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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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Contents

Page

Foreword

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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).

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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;

— 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.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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
$q_{\mathrm{th,P}}$
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
$q_{\mathrm{th,R}}$
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
$R_e = \frac{4q_m}{\pi d \mu_0}$

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:

$$M_{aC} = \frac{q_m}{\frac{\pi D^2}{4}\rho_0} \frac{1}{\sqrt{\gamma \frac{R}{M} T_0}}$$

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	$\mathrm{kg\ mol^{-1}}$
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	$\mathrm{ML^{-1}T^{-2}}$	Pa
p_0	Stagnation pressure of the gas at the CFN inlet	$\mathrm{ML^{-1}T^{-2}}$	Pa
p_1	Static pressure of the gas measured through the upstream wall pressure tapping	$\mathrm{ML^{-1}T^{-2}}$	Pa
p_2	Static pressure of the gas at the diffuser exit	$\mathrm{ML^{-1}T^{-2}}$	Pa
$p_{2\mathrm{i}}$	Theoretical static pressure of the gas at the diffuser exit when the nozzle is choked but the flow in the diffuser is fully subsonic	$\mathrm{ML^{-1}T^{-2}}$	Pa
p_{den}	Static pressure in the gas at densitometer	$\mathrm{ML^{-1}T^{-2}}$	Pa
P_{r}	The Prandtl number	Dimensionless	—
p^*	Static pressure at the critical point	$\mathrm{ML^{-1}T^{-2}}$	Pa
p^*_{P}	Theoretical static pressure at the critical point of perfect gas	$\mathrm{ML^{-1}T^{-2}}$	Pa
q_m	Mass flow rate (True mass flow rate)	$\mathrm{MT^{-1}}$	$\mathrm{kg{\cdot}s^{-1}}$
$q_{\mathrm{th,P}}$	Theoretical mass flow rate of perfect gas	$\mathrm{MT^{-1}}$	$\mathrm{kg{\cdot}s^{-1}}$
$q_{\mathrm{th,R}}$	Theoretical mass flow rate of real gas	$\mathrm{MT^{-1}}$	$\mathrm{kg{\cdot}s^{-1}}$
q_V	Volume flow rate	$\mathrm{MT^{-1}}$	$\mathrm{kg{\cdot}s^{-1}}$
R	Universal gas constant (8,314 5 J/(mol·K))	$\mathrm{M\ L^2T^{-2}\Theta^{-1}}$	$\mathrm{J{\cdot}mol^{-1}K^{-1}}$
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
$V_{i,j}$	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}	$kg{\cdot}m^{-3}$
$\rho*$	Theoretical density of the gas at the critical point	ML^{-3}	$kg{\cdot}m^{-3}$
$\rho*_p$	Theoretical density of the gas at the critical point of perfect gas	ML^{-3}	$kg{\cdot}m^{-3}$

M = mass

L = length

T = time

Θ = temperature

[a] Same as the corresponding quantity.

[b] Depending on each terms of the equation.

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);

$$\frac{p^{\gamma-1}}{T^{\gamma}}=\text{const.} \tag{1}$$

$$\frac{p}{\rho^{\gamma}}=\text{const.} \tag{2}$$

5.1.2 State equation

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

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

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);

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

5.2.2 Static pressure

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

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