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Measurement of gas flow by means of critical flow Venturi nozzles

Mesure de débit de gaz au moyen de Venturi-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.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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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*.

This second edition cancels and replaces the first edition (ISO 9300:1990), which has been technically revised.

Measurement of gas flow by means of critical flow Venturi nozzles

1 Scope

This International Standard specifies the geometry and method of use (installation in a system and operating conditions) of critical flow Venturi nozzles (CFVN) used to determine the mass flow-rate of a gas flowing through a system. It also gives the information necessary for calculating the flow-rate and its associated uncertainty.

It is applicable to Venturi nozzles in which the gas flow accelerates to the critical velocity at the throat (this being equal to the local sonic velocity), and only where there is steady flow of single-phase gases. At the critical velocity, the mass flow-rate of the gas flowing through the Venturi nozzle is the maximum possible for the existing upstream conditions while CFVN can only be used within specified limits, e.g. limits for the nozzle throat to inlet diameter ratio and throat Reynolds number. This International Standard deals with CFVN 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.

Information is given for cases where the pipeline upstream of the CFVN is of circular cross-section, or it can be assumed that there is a large space upstream of the CFVN or upstream of a set of CFVN mounted in a cluster. The cluster configuration offers the possibility of installing CFVN in parallel, thereby achieving high flow-rates.

For high-accuracy measurement, accurately machined Venturi nozzles are described for low Reynolds number applications.

2 Terms and definitions

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

2.1 Pressure measurement

2.1.1
wall pressure tapping
hole drilled in the wall of a conduit in such a way that the edge of the hole is flush with the internal surface of the conduit

NOTE The tapping is achieved such that the pressure within the hole is the static pressure at that point in the conduit.

2.1.2
static pressure of a gas
actual pressure of the flowing gas which can be measured by connecting a pressure gauge to a wall pressure tapping

NOTE Only the value of the absolute static pressure is used in this International Standard.

2.1.3
stagnation pressure
pressure which would exist in a gas in a flowing gas stream if the stream were brought to rest by an isentropic process

NOTE Only the value of the absolute stagnation pressure is used in this International Standard.

2.2 Temperature measurement

2.2.1
static temperature
actual temperature of a flowing gas

NOTE Only the value of the absolute static temperature is used in this International Standard.

2.2.2
stagnation temperature
temperature which would exist in a gas in a flowing gas stream if the stream were brought to rest by an isentropic process

NOTE Only the value of the absolute stagnation temperature is used in this International Standard.

2.3 Venturi nozzles

2.3.1
Venturi nozzle
convergent/divergent restriction inserted in a system intended for the measurement of flow-rate

2.3.2
normally machined Venturi nozzle
Venturi nozzle machined by a lathe and surface polished to achieve the desired smoothness

2.3.3
accurately machined Venturi nozzle
Venturi nozzle machined by a super-accurate lathe to achieve a mirror finish without polishing

2.3.4
throat
section of minimum diameter of a Venturi nozzle

2.3.5
critical flow Venturi nozzle
CFVN
Venturi nozzle for which the nozzle geometrical configuration and conditions of use are such that the flow-rate is critical at the nozzle throat

2.4 Flow

2.4.1
mass flow-rate
q_m
mass of gas per unit time passing through the CFVN

NOTE In this International Standard, the term flow-rate always refers to *mass flow-rate*.

2.4.2
throat Reynolds number
Re_{nt}
dimensionless parameter calculated from the gas flow-rate and the gas dynamic viscosity at nozzle inlet stagnation conditions

NOTE The characteristic dimension is taken as the throat diameter at stagnation conditions. The throat Reynolds number is given by the formula:

$$Re_{\mathrm{nt}} = \frac{4q_m}{\pi d \mu_0}$$

2.4.3
isentropic exponent

κ

ratio of the relative variation in pressure to the corresponding relative variation in density under elementary reversible adiabatic (isentropic) transformation conditions

NOTE 1 The isentropic exponent is given by the formula:

$$\kappa = \frac{\rho}{p} \left(\frac{\mathrm{d}p}{\mathrm{d}\rho} \right)_{\mathrm{s}} = \frac{\rho c^2}{p}$$

where

p is the absolute static pressure of the gas;

ρ is the density of the gas;

c is the local speed of sound;

s signifies “at constant entropy”.

NOTE 2 For an ideal gas, κ is equal to the ratio of specific heat capacities γ and is equal to 5/3 for monatomic gases, 7/5 for diatomic gases, 9/7 for triatomic gases, etc.

NOTE 3 In real gases, the forces exerted between molecules as well as the volume occupied by the molecules have a significant effect on the gas behaviour. In an ideal gas, intermolecular forces and the volume occupied by the molecules can be neglected.

2.4.4
discharge coefficient

C_{d}

dimensionless ratio of the actual flow-rate to the ideal flow-rate of non-viscous gas that would be obtained with one-dimensional isentropic flow for the same upstream stagnation conditions

NOTE This coefficient corrects for viscous and flow field curvature effects. For each type of nozzle design and installation conditions specified in this International Standard, it is only a function of the throat Reynolds number.

2.4.5
critical flow

maximum flow-rate for a particular Venturi nozzle, which can exist for the given upstream conditions

NOTE When critical flow exists, the throat velocity is equal to the local value of the speed of sound (acoustic velocity), the velocity at which small pressure disturbances propagate.

2.4.6
critical flow function

C_*

dimensionless function which characterises the thermodynamic flow properties of an isentropic and one-dimensional flow between the inlet and the throat of a Venturi nozzle

NOTE It is a function of the nature of the gas and of stagnation conditions (see 4.2).

2.4.7
real gas critical flow coefficient

C_{R}

alternative form of the critical flow function, more convenient for gas mixtures

NOTE It is related to the critical flow function as follows:

$$C_{\mathrm{R}} = C_* \sqrt{Z}$$

2.4.8
critical pressure ratio

r_*

ratio of the static pressure at the nozzle throat to the stagnation pressure for which the gas mass flow-rate through the nozzle is a maximum

NOTE This ratio is calculated in accordance with the equation given in 8.5.

2.4.9
back-pressure ratio

ratio of the nozzle exit static pressure to the nozzle upstream stagnation pressure

2.4.10
Mach number

Ma

⟨at nozzle upstream static conditions⟩ ratio of the mean axial fluid velocity to the velocity of sound at the location of the upstream pressure tapping

2.4.11
compressibility factor

Z

correction factor expressing numerically the deviation from the ideal gas law of the behaviour of a real gas at given pressure and temperature conditions

NOTE It is defined by the formula:

$$Z = \frac{pM}{\rho RT}$$

where R, the universal gas constant, equals 8,314 51 J/(mol·K).

2.5
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 Symbols

Symbol	Description	Dimension	SI unit
A_2	Cross-sectional area of Venturi nozzle exit	L^2	m^2
A_{nt}	Cross-sectional area of Venturi nozzle throat	L^2	m^2
$C_{\mathrm{d}'}$	Coefficient of discharge	Dimensionless	
C_{R}	Critical flow coefficient for one-dimensional flow of a real gas	Dimensionless	
C_*	Critical flow function for one-dimensional flow of a real gas	Dimensionless	
C_{*i}	Critical flow function for one-dimensional isentropic flow of a perfect gas	Dimensionless	
D	Diameter of the upstream conduit	L	m
d	Diameter of Venturi nozzle throat	L	m
M	Molar mass	M	$\mathrm{kg\ mol}^{-1}$
Ma_1	Mach number at the location of the upstream pressure tapping	Dimensionless	
p_1	Absolute static pressure of the gas at nozzle inlet	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
p_2	Absolute static pressure of the gas at nozzle exit	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
p_0	Absolute stagnation pressure of the gas at nozzle inlet	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
p_{nt}	Absolute static pressure of the gas at nozzle throat	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
p_{*i}	Absolute static pressure of the gas at nozzle throat for one-dimensional isentropic flow of a perfect gas	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
$(p_2/p_0)_i$	Ratio of nozzle exit static pressure to inlet stagnation pressure for one-dimensional isentropic flow of a perfect gas	Dimensionless	
q_m	Mass flow-rate	MT^{-1}	$\mathrm{kg\cdot s}^{-1}$
q_{mi}	Mass flow-rate for one-dimensional isentropic flow of an inviscid gas	MT^{-1}	$\mathrm{kg\cdot s}^{-1}$
R	Universal gas constant	$\mathrm{M\ L}^2\mathrm{T}^{-2}\Theta^{-1}$	$\mathrm{J\cdot mol}^{-1}\mathrm{K}^{-1}$
Re_{nt}	Nozzle throat Reynolds number	Dimensionless	
r_{c}	Radius of curvature of nozzle inlet	L	m
r_*	Critical pressure ratio p_{nt}/p_0	Dimensionless	
U'	Relative uncertainty	Dimensionless	
T_1	Absolute temperature of the gas at nozzle inlet	Θ	K
T_0	Absolute stagnation temperature of the gas at nozzle inlet	Θ	K
T_{nt}	Absolute static temperature at nozzle throat	Θ	K
v_{nt}	Throat sonic flow velocity; critical flow velocity at nozzle throat	LT^{-1}	$\mathrm{m\cdot s}^{-1}$
Z	Compressibility factor	Dimensionless	
β	Diameter ratio d/D	Dimensionless	
γ	Ratio of specific heat capacities	Dimensionless	
δ	Absolute uncertainty	[a]	[a]
κ	Isentropic exponent	Dimensionless	
μ_0	Dynamic viscosity of the gas at stagnation conditions	$\mathrm{ML}^{-1}\mathrm{T}^{-1}$	$\mathrm{Pa\cdot s}$
μ_{nt}	Dynamic viscosity of the gas at nozzle throat	$\mathrm{ML}^{-1}\mathrm{T}^{-1}$	$\mathrm{Pa\cdot s}$
ρ_0	Gas density at stagnation conditions at nozzle inlet	ML^{-3}	$\mathrm{kg\cdot m}^{-3}$
ρ_{nt}	Gas density at nozzle throat	ML^{-3}	$\mathrm{kg\cdot m}^{-3}$

M = mass

L = length

T = time

Θ = temperature

[a] Same as the corresponding quantity.

4 Basic equations

4.1 State equation

The behaviour of a real gas can be described by the formula:

$$\frac{p}{\rho} = \left(\frac{R}{M}\right) TZ \tag{1}$$

4.2 Flow-rate under ideal conditions

For ideal critical flow to exist, three main conditions are necessary:

a) the flow must be one-dimensional;

b) the flow must be isentropic;

c) the gas must be perfect (i.e. $Z = 1$ and $\kappa = \gamma$).

Under these conditions, the critical flow-rate is given by:

$$q_{mi} = \frac{A_{\mathrm{nt}} C_{*i} p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}} \tag{2}$$

or

$$q_{mi} = A_{\mathrm{nt}} C_{*i} \sqrt{p_0 \rho_0} \tag{3}$$

where

$$C_{*i} = \sqrt{\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{4}$$

4.3 Flow-rate under real conditions

For flow-rates under real conditions, the formula for critical flow-rate becomes:

$$q_m = \frac{A_{\mathrm{nt}} C_{\mathrm{d'}} C_* p_0}{\sqrt{\left(\frac{R}{M}\right) T_0}} \tag{5}$$

or

$$q_m = A_{\mathrm{nt}} C_{\mathrm{d'}} C_{\mathrm{R}} \sqrt{p_0 \rho_0} \tag{6}$$

since

$$C_{\mathrm{R}} = C_* \sqrt{Z_0} \tag{7}$$

where Z_0 is the value of the compressibility factor at upstream stagnation conditions:

$$Z_0 = \frac{p_0 M}{\rho_0 R T_0} \tag{8}$$

It should be noted that C_* and C_R are not equal to C_{*i} because the gas is not perfect. $C_{\mathrm{d}'}$ is less than unity since the flow is not one-dimensional and a boundary layer exists owing to viscous effects.

4.4 Critical mass flux

For the flow-rate under ideal conditions, critical mass flux = $\dfrac{q_{mi}}{A_\mathrm{nt}}$

For the flow-rate under real conditions, critical mass flux = $\dfrac{q_m}{A_\mathrm{nt} C_{\mathrm{d}'}}$

5 Applications for which the method is suitable

Each application should be evaluated to determine whether a CFVN or some other device is the most suitable. An important consideration is that the flow through the Venturi nozzle is independent of the downstream pressure (see 9.5) within the pressure range for which the Venturi nozzle can be used for critical flow measurement.

Some other considerations are as follows.

For CFVN the only measurements required are the gas pressure and the gas temperature or density upstream of the critical Venturi nozzle, since the throat conditions can be calculated from thermodynamic considerations.

The velocity in the CFVN throat is the maximum possible for the given upstream stagnation conditions, and therefore the sensitivity to installation effects is minimized, except for those of swirl which shall not exist in the inlet part of the CFVN.

When comparing CFVN with subsonic pressure-difference meters, it can be noted that in the case of the CFVN, the flow is directly proportional to the nozzle upstream stagnation pressure and not, as in the case of the subsonic meter, to the square root of a measured differential pressure.

The maximum flow range which can be obtained for a given CFVN is generally limited to the range of inlet pressures which are available above the inlet pressure at which the flow becomes critical.

The most common applications to date for CFVN have been for tests, calibration and flow control.

6 Standard critical flow Venturi nozzles (CFVN)

6.1 General requirements

6.1.1 Materials

The CFVN shall be manufactured from material suitable for the intended application. Some considerations are that

a) it should be possible to finish the material to the required condition (as given in 6.1.2 and 6.1.3), taking into account that some materials are unsuitable owing to the inclusion of pits, voids and other inhomogeneities,

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 (if it is to be used at a temperature other than that at which the throat diameter has been measured), so that the appropriate throat diameter correction can be made.

6.1.2 Surface finish of the throat and the inlet

The throat and toroidal inlet up to the conical divergent section of the CFVN shall be smoothly finished so that the arithmetic average roughness Ra does not exceed $15 \times 10^{-6}\,d$ and 0,04 µm for normally and accurately machined Venturi nozzles, respectively.

The throat and toroidal inlet up the conical divergent section shall be free from dirt or any other contaminants.

For a normally machined CFVN, it is allowable to use a toroidal throat CFVN with a diameter step at the throat not larger than 10 % of the throat diameter.

6.1.3 Conical divergent

The form of the conical divergent section of the CFVN shall be checked to ensure that any steps, discontinuities, irregularities and lack of concentricity do not exceed 1 % of the local diameter. The arithmetic average roughness Ra of the conical divergent section shall not exceed $10^{-4}d$.

6.2 Design

6.2.1 General

There are two designs of standard CFVN: the toroidal-throat Venturi nozzle and the cylindrical throat Venturi nozzle. Accurately machined Venturi nozzles shall be built according to the toroidal design.

6.2.2 Toroidal-throat Venturi nozzle

6.2.2.1 The CFVN shall conform with the specifications shown in Figure 1.

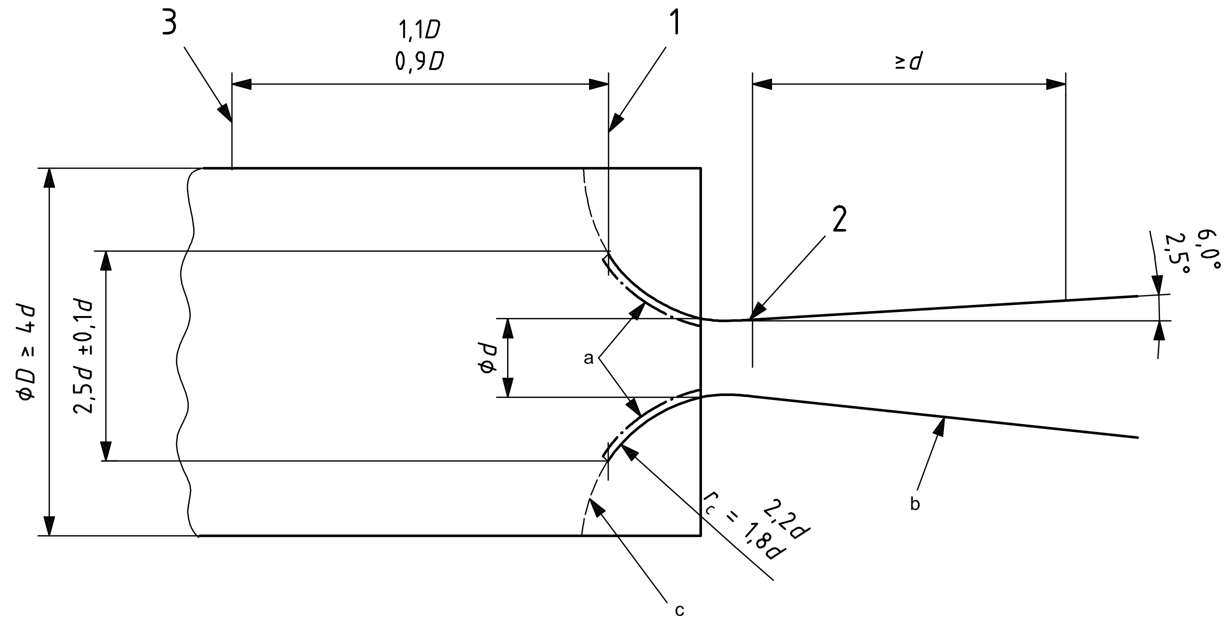
6.2.2.2 For purposes of locating other elements of the CFVN metering system, the inlet plane of the CFVN is defined as that plane perpendicular to the axis of symmetry which intersects the inlet at a diameter equal to $2{,}5d \pm 0{,}1d$.

6.2.2.3 The convergent section of the CFVN nozzle (inlet) shall be a portion of a torus which shall extend from the inlet plane through the minimum area section (throat) and be tangential to the divergent section. The contour of the inlet upstream of the inlet plane (see 6.2.2.2) is not specified, except that the surface at each axial location shall have a diameter greater than or equal to the extension of the toroidal contour.

6.2.2.4 The toroidal surface of the CFVN located between the inlet plane and the divergent section (see Figure 1) shall not deviate from the shape of a torus by more than $\pm\, 0{,}001d$. The radius of curvature r_c of this toroidal surface in a plane in which the axis of symmetry lies shall be $1{,}8d$ to $2{,}2d$.

6.2.2.5 The divergent section of the CFVN downstream of the point of tangency with the torus shall form a frustum of a cone with a half-angle between 2,5° and 6°. The length of the divergent section shall be not less than the throat diameter.

6.2.2.6 The uncertainty in the measurement of flow-rate using CFVN built in accordance with this International Standard depends in particular on the uncertainly in the throat cross-sectional area. It is difficult to measure precisely the throat diameter of a toroidal throat CFVN, particularly in the case of small nozzles, and great care should be taken.



Key

1 inlet plane

2 intersection of toroidal surface and divergent section

3 location of pressure indicating device

[a] In this region the arithmetic average roughness Ra shall not exceed $15 \times 10^{-6}\, d$ and 0,04 μm for normally and accurately machined Venturi nozzles, respectively, and the contour shall not deviate from toroidal form by more than ± 0,001d.

[b] In this region the arithmetic roughness value shall not exceed $10^{-4}d$.

[c] Inlet surface shall lie outside this contour.

Figure 1 — Toroidal-throat Venturi nozzle

6.2.3 Cylindrical-throat Venturi nozzles

6.2.3.1 The CFVN shall conform with the specifications shown in Figure 2.

6.2.3.2 The inlet plane is defined as that plane which is tangential to the inlet contour of the CFVN and perpendicular to the nozzle centre-line.

6.2.3.3 The convergent section of the CFVN (inlet) shall be a quarter of a torus tangential on one hand to the inlet plane (see 6.2.3.2) and on the other hand to the cylindrical throat. The length of the cylindrical throat and the radius of curvature r_c of the quarter of torus shall be equal to the throat diameter.

6.2.3.4 The inlet toroidal surface of the CFVN shall not deviate from the shape of a torus by more than ± 0,001d.

6.2.3.5 The flow-rate shall be calculated from the mean diameter at the cylindrical throat outlet section. The mean diameter shall be determined by measuring at least four angularly equally distributed diameters on the cylindrical throat outlet. No diameter along the throat length shall deviate by more than ± 0,001d from the mean diameter.

The length of the throat shall not deviate from the throat diameter by more than 0,05d. The connection between the quarter of torus and the cylindrical throat shall be inspected visually and no defect should be observed. When a defect of connection is observed, it shall be checked that the local radius of curvature in a