will result in an unusual discharge coefficient curve such as a curve greater than unity; however, the resulting mass flow rate will be unaffected by the unusual curve provided using the same value for the throat diameter both in the calibration and application (see Annex E).

If the CFN is small, the flow calibration is generally preferred because the forms of contraction and throat are difficult to machine accurately and also difficult to inspect.

Annex H (informative)

Critical back pressure ratio

H.1 General

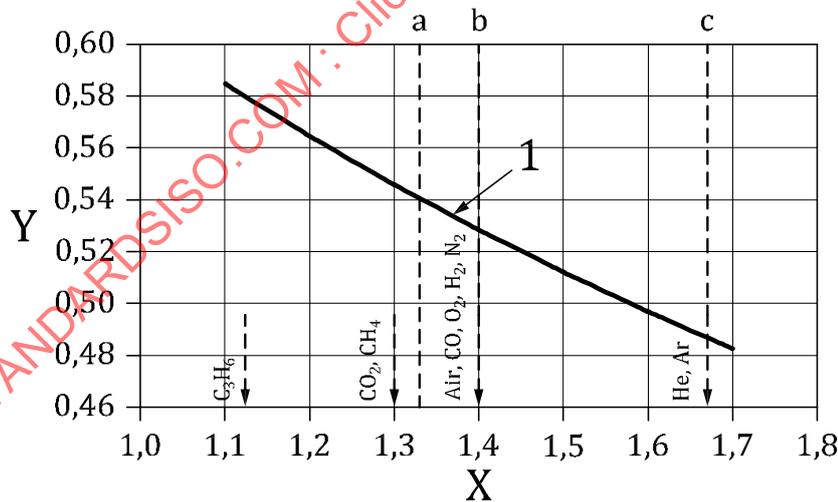
The theoretical critical back-pressure ratio (CBPR) assumes the fully attached one-dimensional isentropic flow of perfect gas in the diffuser, which is given by p_{2i}/p_0 (see Figure 6 a)). It depends only on the area ratio of diffuser exit to the throat for a specific gas.

The actual CBPR is always smaller than the theoretical value because there are pressure losses in the diffuser and also a decrease of flowing area at the diffuser exit. Formula (23), which was developed based on experiments by Hillbrath^[3], estimates the efficiency deficit in a frustum diffuser at high Reynolds numbers. Even in this empirical equation, the CBPR depends only on the area ratio of the throat and diffuser exit for a specific gas.

However, the recent experiments revealed that the CBPR depends significantly on the Reynolds number in a manner specific to each CFN and its installing conditions^{[11][13]}.

At high Reynolds numbers, most diffusers operate roughly as predicted by the empirical equation or even by the simple theory (see Figure H.4).

At low Reynolds numbers, CFN will face the premature unchoking phenomenon (PUP), by which the flow rate may decrease significantly at the back-pressure ratios (BPRs) at which the CFN should choke by the diffuser effect in theory, i.e., at the BPRs greater than the critical pressure ratio (e.g. approximately 0,53 for diatomic gases, see Figure H.1).



Key

- X specific heat, γ
- Y critical pressure ratio ρ_1^*/ρ_0
- 1 curve by Formula (7)
- a Polyatomic.
- b Diatomic.
- c Monoatomic.

Figure H.1 — Theoretical critical pressure ratio

The mechanism and cause of the PUP is still unclear: accordingly it is not possible to predict the conditions where the PUP occurs. Although it is not difficult to detect the PUP experimentally (see H.4), the effect of PUP in a specific CFN may depend significantly on its installation condition; therefore, in order to predict the PUP occurrence in a specific CFN based on experiments, the measurement should be performed on the very CFN to be used in the application installed in its own upstream and downstream conduits. One of the causes of the PUP is considered to be the resonance of vibrating shock waves^{[5][10]} that may cause its dependence on the installing condition.

In general, for CFNs complying with this document, the typical Reynolds number at which the PUP may start affecting the flow rate is about 10^5 , which corresponds to, for example, a CFN with $d_{nt} \approx 10$ mm (ca. $50 \text{ m}^3/\text{h}$) operating at the atmospheric pressure. The decrease of discharge coefficient caused by the PUP may be reduced by lengthening the diffuser, accordingly, this document recommends to let the diffuser length be as long as possible, at least $4d_{nt}$. At the Reynolds numbers lower than that the PUP starts affecting, the user should assume that there is no diffuser effect at all; i.e., the BPRs higher than the critical pressure ratio may cause serious error.

When the PUP is weak (at relatively high Reynolds numbers in the range where the PUP is suspected), most CFNs may choke at the BPRs slightly smaller than the critical pressure ratio. However, at very low Reynolds numbers approaching the lowest extreme of this document, the decrease of flow rate may occur at BPRs considerably smaller than the critical pressure ratio possibly because of the shock wave resonance. Accordingly, this document recommends keeping the BPR at 0,25 or less when the PUP is strong.

For CFNs without a diffuser, and also those with a very short diffuser such as $l = 0,1d_{nt}$, it is recommended to keep the BPR smaller than 0,35 regardless of its Reynolds number if high accuracy is required (see Figure H.5). A slight decrease of the flow rate starts from a BPR of 0,35 and it reaches 0,1 % at 0,5, and then the flow rate decreases very rapidly at BPRs beyond 0,5 because the flow is totally subsonic; however, if 0,1 % deviation is tolerable in the application, a BPR of 0,5 may be acceptable.

H.2 Theoretical critical back-pressure ratio

Supposing the flow attains the critical flow velocity at the throat but that in the diffuser is fully subsonic and totally attached to the diffuser wall, the Mach number at diffuser exit, M_{a2} , and the ratio of pressure at diffuser exit and stagnation p_{2i}/p_0 , can be calculated by using Formulae (4) and (5) and they are graphed in Figure H.2. Solving them numerically, the CBPR $r_{CBP} = p_{2i}/p_0$ is related to the area ratio as graphed in Figure 6 a).

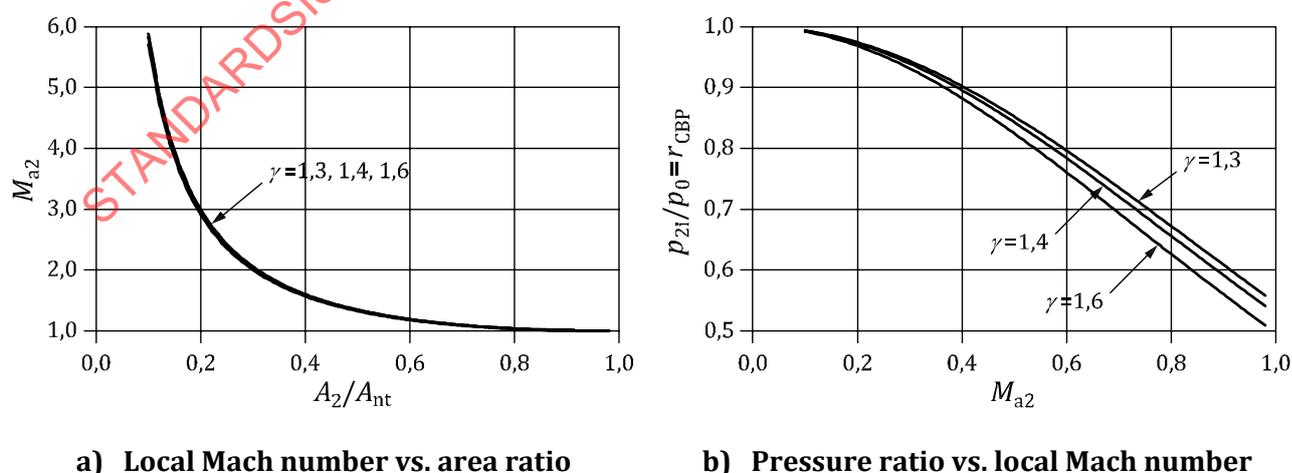


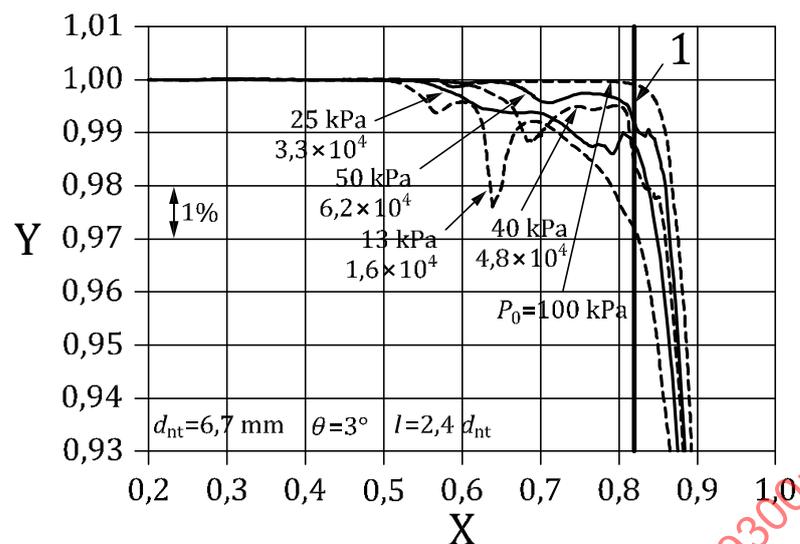
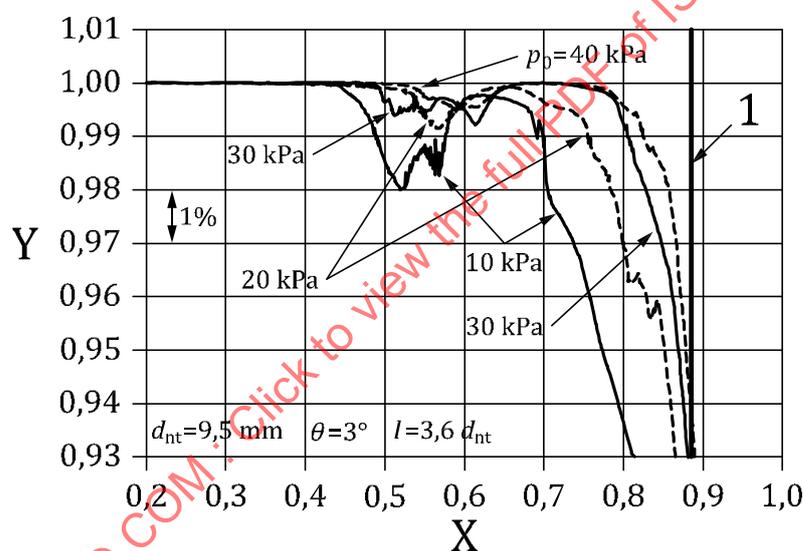
Figure H.2 — Theoretical local Mach number and static pressure ratio at the diffuser exit

H.3 Examples of the typical choking patterns with the PUP

Examples of the typical choking patterns, i.e., the discharge coefficient at a constant stagnation condition plotted against the BPR, when the PUP occurs are shown in Figure H.3. All the measurements were performed at the Reynolds numbers below the valid range of Formula (23). Figure H.3 a) and b) are the patterns of a HPN and NPN, respectively. Each choking pattern is normalized at its own given value at low BPRs; therefore, all the normalized discharge coefficients are unity at low BPRs, regardless of the Reynolds number.

It is noted that these measurements should have been affected by the form of downstream conduit including that of the CFN exit (e.g., diffuser length). Strictly speaking, the measurement should be performed through a pressure tapping drilled at the diffuser exit in order to compare the choking patterns of different CFNs, but they were performed through a pressure tapping drilled on the downstream conduit as specified in 9.2.3.

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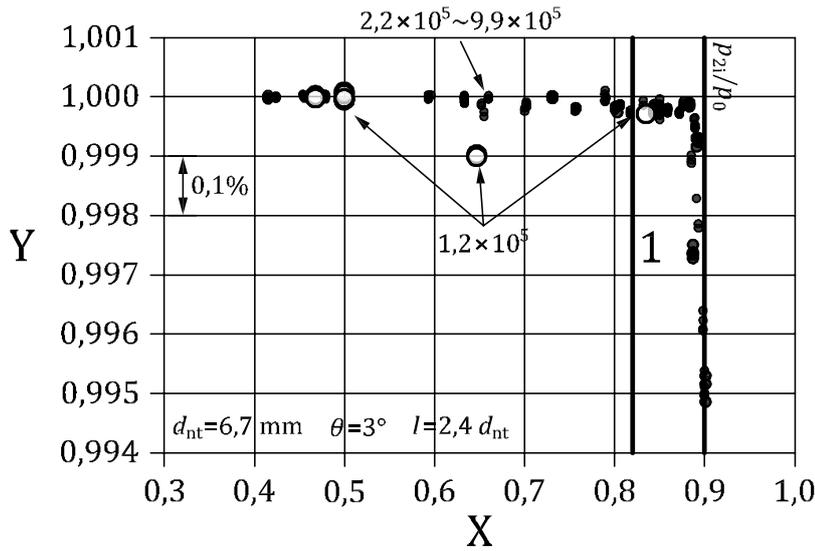
a) HPN, $d_{nt} = 6,7 \text{ mm/air}$ b) NPN, $d_{nt} = 9,5 \text{ mm/air}$ **Key**

- X back pressure ratio p_2/p_0
- Y normalized discharge coefficient
- 1 curve by Formula (23)

Figure H.3 — Examples of the PUP

The flow rate deficit is already observed in the results of both the CFNs at their highest Reynolds numbers. The complex structures of the patterns should depend on the upstream and also downstream conduit structures; for example, some structure put at a location upstream or downstream the CFN may erase the complex structures, resulting in a monotonically decreasing pattern from a BPR specific to each Reynolds number^[11]. The steep decreases of the discharge coefficient often have hysteresis depending on whether the BPR is increased or decreased.

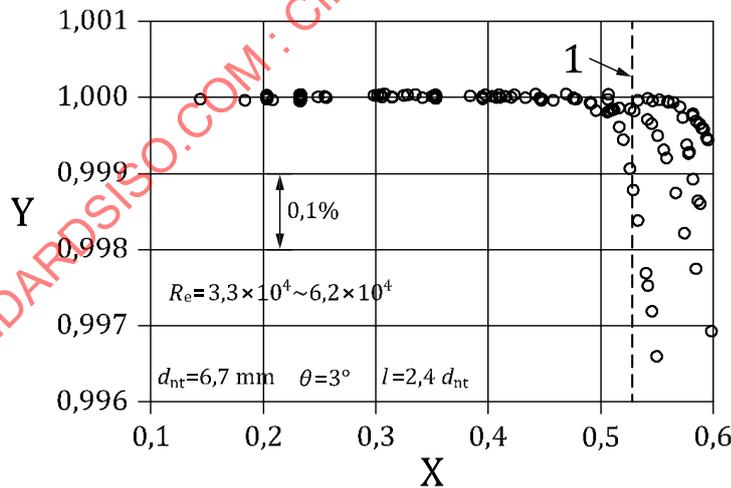
Examples of the choking patterns at high Reynolds numbers of the same HPN as that in Figure H.3 a) are shown in Figure H.4. The PUP is also observed at 110 kPa ($Re = 1,2 \times 10^5$); otherwise, the CBPR reaches almost the theoretical value p_2/p_0 rather than that by Formula (23).



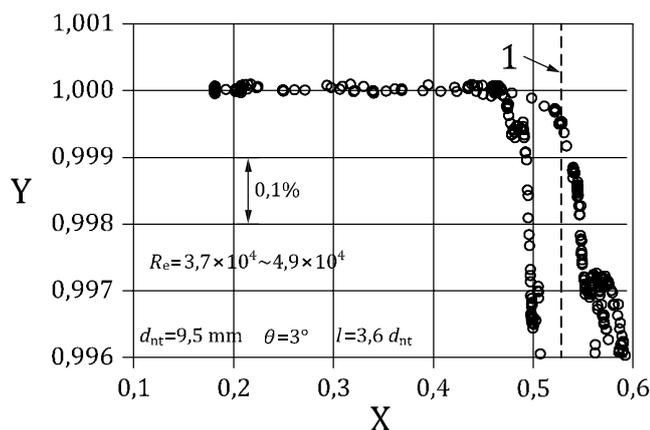
Key
 X back pressure ratio p_2/p_0
 Y normalized discharge coefficient
 1 curve by Formula (23)

Figure H.4 — Examples of the choking patterns at high Reynolds numbers

The choking patterns plotted in Figure H.3 are magnified in Figure H.5, where those at the Reynolds numbers smaller than 2×10^4 are excluded because it is outside the valid range of this document. The discharge coefficients start decreasing rapidly from the BPR of 0,5 or 0,45 depending on the CFNs. The steepness and starting point of the decreases have no systematic dependence on the Reynolds number, which may be because the PUP patterns are affected by the resonance.



a) $d_{nt} = 6,7$ mm, Venturi nozzle/HPN (Figure H.4 a) is magnified)



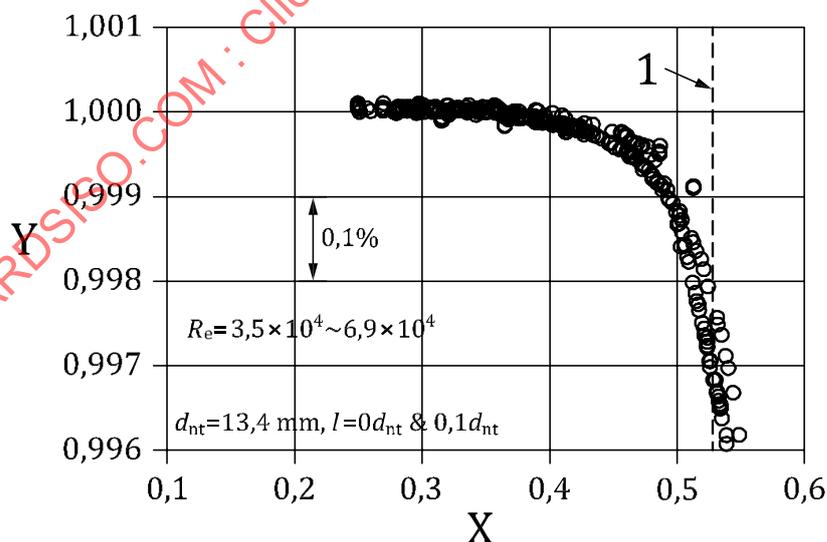
b) $d_{nt} = 9,5$ mm, Venturi nozzle/NPN (Figure H.4 b) is magnified)

Key

- X back pressure ratio p_2/p_0
 Y normalized discharge coefficient
 1 critical pressure ratio

Figure H.5 — Details of the choking patterns at high Reynolds numbers

The choking patterns of CFNs with no diffuser (quadrant CFN) and very short diffuser ($l = 0,1d_{nt}$) are shown in Figure H.6. There is no systematic Reynolds number dependence observed and the critical flow rate is flat at the BPRs of only up to about 0,35, accordingly, this document recommends to keep the BPR less than 0,35 regardless of the Reynolds number for quadrant CFNs and CFNs with very short diffuser. However, the decrease at the BPR of 0,5 is still 0,1 % that may be ignorable in some applications.



Key

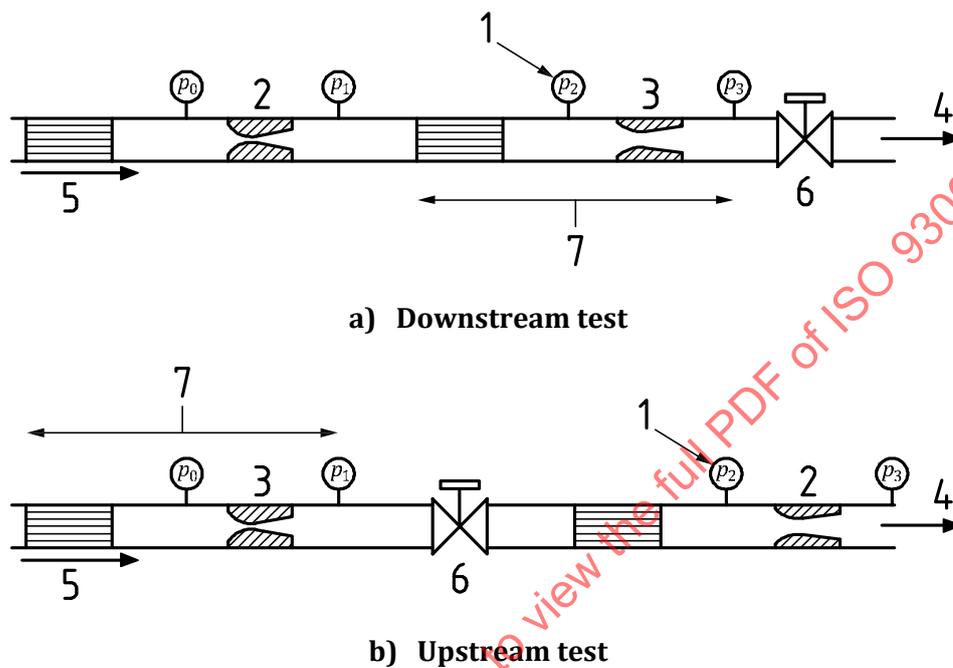
- X back pressure ratio p_2/p_0
 Y normalized discharge coefficient
 1 critical pressure ratio

Figure H.6 — Choking patterns of a quadrant CFN

H.4 Choking test

H.4.1 Against a reference CFN

Examples of the choking test of a CFN using another CFN as a reference meter are shown in Figure H.7. The pressure controller controls the pressure ratio across the CFN under test. Provided p_0 is constant and the reference CFN is always choked, unchoking of the CFN under test in a) and b) induces the higher and lower p_2 , respectively.



Key

- 1 variation indicates unchoking
- 2 reference CFN
- 3 CFN under test
- 4 low pressure
- 5 stable flow at constant p_0
- 6 pressure controller
- 7 CFN conduit

Figure H.7 — Examples of the choking test against a reference CFN

When both the CFNs are choked, the ratio of upstream pressures of the CFNs is approximated by Formula (H.1);

$$\frac{p_2}{p_0} \approx \frac{C_d^U}{C_d^D} \left(\frac{d_{nt}^U}{d_{nt}^D} \right)^2 \quad (H.1)$$

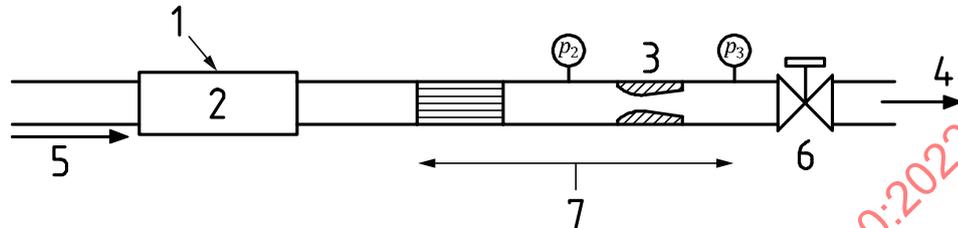
where the superscripts U and D indicate that the variables are for the upstream and downstream CFNs, respectively. According to Formula (H.1), the upstream CFN shall be sufficiently smaller than the downstream one in order to let the both CFNs choked and the downstream pressure of the pipeline shall be further low.

In Figure H.7 configuration b), care shall be taken not to be affected by the unchoking of reference CFN because the higher p_2 induced by the unchoking of reference CFN may cancel out the lower p_2 that

should have been induced by the unchoking of CFN under test. Accordingly, if possible, configuration a) is recommended.

H.4.2 Against a reference flow meter

Some other choking tests are possible as in Figure H.8, repeated primary calibrations with a short suction time, and so on.



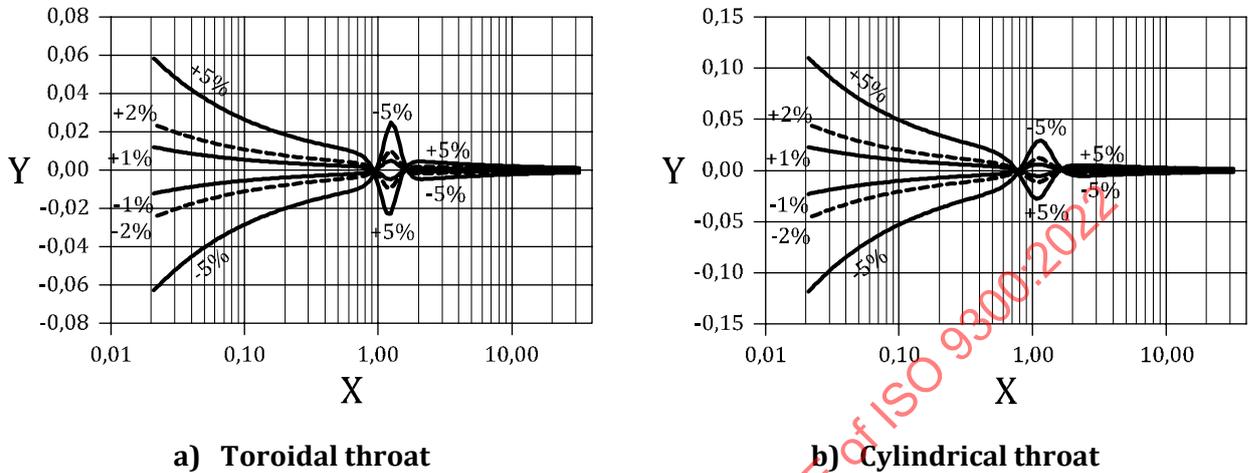
Key

- 1 variation of flow rate indicates unchoking
- 2 reference flow meter
- 3 CFN under test
- 4 low pressure
- 5 stable flow
- 6 pressure controller
- 7 CFN conduit

Figure H.8 — Choking test against a reference flow meter

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The error of viscosity propagates into the Reynolds number at the same magnitude because the Reynolds number is (inversely) proportional to the viscosity. Figure I.2 shows the error that will be produced in the discharge coefficient that is expressed or approximated by Formula (17) by the error in Re specified in the figure. It shows that 2 % error in the viscosity is mostly negligible in the measurements complying with this document.



Key

X Reynolds number, Re ($\times 10^6$)
 Y error in C_d (%)

NOTE C_d is expressed >or approximated by Formula (17).

Figure I.2 — Error of C_d caused by Re indicated in the graph

Considering the user's convenience, the fitting was stopped when the maximum absolute deviation from the REFPROP values become smaller than 2 % although the higher accuracy may be available if allowing more coefficients of more digit number.

I.2 Nitrogen

The coefficients, valid range, and deviation from the REFPROP values are given in Table I.1.

Table I.1 — Coefficients V_{ij} , range, and deviation (nitrogen)

V_{ij} i	j			
	0	1	2	3
0	-2,37372924E+03	-2,15205006E+02	3,80697293E+01	-7,19569669E-01
1	6,17528263E+03	4,96563894E+02	-8,52196892E+01	1,61553774E+00
2	-5,35004624E+03	-3,80864753E+02	6,36511321E+01	-1,20998758E+00
3	1,55080318E+03	9,71508454E+01	-1,58613477E+01	3,02299893E-01

Coefficients:

$$T_{\mu} = 150$$

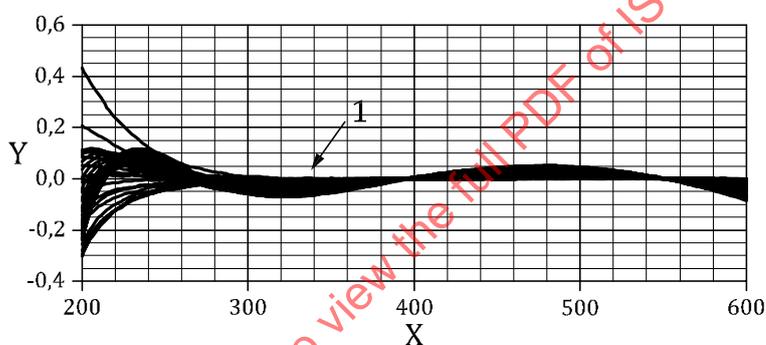
$$C_{\mu} = 0,05$$

Range:

$$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$$

$$200 \text{ K} \leq T \leq 600 \text{ K}$$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

1 $p=0,1 \text{ Mpa}, 0,5 \text{ Mpa} \sim 20 \text{ Mpa}/0,5 \text{ MPa}$ step and $T = 200 \text{ K} \sim 600 \text{ K}/5 \text{ K}$ step

I.3 Argon

The coefficients, valid range, and deviation from the REFPROP values are given in Table I.2.

Table I.2 — Coefficients V_{ij} , range, and deviation (argon)

V_{ij} i	j						
	0	1	2	3	4	5	6
0	9,45120578 E+03	3,25597090 E+02	-1,63030985 E+02	3,87470871 E+01	-4,13638599 E+00	1,80930325 E-01	-2,71567168 E-03
1	-3,36790505 E+04	-1,26544548 E+03	6,31719943 E+02	-1,49715525 E+02	1,59988850 E+01	-6,99801783 E-01	1,04967036 E-02
2	4,01645241 E+04	1,63641921 E+03	-8,15651169 E+02	1,92681903 E+02	-2,06126026 E+01	9,01619877 E-01	-1,35147928 E-02
3	-1,60032862 E+04	-7,03779844 E+02	3,50937278 E+02	-8,25947681 E+01	8,84593129 E+00	-3,86946668 E-01	5,79617377 E-03

Coefficients:

$$T_{\mu} = 165$$

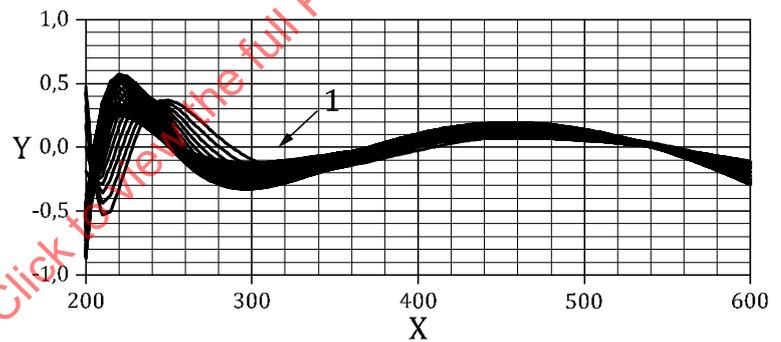
$$c_{\mu} = -0,05$$

Range:

$$0,1 \text{ MPa} \leq p \leq 20 \text{ MPa}$$

$$200 \text{ K} \leq T \leq 600 \text{ K}$$

Deviation from the REFPROP values:



Key

X temperature (kelvin)

Y deviation (%)

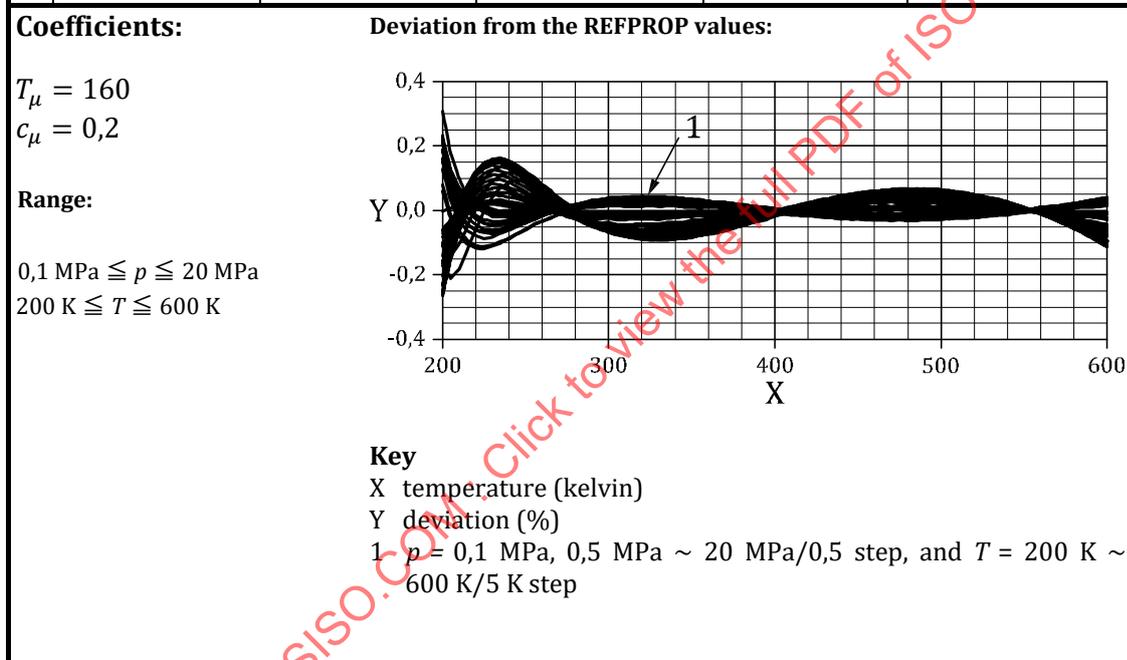
1 $p = 0,1 \text{ MPa}, 0,5 \text{ MPa} \sim 20 \text{ MPa}/0,5 \text{ step}$, and $T = 200 \text{ K} \sim 600 \text{ K}/5 \text{ K step}$

I.4 Dry air

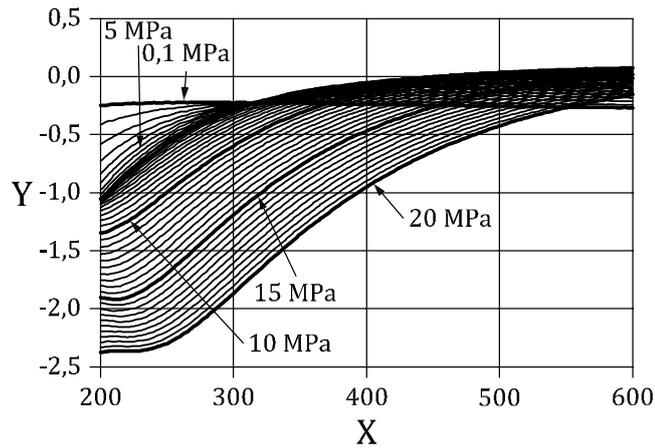
The coefficients, valid range, and deviation from the REFPROP values are given in Table I.3. The air is supposed to have the CIPM 2007 composition specified in Table B.7 (no CO₂).

Table I.3 — Coefficients V_{ij} , range, and deviation (dry air/CIPM 2007 composition)

V_{ij} i	j				
	0	1	2	3	4
0	2,195671E+01	-1,072776E+00	2,099647E-01	5,337098E-02	-1,934377E-03
1	-1,028073E+01	1,583527E+00	-1,646644E-01	-5,353841E-02	1,932906E-03
2	1,548471E+00	-6,213702E-01	4,405660E-02	1,782954E-02	-6,427325E-04
3	6,732455E-01	7,465762E-02	-4,008054E-03	-1,972206E-03	7,109563E-05



As an example, the differences of viscosity of air A from that of air C (CIPM 2007 composition) in Table B.10 are shown in Figure I.3. Especially at high pressures and also at low temperature, it may be recommended to use a database such as the REFPROP to compute the viscosity values based on the accurate composition.

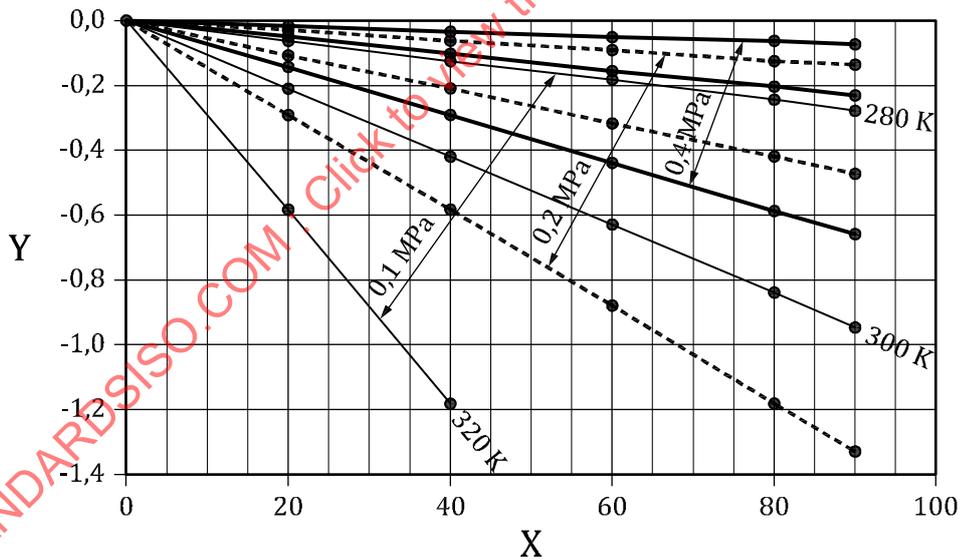


Key

- X temperature (kelvin)
- Y deviation of viscosity (%)

Figure I.3 — Example of difference of viscosities of dry air caused by different compositions (air A - air C)

Deviations of the viscosities of humid air from those of dry air are shown in percent in Figure I.4. The REFPROP cannot produce viscosity where there is no data in the figure. The effect of the humidity on the viscosity may be negligible in this document.



Key

- X humidity (%)
- Y deviation(%) from the dry air viscosity

Figure I.4 — Deviations of the viscosities of humid air from those of dry air

I.5 Methane

The coefficients, valid range, and deviation from the REFPROP values are given in Tables I.4 to I.7 for each range.

Table I.4 — Coefficients V_{ij} , range, and deviation (methane/low pressure)

V_{ij} i	j				
	0	1	2	3	4
0	8,412167E+00	-1,902221E+00	2,127231E+00	-8,939054E-01	1,299924E-01
1	3,490053E-01	2,274401E+00	-2,330664E+00	1,014824E+00	-1,454548E-01
2	-1,738028E+00	-8,255381E-01	8,493656E-01	-3,783110E-01	5,359155E-02
3	7,878219E-01	9,662284E-02	-1,026505E-01	4,638343E-02	-6,507910E-03

Coefficients:

Deviation from the REFPROP values:

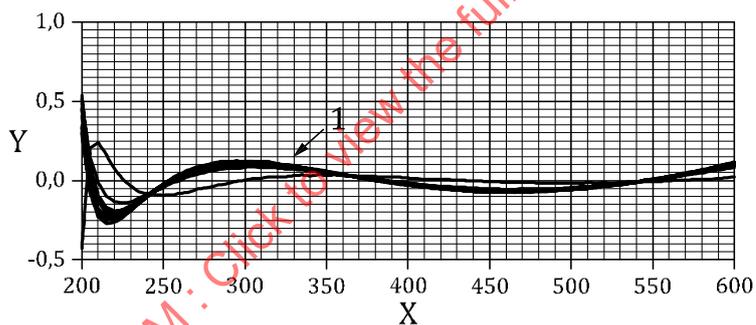
$T_{\mu} = 190$

$c_{\mu} = 0,2$

Range:

$0,1 \text{ MPa} \leq p \leq 5 \text{ MPa}$

$200 \text{ K} \leq T \leq 600 \text{ K}$



Key

X temperaure (kelvin)

Y deviation (%)

1 $p = 0,1 \text{ MPa}, 0,5 \text{ MPa} \sim 20 \text{ MPa}/0,5 \text{ step}, \text{ and } T = 200 \text{ K} \sim 600 \text{ K}/5 \text{ K step}$