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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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Contents

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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.

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.

International Standard ISO 9300 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits.*

Annexes A, B and C form an integral part of this International Standard. Annexes D and E are for information only.

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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 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 applies to Venturi nozzles in which the gas flow accelerates to the critical velocity at the throat (this being equal to the local sonic velocity). 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.

This International Standard is applicable only where there is steady flow of single-phase gases. The critical flow Venturi nozzles dealt with can only be used within specified limits, e.g. limits for the nozzle throat to inlet diameter ratio and throat Reynolds number. It deals with Venturi nozzles for which direct calibration experiments have been made in sufficient number and quantity to enable inherent systems of application to be based on their results and to enable coefficients to be given with certain predictable limits of uncertainty.

The Venturi nozzles specified in this International Standard are called "primary devices". The other instruments necessary for the measurement of the flow-rate are known as "secondary devices". This International Standard principally covers primary devices; secondary devices are discussed only occasionally.

Information is given in this International Standard for cases where

a) the pipeline upstream of the Venturi nozzle is of circular cross-section, or

b) it can be assumed that there is a large space upstream of the Venturi nozzle.

2 Definitions and symbols

2.1 Definitions

For the purposes of this International Standard, the following definitions apply.

2.1.1 Pressure measurement

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

2.1.1.2 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.

2.1.1.3 stagnation pressure of a gas: Pressure which would exist in the 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.

2.1.2 Temperature measurement

2.1.2.1 static temperature of a gas: Actual temperature of the flowing gas.

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

2.1.2.2 stagnation temperature of a gas: Temperature which would exist in the 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.

2.1.3 Critical flow nozzles

2.1.3.1 Venturi nozzle: Convergent/divergent restriction inserted in a system, intended for the measurement of flow-rate.

2.1.3.2 throat: Section of minimum diameter of a Venturi nozzle.

2.1.3.3 critical Venturi nozzle: Venturi nozzle for which the nozzle geometrical configuration and conditions of use are such that the flow-rate is critical.

2.1.4 Flow

2.1.4.1 mass flow-rate, q_m**:** Mass of gas per unit time passing through the Venturi nozzle.

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

2.1.4.2 throat Reynolds number, Re_d**:** Dimensionless parameter calculated from the gas velocity, the gas density at the nozzle throat and the gas dynamic viscosity at nozzle inlet stagnation conditions. The characteristic dimension is taken as the throat diameter at working conditions. The throat Reynolds number is given by the formula

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

2.1.4.3 isentropic exponent, κ**:** Ratio of the relative variation in pressure to the corresponding relative variation in density under elementary reversible adiabatic (isentropic) transformation conditions:

$$\kappa = \frac{\varrho}{p}\left(\frac{\partial p}{\partial \varrho}\right)_S = \frac{\varrho c^2}{p}$$

where

p is the absolute static pressure of the gas;

ϱ is the density of the gas;

c is the local speed of sound;

the subscript S means "at constant entropy".

For an ideal gas[1], 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.

2.1.4.4 discharge coefficient, C**:** Dimensionless ratio of the actual flow-rate to the ideal flow-rate that would be obtained with one-dimensional isentropic flow for the same upstream stagnation conditions. This coefficient corrects for viscous and flow field curvature effects. For the nozzle design and installation conditions specified in this International Standard, it is a function of the throat Reynolds number only.

2.1.4.5 critical flow: Maximum flow-rate for a particular Venturi nozzle which can exist for the given upstream conditions. 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.

2.1.4.6 critical flow function, C_***:** Dimensionless function which characterizes the thermodynamic flow properties of an isentropic and one-dimensional flow between the inlet and the throat of a Venturi nozzle. It is a function of the nature of the gas and of stagnation conditions (see 3.2).

2.1.4.7 real gas critical flow coefficient, C_R**:** Alternative form of the critical flow function, more convenient for gas mixtures. It is related to the critical flow function as follows:

$$C_R = C_* Z^{1/2}$$

2.1.4.8 critical pressure ratio, r_***:** Ratio of the absolute static pressure of the gas at the nozzle throat to the absolute stagnation pressure for which the gas mass flow-rate through the nozzle is a maximum.

2.1.4.9 back-pressure ratio: Ratio of the absolute nozzle exit static pressure to the absolute nozzle upstream stagnation pressure at which the flow becomes critical.

2.1.4.10 Mach number, Ma_1 (at nozzle upstream static conditions)**:** Ratio of the mean axial fluid velocity to the velocity of sound at the inlet of the Venturi nozzle.

2.1.4.11 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. It is defined by the formula

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

where R, the molar gas constant, equals 8,314 3 J/(mol·K).

2.1.5 uncertainty: Estimate characterizing the range of values within which the true value of a measurand lies, at 95 % probability.

In some cases, the confidence level which can be attached to this range of values will be greater than 95 %, but this will be so only where the value of a quantity used in the calculation of flow-rate is known with a confidence level in excess of 95 %; in such a case, reference should be made to ISO 5168.

2.2 Symbols

The symbols used in this International Standard are specified in table 1.

3 Basic equations

3.1 State equation

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

$$p/\varrho = (R/M)\,TZ$$

3.2 Flow-rate under ideal conditions

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

a) the flow is one-dimensional;

b) the flow is isentropic;

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

1) 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.

Table 1 — Symbols

Symbol	Quantity	Dimensions[1]	SI unit
A_2	Cross-sectional area of Venturi nozzle exit	L^2	m^2
A_*	Cross-sectional area of Venturi nozzle throat	L^2	m^2
C	Discharge coefficient	dimensionless	
C_R	Real gas 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 upstream conduit	L	m
d	Diameter of Venturi nozzle throat	L	m
E	Relative uncertainty	dimensionless	
e	Absolute uncertainty	[2]	
M	Molar mass	M	$kg\ kmol^{-1}$
Ma_1	Mach number at nozzle inlet static conditions	dimensionless	
p_1	Absolute static pressure of the gas at nozzle inlet	$ML^{-1}\ T^{-2}$	Pa
p_2	Absolute static pressure of the gas at nozzle exit	$ML^{-1}\ T^{-2}$	Pa
p_0	Absolute stagnation pressure of the gas at nozzle inlet	$ML^{-1}\ T^{-2}$	Pa
p_*	Absolute static pressure of the gas at nozzle throat	$ML^{-1}\ T^{-2}$	Pa
p_{*i}	Absolute static pressure of the gas at nozzle throat for one-dimensional isentropic flow of a perfect gas	$ML^{-1}\ T^{-2}$	Pa
$(p_2/p_0)_i$	Ratio of nozzle exit static pressure to nozzle inlet stagnation pressure for one-dimensional isentropic flow of a perfect gas	dimensionless	
q_m	Mass flow-rate	MT^{-1}	$kg \cdot s^{-1}$
q_{mi}	Mass flow-rate for one-dimensional isentropic flow of an inviscid gas	MT^{-1}	$kg \cdot s^{-1}$
R	Universal gas constant	$ML^2\ T^{-2}\ \Theta^{-1}$	$J \cdot kmol^{-1}\ K^{-1}$
Re_d	Nozzle throat Reynolds number	dimensionless	
r_c	Radius of curvature of nozzle inlet	L	m
r_*	Critical pressure ratio p_*/p_0	dimensionless	
T_0	Absolute stagnation temperature of the gas at nozzle inlet	Θ	K
T_1	Absolute static temperature of the gas at nozzle inlet	Θ	K
T_*	Absolute static temperature of the gas at nozzle throat	Θ	K
v_*	Throat sonic flow velocity; critical flow velocity at the throat	LT^{-1}	$m \cdot s^{-1}$
Z	Compressibility factor	dimensionless	
β	Diameter ratio d/D	dimensionless	
γ	Ratio of the specific heat capacity at constant pressure c_p to the specific heat capacity at constant volume c_V	dimensionless	
κ	Isentropic exponent	dimensionless	
μ_0	Dynamic viscosity of the gas at stagnation conditions at nozzle inlet	$ML^{-1}\ T^{-1}$	$Pa \cdot s$
μ_*	Dynamic viscosity of the gas at nozzle throat	$ML^{-1}\ T^{-1}$	$Pa \cdot s$
ϱ_0	Gas density at stagnation conditions at nozzle inlet	ML^{-3}	$kg \cdot m^{-3}$
ϱ_*	Gas density at nozzle throat	ML^{-3}	$kg \cdot m^{-3}$

1) M = mass; L = length; T = time; Θ = temperature.

2) The dimension of this parameter is the dimension of the quantity to which it relates.

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

$$q_{mi} = \frac{A_* C_{*i} p_0}{[(R/M)\,T_0]^{1/2}}$$

or

$$q_{mi} = A_* C_{*i} (p_0 \varrho_0)^{1/2}$$

where

$$C_{*i} = \gamma^{1/2} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/2\,(\gamma-1)}$$

3.3 Flow-rate under real conditions

For flow-rates under real conditions, the formulae for critical flow-rates become

$$q_m = \frac{A_* C C_* p_0}{[(R/M)\,T_0]^{1/2}}$$

or

$$q_m = A_* C C_R (p_0 \varrho_0)^{1/2}$$

since

$$C_R = C_* Z_0^{1/2}$$

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

$$Z_0 = p_0 M / \varrho_0 R T_0$$

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

4 Applications for which the method is suitable

Each application should be evaluated to determine whether a critical flow Venturi nozzle or some other device is the most suitable. An important consideration is that the flow through the Venturi nozzle be independent of the downstream pressure (see 7.6) within the pressure range for which the Venturi nozzle can be used for critical flow measurement.

Some other considerations are as follows.

For critical flow Venturi nozzles 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 critical Venturi nozzle 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 Venturi nozzle.

When comparing sonic Venturi nozzles with subsonic pressure-difference meters it can be noted that in the case of the critical nozzle, 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 critical Venturi nozzle 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 of critical flow Venturi nozzles have been for tests, calibration and flow control.

5 Standard critical flow Venturi nozzles

5.1 General requirements

5.1.1 The Venturi nozzle shall be inspected to determine that it conforms with the requirements of this International Standard.

5.1.2 The Venturi nozzle 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; 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.

5.1.3 The throat and toroidal inlet up the conical divergent section of the Venturi nozzle shall be smoothly finished so that the arithmetic average roughness R_a does not exceed $15 \times 10^{-6} d$.

5.1.4 The throat and toroidal inlet up the conical divergent section shall be free from dirt, films or other contamination.

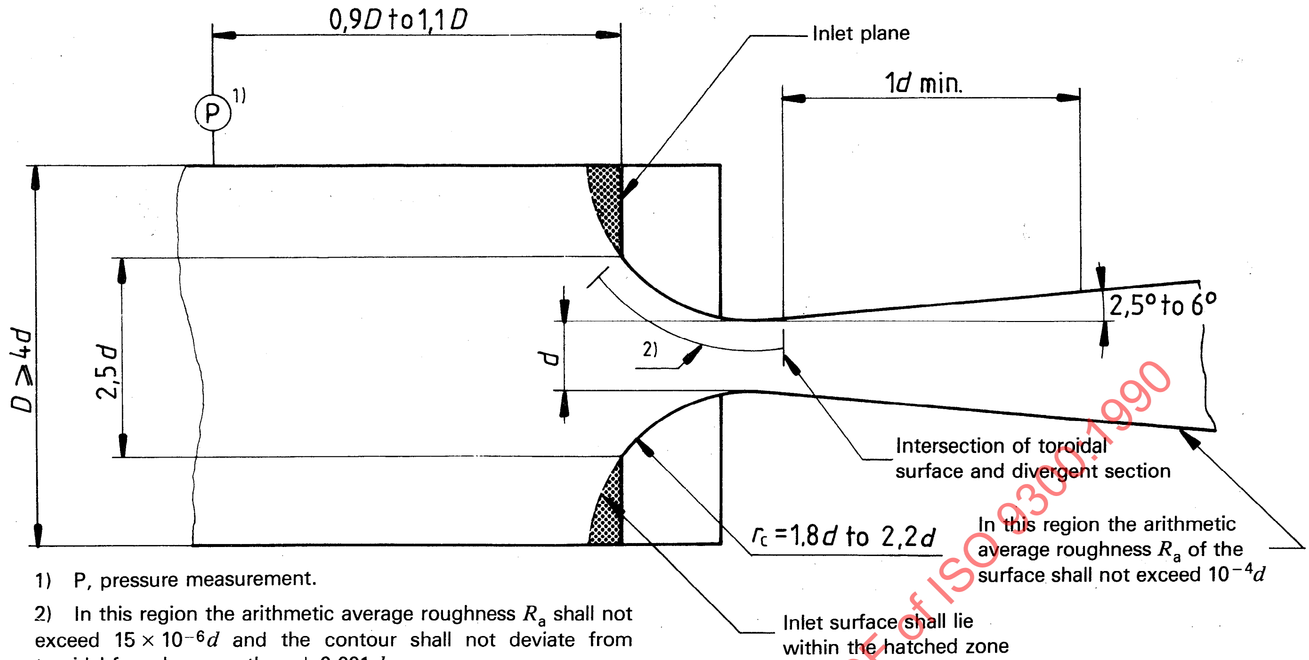
5.1.5 The form of the conical divergent section of the Venturi nozzle shall be checked to ensure that any steps, discontinuities, irregularities and lack of concentricity do not exceed 1 % of the local diameter. The arithmetic average roughness R_a of the conical divergent section shall not exceed $10^{-4}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

5.2 Design

There are two designs of standard Venturi nozzles, i.e. the toroidal throat Venturi nozzle and the cylindrical throat Venturi nozzle.

5.2.1 Toroidal throat Venturi nozzle

5.2.1.1 The Venturi nozzle shall conform with the specifications shown in figure 1.



1) P, pressure measurement.

2) In this region the arithmetic average roughness R_a shall not exceed $15 \times 10^{-6} d$ and the contour shall not deviate from toroidal form by more than $\pm 0{,}001 d$.

Figure 1 — Toroidal throat Venturi nozzle

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

5.2.1.3 The convergent section of the Venturi nozzle (inlet) shall be a portion of a torus which shall extend through the minimum area section (throat) and shall be tangential to the divergent section. The contour of the inlet upstream of the inlet plane (see 5.2.1.2) is not specified, except that the surface at each axial location shall have a diameter equal to or greater than the extension of the toroidal contour.

5.2.1.4 The toroidal surface of the Venturi nozzle 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 $2{,}2d$.

5.2.1.5 The divergent section of the Venturi nozzle 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.

5.2.2 Cylindrical throat Venturi nozzle

5.2.2.1 The Venturi nozzle shall conform with the specifications shown in figure 2.

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

5.2.2.3 The convergent section of the Venturi nozzle (inlet) shall be a quarter of a torus tangential on one hand to the inlet plane (see 5.2.2.2) 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.

5.2.2.4 The inlet toroidal surface of the Venturi nozzle shall not deviate from the shape of a torus by more than $\pm 0{,}001d$.

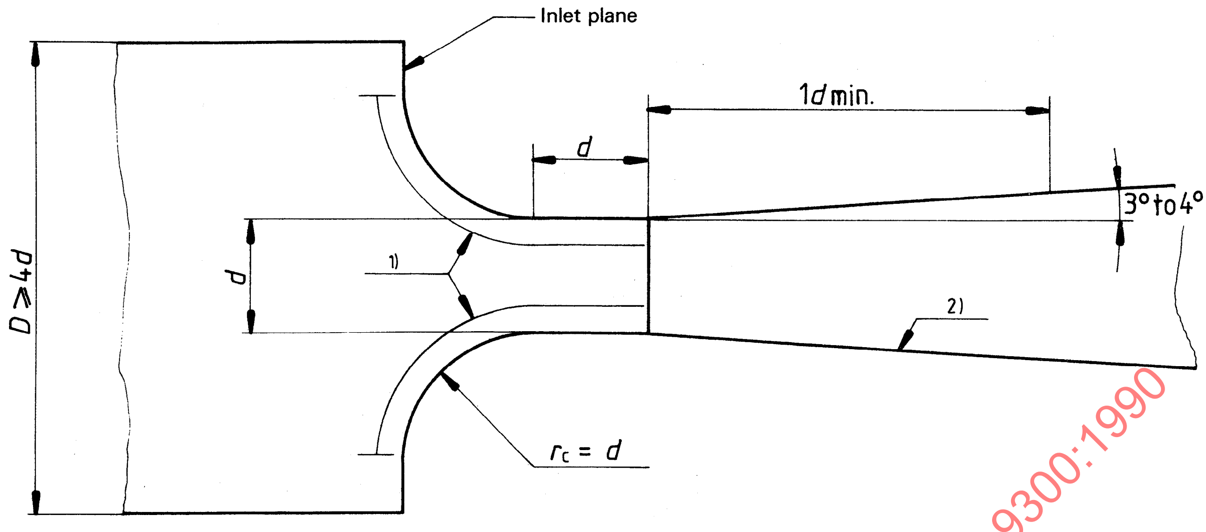
5.2.2.5 The flow-rate shall be calculated from the mean diameter at the cylindrical throat outlet section. The mean diameter shall be determined by measuring at least four angularly equally distributed diameters on the cylindrical throat outlet. No diameter along the throat length shall deviate by more than $\pm 0{,}001d$ 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 plane in which the axis of symmetry lies is never less than $0{,}5d$ throughout the inlet surface (quarter of torus and cylindrical throat). The total area of the inlet surface shall be properly polished so that the arithmetic average roughness R_a does not exceed $15 \times 10^{-6} d$.

The connection between the cylindrical throat and the divergent section shall also be visually inspected and no defect shall be observed.

5.2.2.6 The divergent section of the Venturi nozzle comprises a frustum of a cone with a half-angle between 3° and 4°. The length of the divergent section shall be not less than the throat diameter.



1) In this region the arithmetic average roughness R_a of the surface shall not exceed $15 \times 10^{-6} d$ and the contour shall not deviate from toroidal and cylindrical form by more than $\pm 0{,}001 d$.

2) In the conical divergent section the arithmetic average roughness R_a shall not exceed $10^{-4} d$.

Figure 2 — Cylindrical throat Venturi nozzle

6 Installation requirements

6.1 General

This International Standard applies to the installation of critical Venturi nozzles when either

a) the pipeline upstream of the Venturi nozzle is of circular cross-section, or

b) it can be assumed that there is a large space upstream of the Venturi nozzle.

For case a), the primary device shall be installed in a system meeting the requirements of 6.2. For case b), the primary device shall be installed in a system meeting the requirements of 6.3. In both cases, swirl shall not exist upstream of the Venturi nozzle. Where a pipeline exists upstream of the nozzle, swirl-free conditions can be ensured by installing a flow straightener of the design shown in figure 3 at a distance $l_1 > 5D$ upstream of the nozzle inlet plane.

6.2 Upstream pipeline

The primary device may be installed in a straight circular conduit which shall be concentric within $\pm 0{,}02D$ with the centre-line of the Venturi nozzle. The inlet conduit up to $3D$ upstream of the Venturi nozzle shall not deviate from circularity by more than $0{,}01D$ and shall have an arithmetic average roughness R_a which shall not exceed $10^{-4}D$. The diameter of the inlet conduit shall be a minimum of $4d$.

6.3 Large upstream space

It can be assumed that there is a large space upstream of the primary device if there is no wall closer than $5d$ to the axis of the primary device or to the inlet plane of the primary device, as defined in 5.2.1.2 or 5.2.2.2.

6.4 Downstream requirements

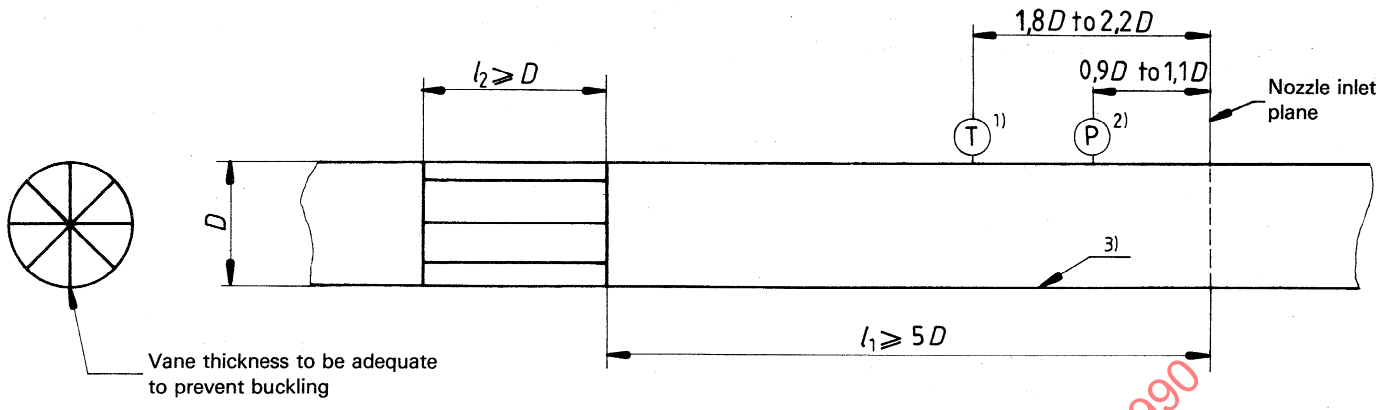
No requirements are imposed on the outlet conduit except that it shall not restrict the flow so as to prevent critical flow in the Venturi nozzle.

6.5 Pressure measurement

6.5.1 When a circular conduit is used upstream of the primary device the upstream static pressure shall preferably be measured at a wall pressure tapping at a distance $0{,}9D$ to $1{,}1D$ from the inlet plane of the Venturi nozzle (see figure 1). The wall pressure tapping may be located upstream or downstream of this position provided that it has been demonstrated that the measured pressure can be used reliably to give the nozzle inlet stagnation pressure.

6.5.2 When it can be assumed that there is a large space upstream of the primary device the upstream wall pressure tapping shall preferably be located in a wall perpendicular to the inlet face of the primary device and within a distance of $10d \pm 1d$ from that plane. The wall pressure tapping may be located upstream or downstream of this position provided that it has been demonstrated that the measured pressure can be used reliably to give the nozzle inlet stagnation pressure.

6.5.3 For the wall pressure tapping mentioned in 6.5.1, and preferably also for that mentioned in 6.5.2, the centre-line of the wall pressure tapping shall meet the centre-line of the primary device and be at right angles to it. At the point of the breakthrough, the hole shall be circular. The edges shall be free



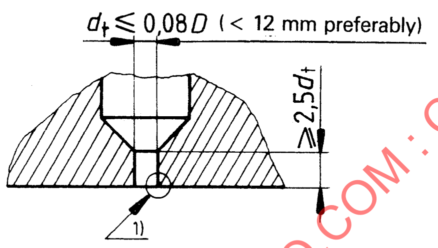
1) P, pressure measurement.

2) T, temperature measurement.

3) In this region the surface roughness shall not exceed $10^{-4}D$.

Figure 3 — Installation requirements for an upstream pipework configuration

from burrs, and shall be square or lightly rounded to a radius not exceeding 0,1 times the diameter of the wall pressure tapping. It shall be confirmed by visual inspection that the wall pressure tappings comply with these requirements. When an upstream pipeline is used the diameter of the wall pressure tapping shall be less than $0{,}08D$ and preferably less than 12 mm. The wall pressure tapping shall be cylindrical for a minimum length of 2,5 times the diameter of the tapping (see figure 4).



1) Edge of hole flush with internal surface of conduit, burr-free and square to a radius not exceeding $0{,}1d_t$.

Figure 4 — Detail of a wall pressure tapping when an upstream pipeline is used

6.5.4 The downstream pressure shall be measured to ensure that critical flow is maintained. This pressure shall be measured by using a conduit wall pressure tapping located within 0,5 times the conduit diameter of the exit plane of the divergent section.

6.5.5 In some applications the outlet pressure can be determined without the use of a wall pressure tapping. For example, the Venturi nozzle may discharge directly into the atmosphere or other region of known pressure. In these applications the outlet pressure need not be measured.

6.6 Drain holes

The conduit may be provided with the necessary drain holes for the removal of condensate or other foreign substances that may collect in some applications. There should be no flow through these drain holes while the flow measurement is in progress. If drain holes are required they shall be located upstream of the nozzle upstream wall pressure tapping. The diameter of the drain holes should be smaller than $0{,}06D$. The axial distance from the drain hole to the plane of the upstream wall pressure tapping shall be greater than D and the hole shall be located in an axial plane different from that of the wall pressure tapping.

6.7 Temperature measurement

The inlet temperature shall be measured using one or more sensors located upstream of the Venturi nozzle. When an upstream pipeline is used the recommended location of these sensors is $1{,}8D$ to $2{,}2D$ upstream of the inlet plane of the Venturi nozzle. The diameter of the sensing element shall be not larger than $0{,}04D$ and the element shall not be aligned with a wall pressure tapping in the flow direction. If it is impracticable to use a sensing element of diameter less than $0{,}04D$, the sensing element shall be so located that it can be demonstrated that it does not affect the pressure measurement. The sensor can be located further still upstream provided that it has been demonstrated that the measured temperature can be used reliably to give the nozzle inlet stagnation temperature.

Particular care has to be exercized in the selection of the temperature sensor and the insulation of pipework if the stagnation temperature of the flowing gas differs from that of the medium surrounding the pipeline by more than 5 K. In these cases the sensor selected shall be insensitive to radiation error and the pipework shall be well lagged to minimize heat transfer between the flowing gas and the surrounding medium. If the temperatures of the flowing gas and the pipe wall differ significantly it is extremely difficult to measure the gas temperature accurately.

6.8 Density measurement

For some applications, it may be desirable to measure directly the gas density at the nozzle inlet, for instance when the molar mass of the gas is not known with a sufficient accuracy.

When a densitometer is used, it shall be installed upstream of the nozzle and of the upstream pressure and temperature tappings. To achieve correct measurement of the inlet gas density, particular attention shall be given to the following points.

a) The installation of the densitometer shall not disturb the pressure and temperature measurements.

b) When the densitometer is located outside the main upstream pipe, checks shall be carried out to ensure that the gas in the device is the same as the gas flowing in the main conduit.

c) The pressure and temperature conditions at the densitometer should be as close as possible to the nozzle inlet conditions in order to avoid corrections. If necessary, the inlet density shall be computed from the measured density using the equation of state:

$$\varrho_0 = \varrho_d \frac{p_0}{p_d} \frac{T_d}{T_0} \frac{Z_d}{Z_0}$$

where the subscript d indicates "relative to the densitometer".

7 Calculation methods

7.1 Mass flow-rate

The actual mass flow-rate shall be computed from one of the following equations:

$$q_m = A_* C C_* p_0 \Big/ \left(\frac{R}{M} T_0\right)^{1/2}$$

or

$$q_m = A_* C C_R (p_0 \varrho_0)^{1/2}$$

7.2 Discharge coefficient

7.2.1 The discharge coefficient depends largely on the shape of the Venturi nozzle and it shall be noted that at small values of the throat diameter the nozzle geometry is very difficult to control and measure.

7.2.2 The discharge coefficient for the Venturi nozzle may be obtained from the following equation:

$$C = a - b\, Re_d^{-n}$$

The coefficients a, b and n are given in table 2 for each type of Venturi nozzle for the range of throat Reynolds number over which they may be used.

7.2.3 The relative uncertainty in the discharge coefficients obtained from the equation specified in 7.2.2 is ± 0,5 %, at the 95 % confidence level, for both types of nozzle.

Values of the discharge coefficient are given in annex A.

7.3 Critical flow function

The value of C_* used to calculate the gas mass flow-rate may be computed using any method of demonstrable accuracy. Values of C_* for various gases are given in annex B.

7.4 Real gas critical flow coefficient

The value of C_R used to calculate the gas mass flow-rate may be computed using any method of demonstrable accuracy. A method of computation of C_R for natural gases is given in annex C.

7.5 Conversion of measured pressure and temperature to stagnation conditions

The inlet stagnation pressure p_0 may be determined from the relationship

$$\frac{p_0}{p_1} = \left(1 + \frac{\kappa - 1}{2} Ma_1^2\right)^{\kappa/(\kappa - 1)}$$

The inlet stagnation temperature T_0 may be determined from the formula

$$\frac{T_0}{T_1} = 1 + \frac{\kappa - 1}{2} Ma_1^2$$

Table 2 — Coefficients a, b and n

Toroidal throat Venturi nozzle		Cylindrical throat Venturi nozzle	
$10^5 < Re_d < 10^7$	a = 0,993 5 b = 1,525 0 n = 0,5	$3{,}5 \times 10^5 < Re_d < 2{,}6 \times 10^6$	a = 0,988 7 b = n = 0
		$2{,}6 \times 10^6 \leqslant Re_d < 2 \times 10^7$	a = 1 b = 0,216 5 n = 0,2

7.6 Maximum permissible downstream pressure

For Venturi nozzles operating at throat Reynolds numbers greater than 2×10^5 and having exit cones longer than d the maximum permissible downstream pressure is determined from the relationship

$$(p_2/p_0)_{max} = 0{,}8\,[(p_2/p_0)_i - r_*] + r_*$$

where

$$r_* = \left(\frac{2}{\kappa + 1}\right)^{\kappa/(\kappa - 1)}$$

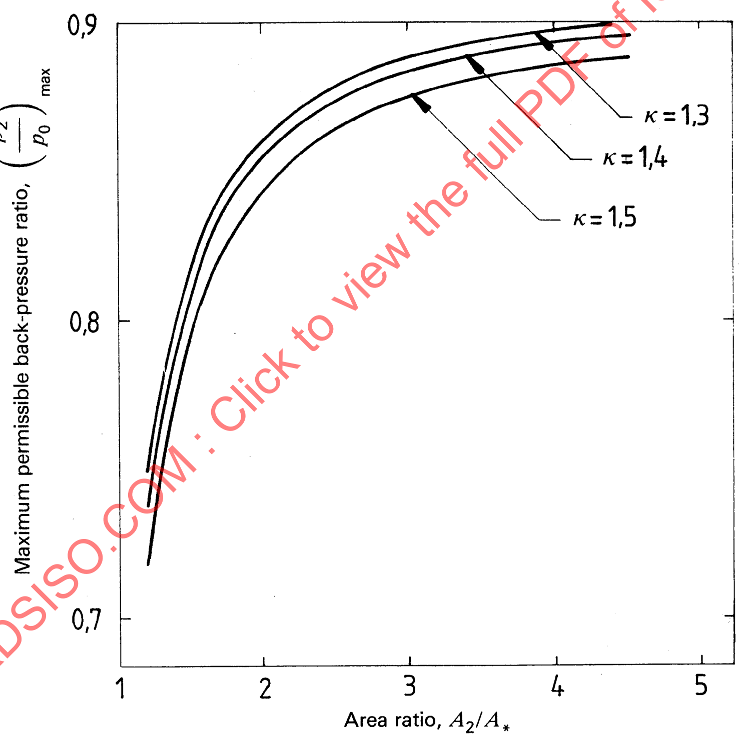
The value of $(p_2/p_0)_i$ is determined from the isentropic ideal gas relationships as a function of the area ratio of the divergent section. Values of $(p_2/p_0)_{max}$ may be determined from figure 5. Higher back-pressure ratios than those shown may be used provided that it can be verified that the flow is critical. The pressure ratio p_2/p_0 is not significantly affected by extending the cone length such that the exit area is greater than four times the throat area, i.e. beyond seven diameters for a cone half-angle of 4°.

8 Uncertainties in the measurement of flow-rate

Useful general information on this subject is given in ISO 5168.

8.1 General

8.1.1 The uncertainty in the measurement of the flow-rate shall be calculated and shall be reported under this name whenever a measurement is claimed to be in conformity with this International Standard.



NOTE — The area ratio A_2/A_* is related to the Venturi nozzle dimensions by the following formulae:

a) for toroidal throat Venturi nozzles

$$\frac{A_2}{A_*} = \left[\frac{2l \tan\theta}{d} + \frac{2r_c}{d}(1 - \cos\theta) + 1\right]^2$$

b) for cylindrical throat Venturi nozzles

$$\frac{A_2}{A_*} = \left(\frac{2l \tan\theta}{d} + 1\right)^2$$

where

l is the length of the divergent;

θ is the half-angle of the divergent.

Figure 5 — Maximum permissible back-pressure ratio for critical flow Venturi nozzles

8.1.2 The uncertainty may be expressed in absolute or relative terms and the results of the flow measurement may then be given in any one of the following forms:

$q_m \pm e(q_m)$

$q_m [1 \pm E(q_m)]$

q_m within $E(q_m)$

where the absolute uncertainty $e(q_m)$ shall have the same dimensions as q_m, and the relative uncertainty $E(q_m) = e(q_m)/q_m$ is non-dimensional.

8.1.3 The uncertainty in the flow measurement as defined in this International Standard (see 2.1.5) is equivalent to twice the standard deviation. As for the standard deviation, the uncertainty is obtained by combining the partial uncertainties of the individual quantities which are used in the calculation of the flow-rate, assuming them to be small, numerous and independent of each other. Although for a single measuring device, and for the coefficients used in one test, some of these uncertainties may in reality be the result of systematic errors (of which only an estimation of their maximum absolute amount is known), their combination is permitted as if they were random errors having a distribution conforming to the Laplace-Gauss normal law.

8.2 Practical computation of uncertainty

8.2.1 The basic formula for the computation of the mass rate of flow q_m is either

$$q_m = A_* C C_* p_0 \bigg/ \left(\frac{R}{M} T_0\right)^{1/2}$$

or

$$q_m = A_* C C_R (p_0 \varrho_0)^{1/2}$$

In fact, the various quantities which appear on the right-hand side of these formulae are not independent and so it is not strictly correct to compute the uncertainty in q_m directly from the uncertainties in these quantities. (For example, C_* and C_R are functions of p_0 and T_0, and C is a function of d, μ_0 and q_m.)

However, it is sufficient for most practical purposes to assume that the uncertainties in the terms on the right-hand side of the equations are independent of each other.

8.2.2 The practical working formula for calculating the relative uncertainty in the mass flow-rate q_m is

$$E(q_m) = \left[E^2(C_*) + E^2(C) + E^2(A_*) + E^2(p_0) + \right.$$
$$\left. + \frac{1}{4} E^2(M) + \frac{1}{4} E^2(T_0)\right]^{1/2}$$

or

$$E(q_m) = \left[E^2(C_R) + E^2(C) + E^2(A_*) + \frac{1}{4} E^2(\varrho_0) + \right.$$
$$\left. + \frac{1}{4} E^2(p_0)\right]^{1/2}$$

When the inlet gas density is not directly measured but is computed from the equation given in 6.8 c), the uncertainty relative to ϱ_0 is given by

$$E(\varrho_0) = \left\{E^2(\varrho_d) + \left[1 - \left(\frac{\partial Z}{\partial p}\right)_d \frac{p_d}{Z_d}\right]^2 E^2(p_d) + \right.$$
$$+ \left[1 - \left(\frac{\partial Z}{\partial p}\right)_0 \frac{p_0}{Z_0}\right]^2 E^2(p_0) +$$
$$+ \left[1 + \left(\frac{\partial Z}{\partial p}\right)_d \frac{T_d}{Z_d}\right]^2 E^2(T_d) +$$
$$\left. + \left[1 + \left(\frac{\partial Z}{\partial T}\right)_0 \frac{T_0}{Z_0}\right]^2 E^2(T_0)\right\}^{1/2}$$

which often simplifies to

$$E(\varrho_0) = [E^2(\varrho_d) + E^2(p_d) + E^2(p_0) + E^2(T_d) +$$
$$+ E^2(T_0)]^{1/2}$$

Annex A
(normative)

Venturi nozzle discharge coefficients

Table A.1 — Toroidal throat Venturi nozzle discharge coefficients

Reynolds number Re_d	Discharge coefficient C
1×10^5	0,988 7
2×10^5	0,990 1
3×10^5	0,990 7
5×10^5	0,991 3
7×10^5	0,991 7
1×10^6	0,992 0
2×10^6	0,992 4
3×10^6	0,992 6
5×10^6	0,992 8
7×10^6	0,992 9
1×10^7	0,993 0

Table A.2 — Cylindrical throat Venturi nozzle discharge coefficients

Reynolds number Re_d	Discharge coefficient C
$3,5 \times 10^5$ to $2,6 \times 10^6$	0,988 7
5×10^6	0,990 1
7×10^6	0,990 7
1×10^7	0,991 4
2×10^7	0,992 5

Annex B
(normative)

Tables of values of the critical flow function C_* for various gases

Table B.1 — Values of C_* for nitrogen

Stagnation temperature °C	C_* for the following values of stagnation pressure (MPa)											
	0	0,5	1	2	3	4	5	6	7	8	9	10
− 50	0,684 8	0,687 8	0,690 8	0,697 0	0,703 5	0,710 2	0,717 1	0,724 3	0,731 5	0,738 9	0,746 2	0,753 6
− 25	0,684 8	0,686 9	0,689 1	0,693 4	0,697 8	0,702 3	0,706 9	0,711 5	0,716 1	0,720 8	0,725 4	0,729 9
0	0,684 8	0,686 3	0,687 9	0,691 0	0,694 1	0,697 2	0,700 4	0,703 5	0,706 7	0,709 7	0,712 8	0,715 8
25	0,684 8	0,685 9	0,687 0	0,689 3	0,691 5	0,693 8	0,696 0	0,698 2	0,700 4	0,702 5	0,704 6	0,706 6
50	0,684 7	0,685 5	0,686 4	0,688 0	0,689 6	0,691 3	0,692 8	0,694 4	0,695 9	0,697 4	0,698 9	0,700 3
75	0,684 6	0,685 3	0,685 9	0,687 1	0,688 2	0,689 4	0,690 5	0,691 6	0,692 7	0,693 8	0,694 8	0,695 8
100	0,684 5	0,685 0	0,685 4	0,686 3	0,687 1	0,688 0	0,688 8	0,689 5	0,690 3	0,691 0	0,691 7	0,692 4

Table B.2 — Values of C_* for oxygen

Stagnation temperature °C	C_* for the following values of stagnation pressure (MPa)											
	0	0,5	1	2	3	4	5	6	7	8	9	10
− 50	0,684 6	0,688 6	0,692 7	0,701 3	0,710 4	0,720 1	0,730 4	0,741 3	0,752 8	0,765 0	0,777 9	0,791 4
− 25	0,684 5	0,687 5	0,690 5	0,696 6	0,703 0	0,709 6	0,716 4	0,723 4	0,730 7	0,738 1	0,745 7	0,753 5
0	0,684 4	0,686 6	0,688 9	0,693 4	0,698 1	0,702 8	0,707 6	0,712 5	0,717 5	0,722 5	0,727 6	0,732 6
25	0,684 2	0,685 9	0,687 6	0,691 1	0,694 6	0,698 1	0,701 6	0,705 2	0,708 7	0,712 3	0,715 9	0,719 4
50	0,683 9	0,685 2	0,686 5	0,689 2	0,691 9	0,694 5	0,697 2	0,699 9	0,702 5	0,705 1	0,707 8	0,710 3
75	0,683 5	0,684 5	0,685 5	0,687 6	0,689 7	0,691 7	0,693 8	0,695 8	0,697 8	0,699 8	0,701 7	0,703 7
100	0,682 9	0,683 7	0,684 5	0,686 1	0,687 7	0,689 3	0,690 9	0,692 5	0,694 0	0,695 5	0,697 0	0,698 4

Table B.3 — Values of C_* for argon

Stagnation temperature °C	C_* for the following values of stagnation pressure (MPa)											
	0	0,5	1	2	3	4	5	6	7	8	9	10
− 50	0,726 2	0,731 0	0,735 8	0,746 0	0,756 7	0,767 9	0,779 7	0,792 2	0,805 3	0,819 1	0,833 5	0,848 4
− 25	0,726 2	0,729 7	0,733 3	0,740 7	0,748 2	0,756 0	0,763 9	0,772 0	0,780 3	0,788 8	0,797 5	0,806 2
0	0,726 2	0,728 9	0,731 6	0,737 2	0,742 7	0,748 4	0,754 0	0,759 8	0,765 5	0,771 3	0,777 2	0,783 0
25	0,726 2	0,728 3	0,730 4	0,734 7	0,738 9	0,743 2	0,747 4	0,751 7	0,755 9	0,760 1	0,764 3	0,768 4
50	0,726 2	0,727 9	0,729 5	0,732 9	0,736 2	0,739 5	0,742 7	0,746 0	0,749 2	0,752 3	0,755 5	0,758 5
75	0,726 2	0,727 5	0,728 9	0,731 5	0,734 2	0,736 7	0,739 3	0,741 8	0,744 3	0,746 7	0,749 1	0,751 5
100	0,726 2	0,727 3	0,728 4	0,703 5	0,732 6	0,734 7	0,736 7	0,738 7	0,740 6	0,742 6	0,744 4	0,746 3