The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

MetHyInfra

Workshop on Critical Flow Nozzle Calibration

Calibration approaches and ISO 9300

20IND11

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Overview

Various calibration approaches are possible for sonic nozzles

“Dry” Calibration

Using ISO 9300 Cd Model
or
From 1st principles e.g. CFD

Requires dimensional characterisation

“Wet” Calibration

Calibration with hydrogen
or
Calibration with alternative gas e.g. air

Combination

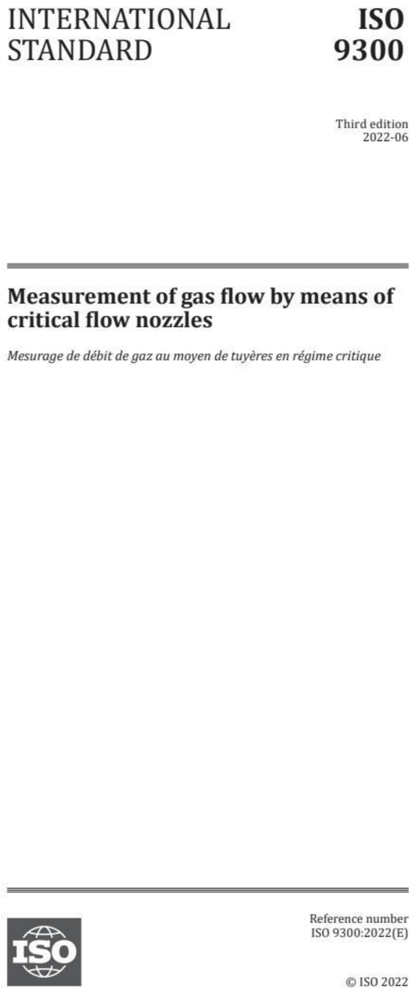
Using both flow calibration and modelling e.g.

The requirements vary for each calibration approach. Regardless, nozzles are usually based on the ISO 9300 shape

What is a sonic nozzle?

ISO 9300 provides detailed guidance on:

- Nozzle Geometry
- Manufacturing requirements
- Installation requirements
- Operating Conditions
- Calculation Methods



INTERNATIONAL STANDARD

ISO 9300

Third edition
2022-06

Measurement of gas flow by means of critical flow nozzles

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

Reference number
ISO 9300:2022(E)

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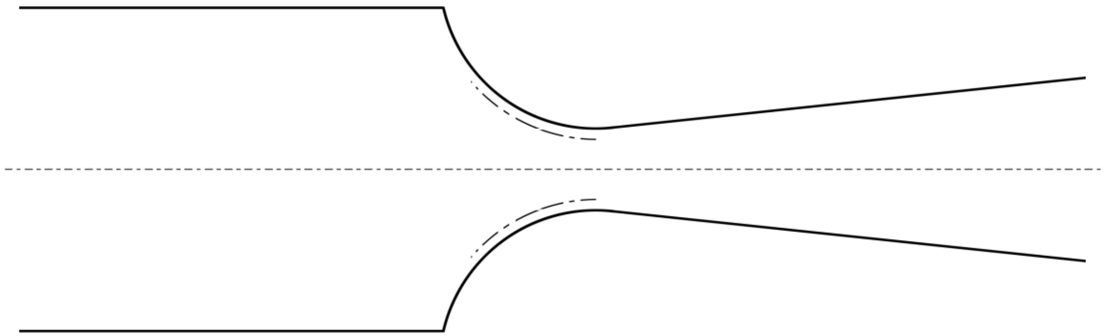
ISO 9300 Requirements

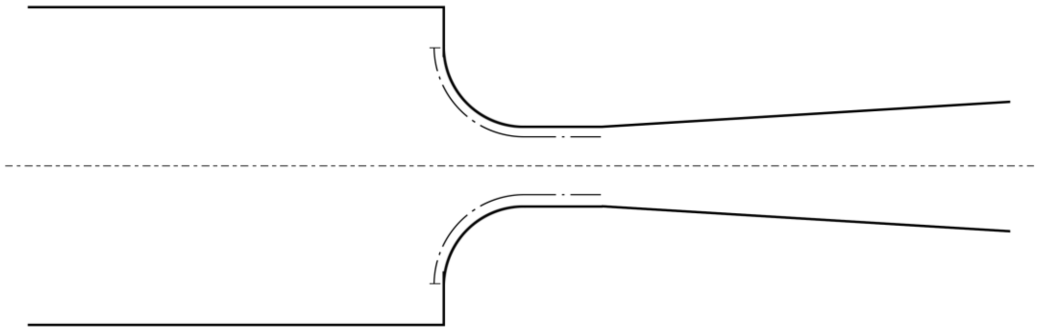
Nozzle Geometry

Two nozzle designs are presented in the standard: the toroidal-throat nozzle and the cylindrical-throat nozzle.

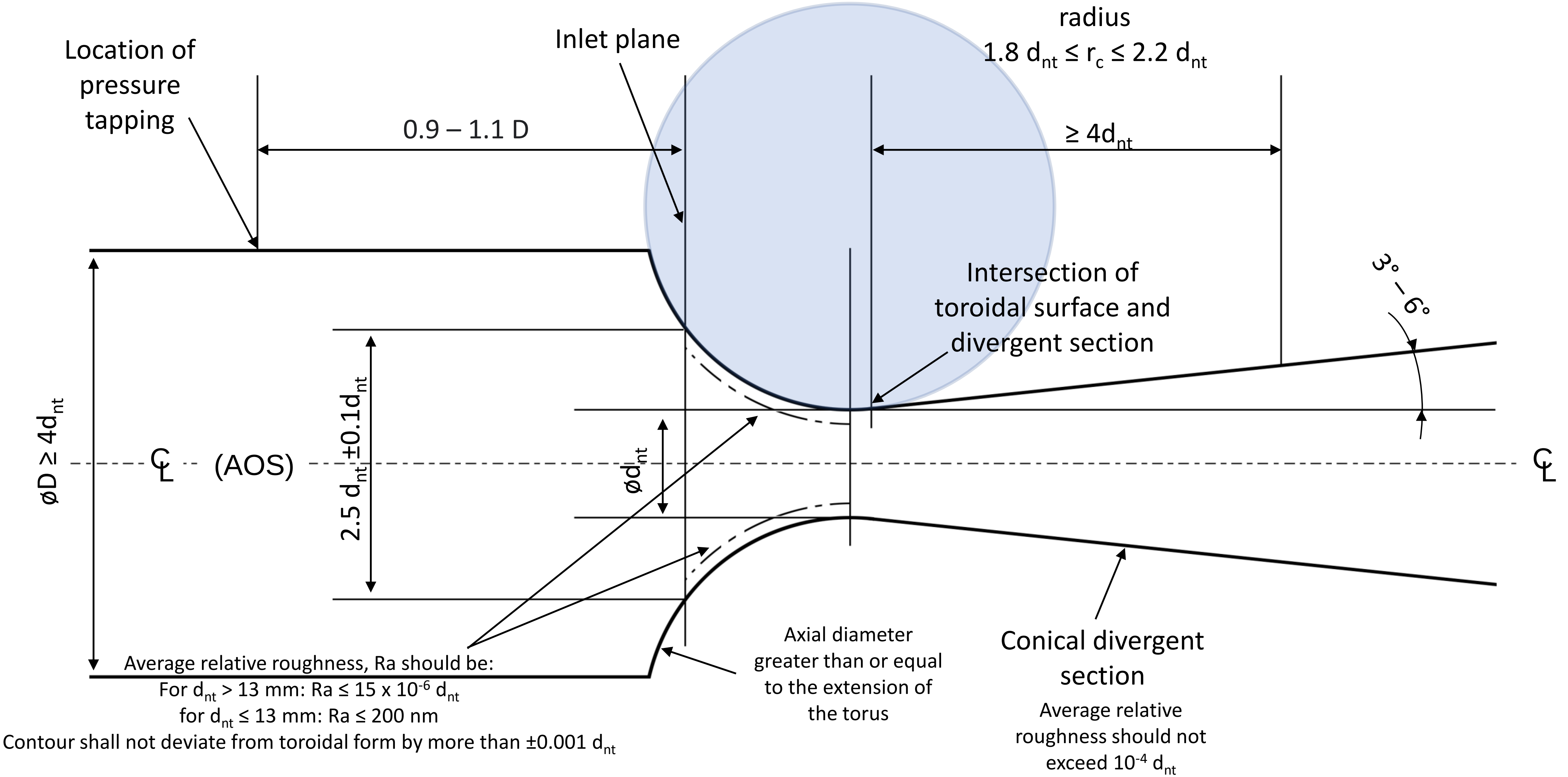
Toroidal-throat



Cylindrical-throat



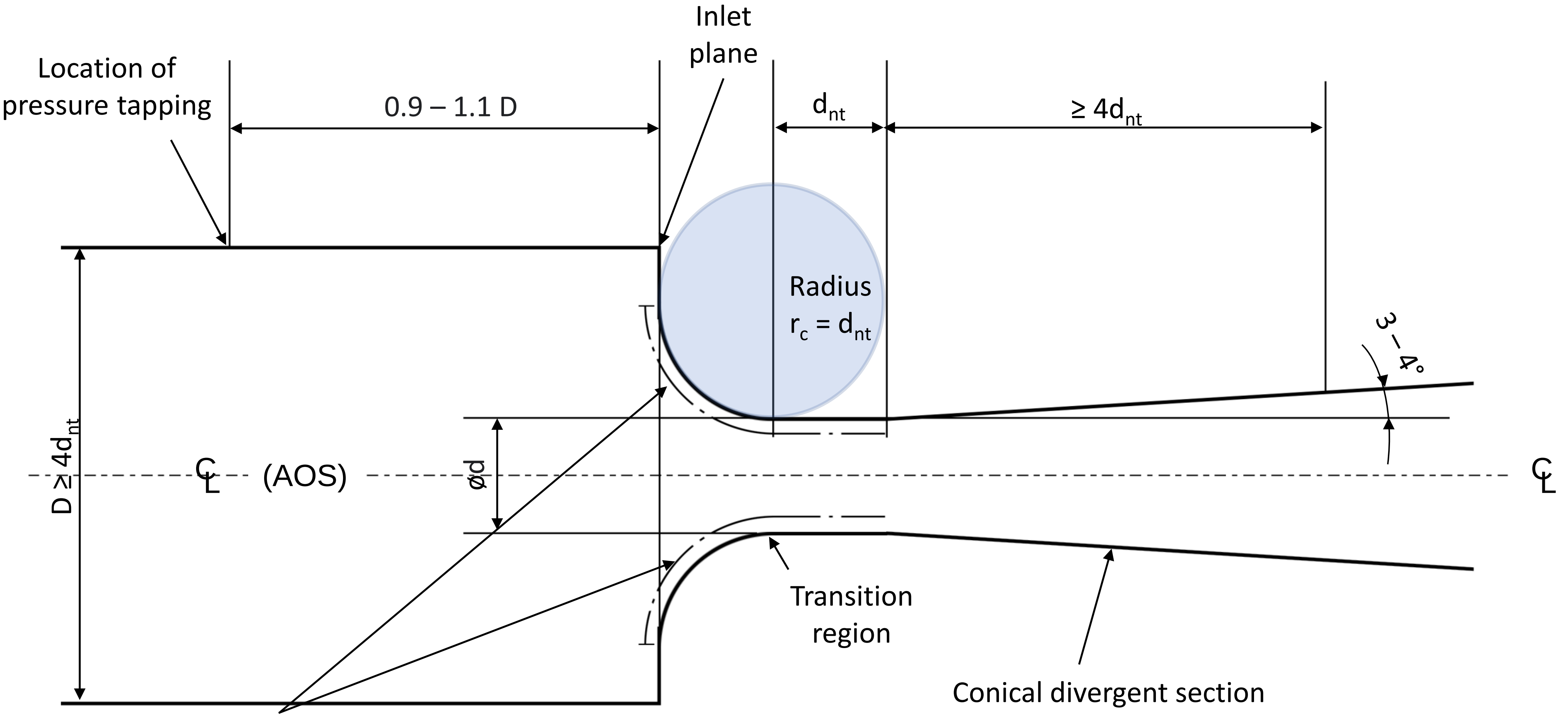
Toroidal-throat



Average relative roughness, Ra should be:
For $d_{nt} > 13$ mm: $Ra \leq 15 \times 10^{-6}\ d_{nt}$
for $d_{nt} \leq 13$ mm: $Ra \leq 200$ nm
Contour shall not deviate from toroidal form by more than $\pm 0.001\ d_{nt}$

Average relative roughness should not exceed $10^{-4}\ d_{nt}$

Cylindrical-throat



Conical divergent section

Average relative roughness shall not exceed 10^{-4} d

Average relative roughness Ra shall not exceed 15 x 10^{-6} d_{nt}.

Contour shall not deviate from toroidal and cylindrical forms by more than ±0.001 d_{nt}

Roughness considerations

ISO 9300 Roughness requirement	
Toroidal, $d_{nt} > 13$ mm	$15 \times 10^{-6}\ d_{nt}$
Toroidal, $d_{nt} \leq 13$ mm	0.2 µm

Manufacturing method	Arithmetic average roughness, Ra
Spark eroded	> 1 µm [1]
Standard lathe, unpolished	< 1 µm [1][2]
Standard lathe, polished	Approx. 0.4 µm [1][2]
Standard lathe, well polished	Approx. 0.1 µm [1][2]
Highly-accurate lathe, unpolished	Approx. 0.03 µm [3]

- Required roughness difficult to achieve
- Some studies found that higher roughness levels can be tolerated
- Some studies show large influence of roughness at high Reynolds numbers

[1] Gibson, J., Stewart, D. Considerations for ISO 9300 – The effects of roughness and form on the discharge coefficient of toroidal throat sonic nozzles, Proceedings of ASME JSME Joint Fluids Engineering Conference, 2003
[2] Wendt, G., von Lavante, E. Influnce of surface roughness on the flowrate behaviour of small critical venturi nozzles, Proceedings of Flomeko 2000
[3] ISHIBASHI, M., TAKAMOTO, M. Theorical discharge coefficient of a critical circular-arc nozzle with laminar boundary layer and its verification by measurements using super-accurate nozzles, Flow Measurement and Instrumentation 11, 305/313, 2000

ISO 9300 Requirements

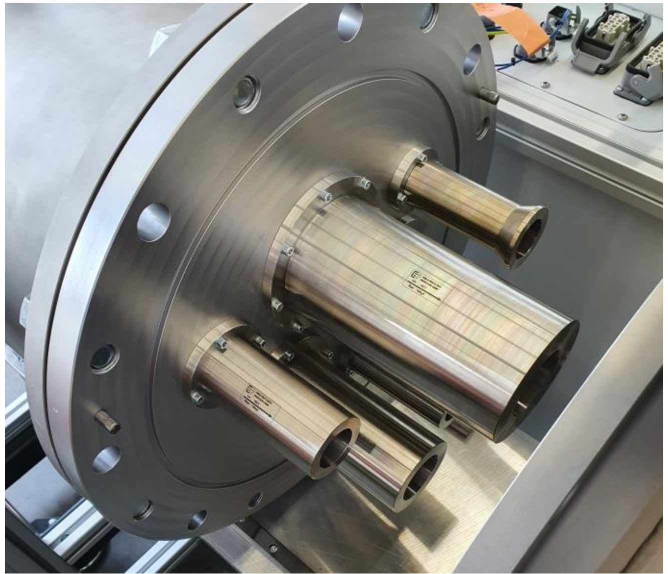
Installation

Two configurations are considered in the standard:

- Installation in a pipe of circular cross section, β ≤ 0.25
- Installation with a large space upstream, including single nozzles or several nozzles in a parallel array, β ≈ 0

In either case, swirl upstream of the nozzle must be eliminated.

Source: NEL



Source: Ehrler Prüftechnik Engineering (EP-E)

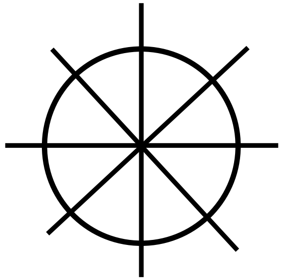
ISO 9300 Requirements

Upstream Pipeline

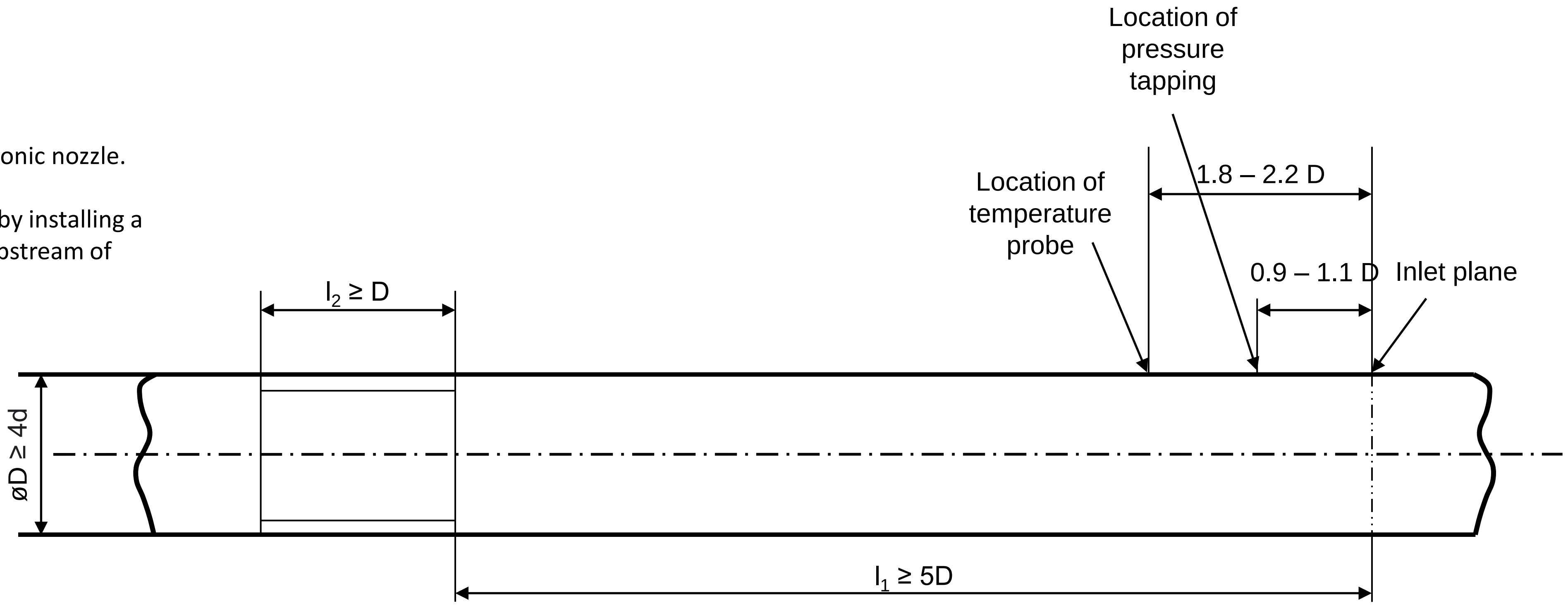
Conduit must be straight and circular, concentric within ±0.02 D with centre line of the sonic nozzle.

Swirl shall not exist upstream of the sonic nozzle.

Swirl-free conditions can be ensured by installing a suitable flow conditioner at l1 > 5D upstream of nozzle inlet plane



Etoile flow straightener



Inlet conduit up to 3D upstream of the nozzle, shall not deviate from circularity by more than 0.01 D, surface roughness shall not exceed 10^{-4} D

ISO 9300 Requirements

Large upstream space

- When there is no pipe wall closer than 5d to the axis of symmetry or to the inlet plane of the sonic nozzle, it can be assumed that there is a “large upstream space”.
- For this installation, multiple nozzles can be connected to the same inlet conduit and used in parallel.
- Pressure tapping should be located in a wall perpendicular to the inlet face of the primary device and within a distance of 10d ± 1d from that plane.

ISO 9300 Requirements

Mass Flow Rate Calculation

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

Where:

q_m = Mass flow rate (kg/s)
A = Flow area (m^2)
Cd = Discharge coefficient (-)
C* = Critical Flow Function (-)
p_0 = Absolute inlet pressure at gas stagnation conditions (Pa)
R = Universal gas constant = 8.314 J/mol·K
M = Molar Mass (kg/mol)
T_0 = Inlet Temperature at gas stagnation conditions (K)

ISO 9300 Requirements

Stagnation Conditions

Fluid properties used in the sonic nozzle calculations are calculated based on pressure and temperature at stagnation conditions i.e. the conditions which would exist if the gas was brought to rest by an isentropic process.

The measured inlet temperature and pressure can be converted to stagnation conditions as follows:

$$\frac{p_0}{p_1} = \left[1 + \frac{1}{2}(\kappa - 1)Ma_1^2\right]^{\kappa/(\kappa-1)} \qquad \frac{T_0}{T_1} = 1 + \frac{1}{2}(\kappa - 1)Ma_1^2$$

Where:

p_0 = Absolute inlet pressure at gas stagnation conditions (Pa)
p_1 = Absolute inlet static pressure (Pa)
T_0 = Absolute Inlet Temperature at gas stagnation conditions (K)
T_1 = Absolute Inlet Temperature (K)
Ma_1 = Mach number at upstream pressure tapping (-)
κ = Isentropic exponent (-)

Note: These corrections can be neglected if β is sufficiently low:

$$p_0 = p_1 \qquad \text{if } \beta \leq 0.15$$
$$T_0 = T_1 \qquad \text{if } \beta \leq 0.25$$

ISO 9300 Requirements

Critical Flow Function (C*)

A dimensionless parameter which characterises the thermodynamic flow properties of an isentropic, one-dimensional flow between the inlet and throat of a sonic nozzle. C* is a function of the nature of the gas and the stagnation conditions.

Annex C of ISO 9300 provides tabulated values and equations for various gases (nitrogen, argon, dry air, methane, carbon dioxide, oxygen and steam) with 0.1% uncertainty (k=2). C* can be calculated for natural gases with 0.05% uncertainty (k=2) using the AGA8 equation of state.

Note that no C* calculation method for hydrogen is currently included in ISO 9300. Addressed in presentation 8.

ISO 9300 Requirements

Discharge Coefficient (C_d)

ISO 9300 provides tabulated discharge coefficients (Annex A) and an equation (17)

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

Where:

Re_{nt} = Nozzle throat Reynolds number

Toroidal-throat Sonic Nozzle	
$2.1 \times 10^4 < Re_{nt} < 3.2 \times 10^7$	a = 0.9990 b = 3.415 c = 0.0031 d = 0.690 e = 10 f = 120 000 n = 0.5
Cylindrical-throat Sonic Nozzle	
$1.5 \times 10^5 < Re_{nt} < 1.2 \times 10^7$	a = 1 b = 6.341 c = 0.009 c = 0.008 for natural gas d = 3 e = 6 f = 170 000 n = 0.5

The relative uncertainty of discharge coefficients calculated with eqn 17 is 0.3% at 95 % confidence level

Note: For the user to achieve these uncertainties in discharge coefficient, the manufacturing tolerances of the nozzle geometry must be adhered to. Alternatively, discharge coefficient can be determined by flow calibration.

ISO 9300 Requirements

Reynolds number

Dimensionless parameter, ratio of inertial to viscous forces for the fluid.

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

Where:

q_m = Mass flow rate (kg/s)
d_{nt} = Throat diameter (m)
μ_0 = dynamic viscosity at gas stagnation conditions (Pa·s)

ISO 9300 Requirements

Critical back-pressure ratio

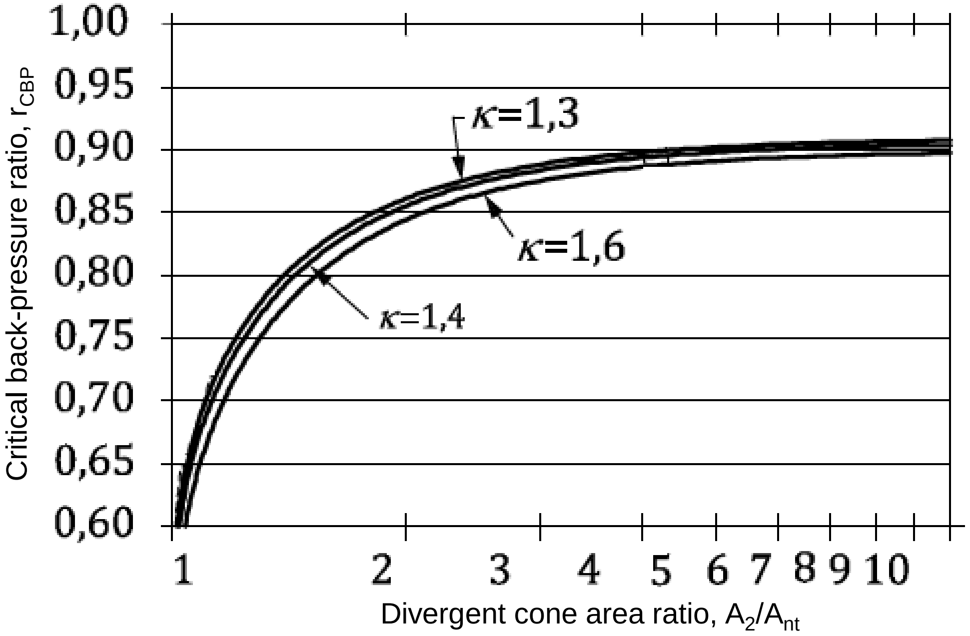
Can be determined from the chart, for nozzles with traditional diffusers, operating at Reynolds numbers above 2 x 10^5.

A Reynolds number dependence is observed at low Reynolds numbers. At Re < 2 x 10^5, the user is advised to:

- Operate the nozzle with back-pressure ratio of 0.25 or below

or

- Perform Nozzle unchoking tests to confirm that premature unchoking does not occur



Measurement Uncertainty

Considering the Mass Flow equation

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

The uncertainty in mass flow rate can be determined from the uncertainty in the inputs to the calculation.

Measurement Uncertainty

Uncertainty Budget – ISO 9300 Cd equation

Parameter	Uncertainty, u (k=2) %	Sensitivity Coefficient, c	u·c	$(u\cdot c)^2$	Contribution to Uncertainty, %
Throat diameter, d	0.1	2	0.2	0.04	26.6
Discharge Coefficient, Cd	0.3	1	0.3	0.09	59.9
Critical Flow Factor, C*	0.1	1	0.1	0.01	6.7
Inlet Pressure, P_0	0.1	1	0.1	0.01	6.7
Universal Gas Constant, R	<0.01	-0.5	<-0.005	$< 2.5 \times 10^{-5}$	<0.02
Molar Mass, M	<0.01	0.5	<0.005	$< 2.5 \times 10^{-5}$	<0.02
Inlet Temperature, T_0	0.03	-0.5	-0.015	2.25×10^{-4}	0.15
Mass Flow Rate, q_m	**0.39**	1	0.39	0.15	

Measurement Uncertainty

Uncertainty Budget – Sonic nozzle after flow calibration

Parameter	Uncertainty, u (k=2) %	Sensitivity Coefficient, c	u·c	$(u\cdot c)^2$	Contribution to Uncertainty, %
Throat diameter, d	0	2	0	0	0
Discharge Coefficient, Cd	0.2	1	0.2	0.04	66.4
Critical Flow Factor, C*	0.1	1	0.1	0.01	16.6
Inlet Pressure, P_0	0.1	1	0.1	0.01	16.6
Universal Gas Constant, R	<0.01	-0.5	<-0.005	$< 2.5 \times 10^{-5}$	<0.04
Molar Mass, M	<0.01	0.5	<0.005	$< 2.5 \times 10^{-5}$	<0.04
Inlet Temperature, T_0	0.03	-0.5	-0.015	2.25×10^{-4}	0.4
Mass Flow Rate, q_m	**0.25**	1	0.25	0.06	

Summary

- Each calibration approach has its uses
- “Dry calibration” particularly useful when service conditions exceed capability of flow calibration labs.
- ISO 9300 provides detailed guidance, but some knowledge gaps for hydrogen, e.g. C* and Cd transferability from other fluids
- Nozzles with small throat diameters are difficult to manufacture (and measure) to required tolerances
- “Wet calibration” is relatively insensitive errors in nozzle dimensions

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