11. TRADITIONAL MEASUREMENT OF VOLUME FLOW RATE

11.1. Volume flow rate deduced from velocity measurement data

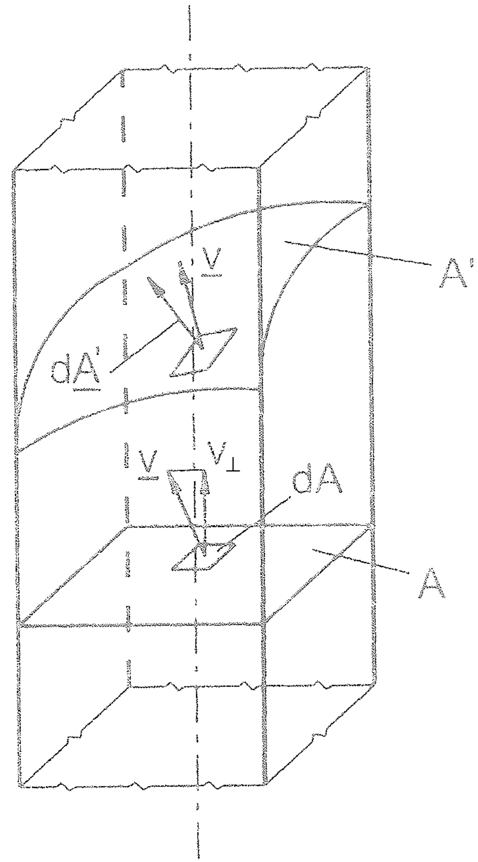
11.1.1. Application example

11.1.2. Principle and layouts

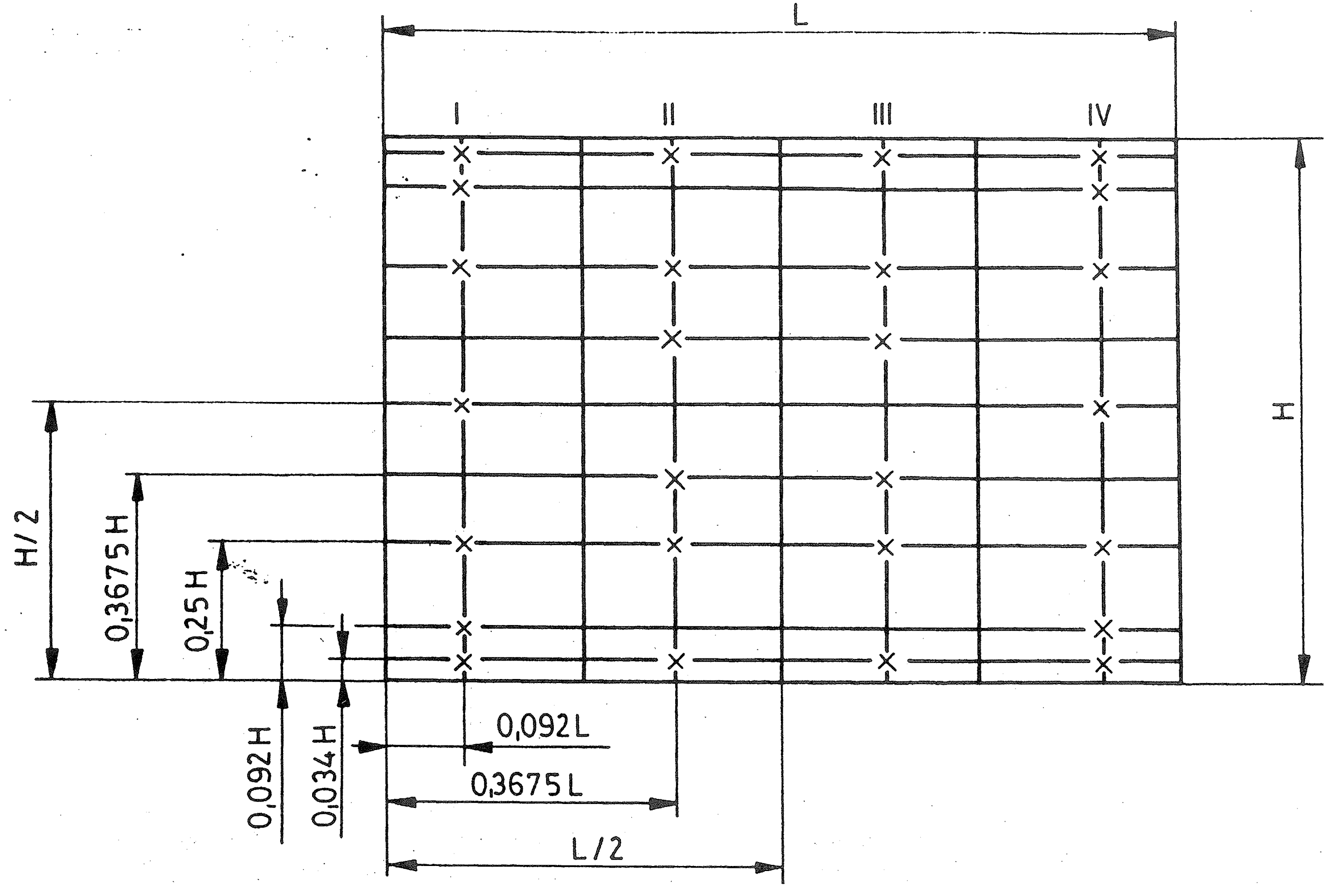
$$q_V = \int_{A'} \underline{v}\, \underline{dA'} = \int_{A} \underline{v}\, \underline{dA} = \int_{A} v_\perp \, dA$$

$$\approx \sum_{i=1}^{n} v_{\perp i} \Delta A_i = \Delta A_i \sum_{i=1}^{n} v_{\perp i}$$

$$= n \cdot \Delta A_i \left(\frac{1}{n} \sum_{i=1}^{n} v_{\perp i} \right) = A\, \overline{v}_\perp$$



DISCRETISATION:
For rectangular cross-sections:
- ***k x k***
- ***Log-lin method ISO 3966-1977***



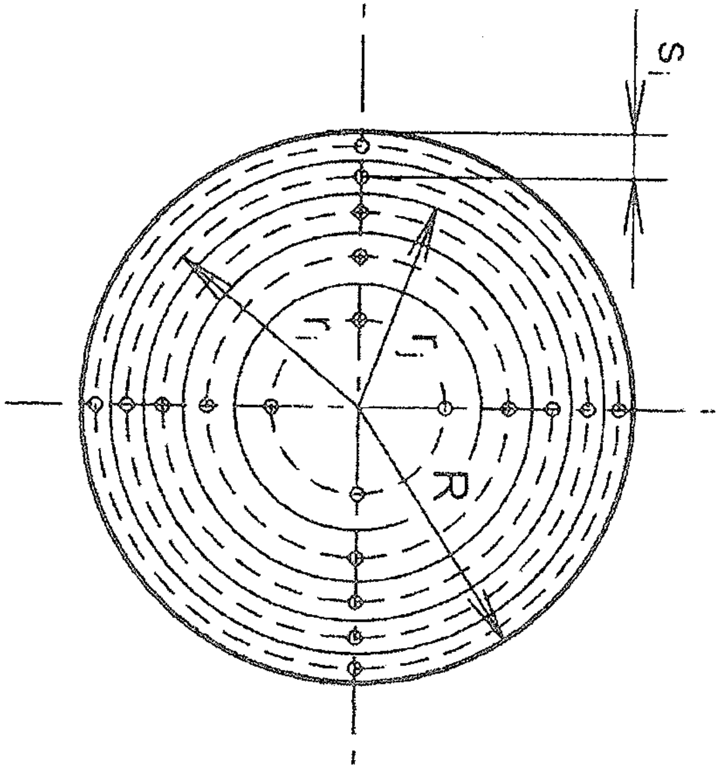
$$\bar{v}_{\perp} = \frac{\sum_{i=1}^{n} k_i v_{\perp i}}{\sum_{i=1}^{n} k_i}$$

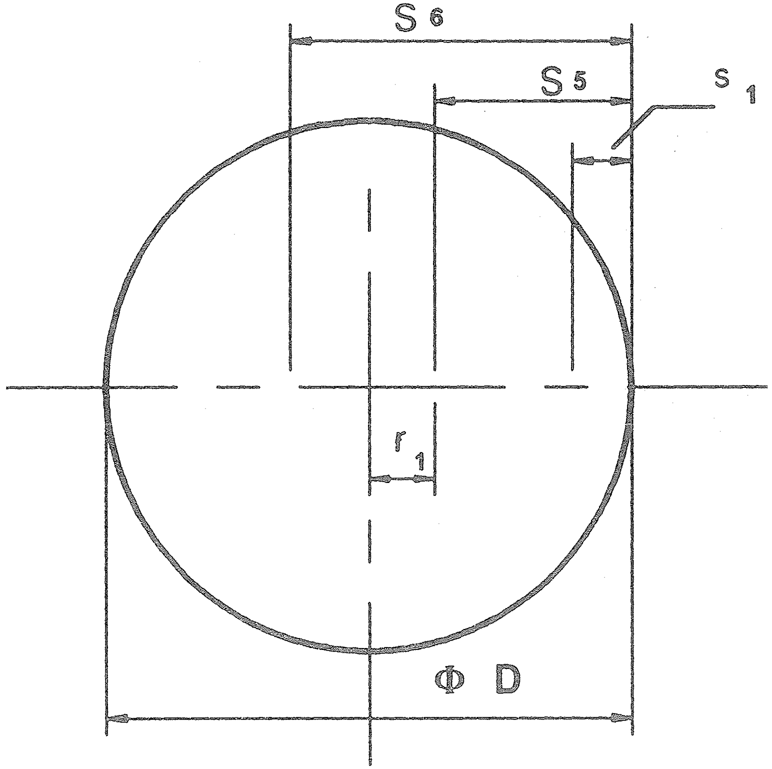
weighting

h/H \ l/L	I	II	III	IV
	0,092	0,367 5	0,632 5	0,908
0,034	2	3	3	2
0,092	2	–	–	2
0,250	5	3	3	5
0,367 5	–	6	6	–
0,500	6	–	–	6
0,632 5	–	6	6	–
0,750	5	3	3	5
0,908	2	–	–	2
0,966	2	3	3	2

For circular cross-sections:
•10-point method

$$v(r_i) = v_{\max}\left[1 - \left(\frac{r_i}{R}\right)^n\right]$$





s_i/D = 0.026; 0.082; 0.146; 0.226; 0.342; 0.658; 0.774; 0.854; 0.918; 0.974

Accurate integration: for 2nd order paraboloid profile only!

- ***Log-lin method ISO 3966-1977***

3 partial areas

$$v_i(y) = A_i \lg y + B_i y + C_i$$

s_i/D = 0.032; 0.135; 0.321; 0,679; 0.865; 0.968

General notes

- The nose of the probe is to be adjusted parallel to the wall of the duct

- $p_{\_dyn\_ref}$ Check of steadiness

$$v_{ref\,0} = \sqrt{\frac{2}{\rho} p_{dyn\_ref\_0}} \qquad v_{ref\_i} = \sqrt{\frac{2}{\rho} p_{dyn\_ref\_i}}$$

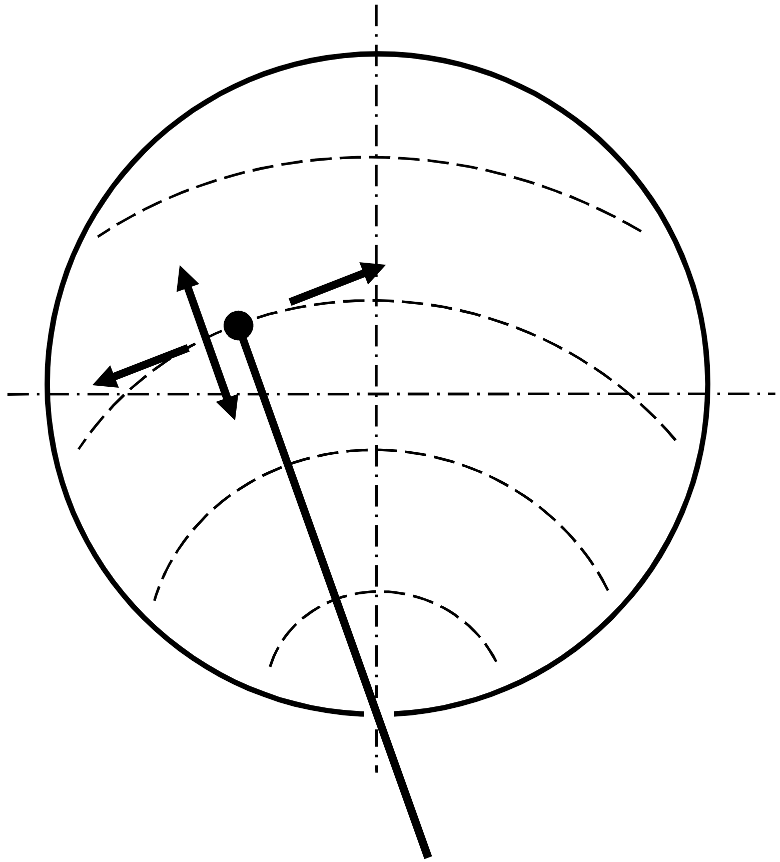
$$v_i = \sqrt{\frac{2}{\rho} p_{dyn\_i}}$$

Correction: $$v_{i\,corr} = v_i \frac{v_{ref\,0}}{v_{ref\;i}} = v_i \sqrt{\frac{p_{dyn\_ref\_0}}{p_{dyn\_ref\_i}}}$$

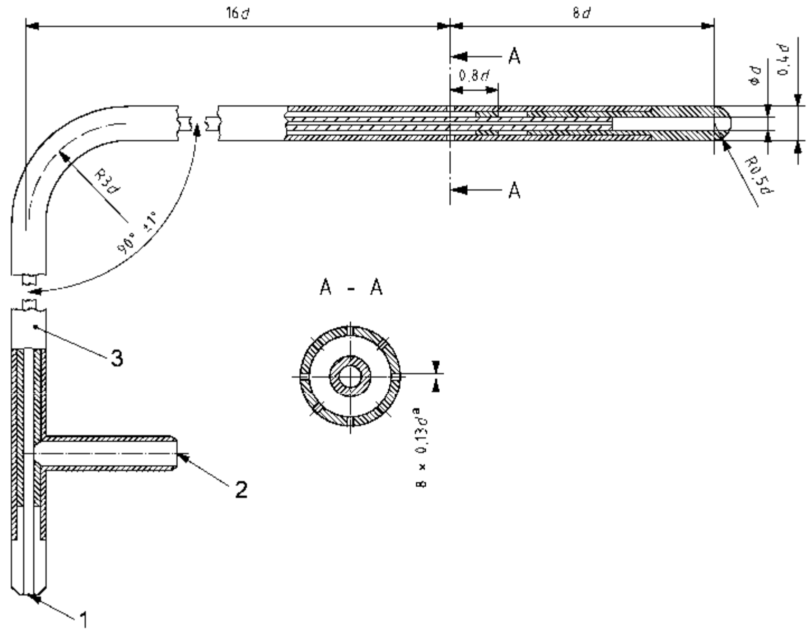
- Obtainment of density

•Advantages and disadvantages

•Quick scanning:



STANDARDS: the recent one, being in effect, is to be used!
Example: ISO 5801:2007(E): **Industrial fans — Performance testing using standardized airways**



Key

1 stagnation pressure connection
2 static pressure connection
3 main stem

[a] Drilled holes shall not exceed 1 mm diameter, they shall be equally spaced and free from burrs. The hole depth shall not be less than the hole diameter.

NOTE 1 The Pitot tube head shall be free from nicks and burrs.

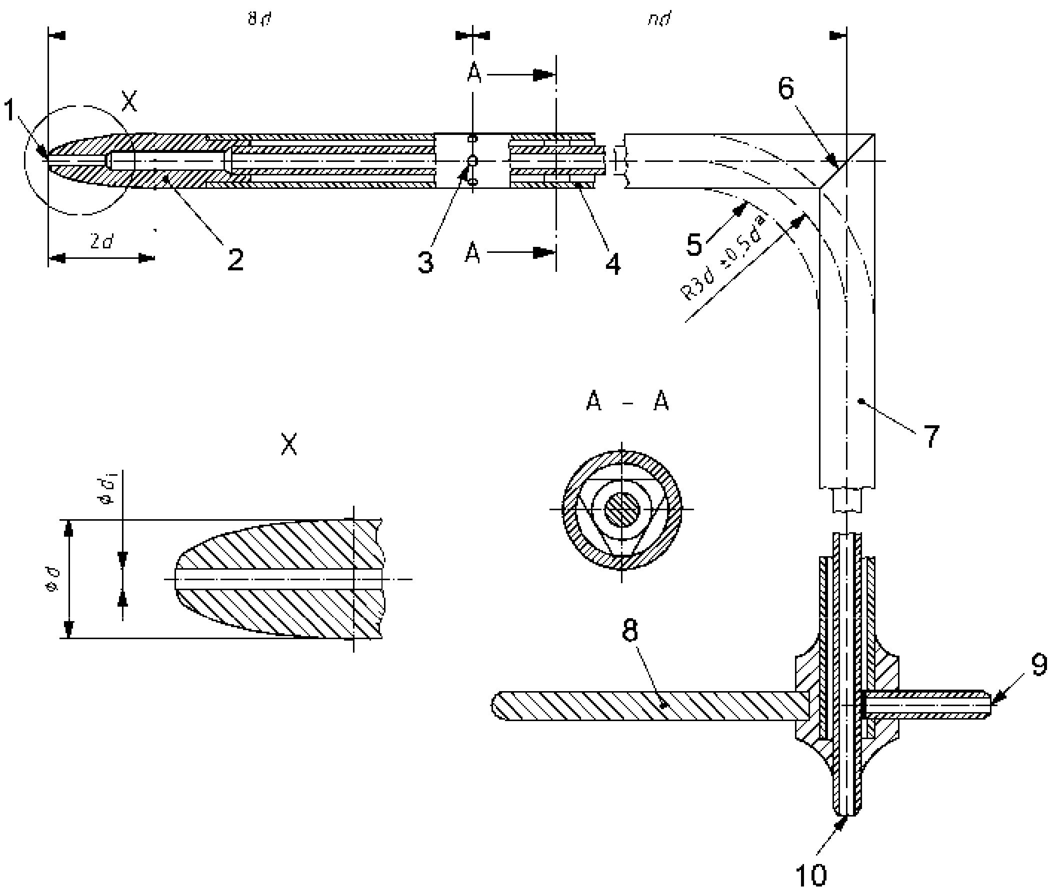
NOTE 2 All dimensions shall be within ± 2 %.

NOTE 3 Surface roughness shall be 0,8 μm or better.

NOTE 4 The static orifices shall not exceed 1 mm in diameter.

NOTE 5 The minimum Pitot tube stem diameter allowed by this International Standard is 2,5 mm. In no case shall the stem diameter exceed 1/30 of the test duct diameter.

a) AMCA type

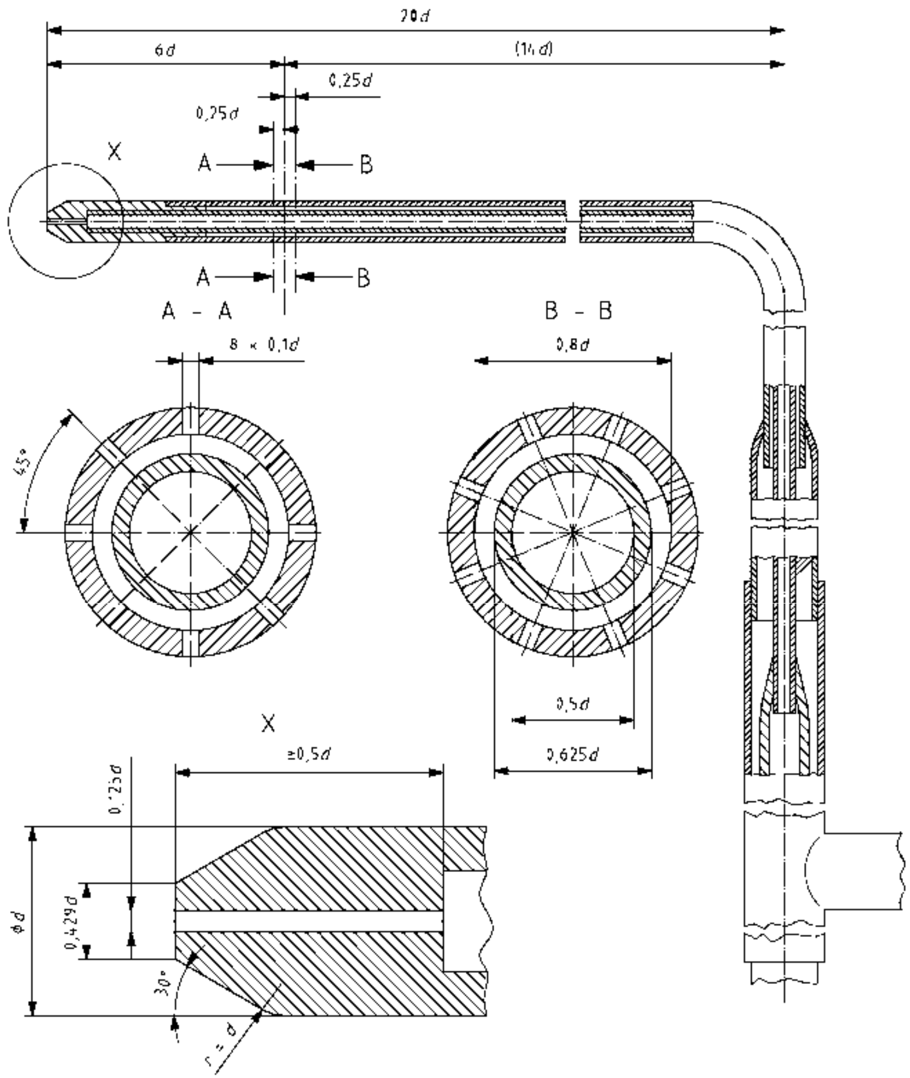


Key

1	stagnation pressure hole	6	mitred junction
2	modified ellipsoidal nose	7	main stem
3	static pressure holes	8	alignment arm
4	internal spacer	9	static pressure connection
5	alternative curved junction	10	stagnation pressure connection

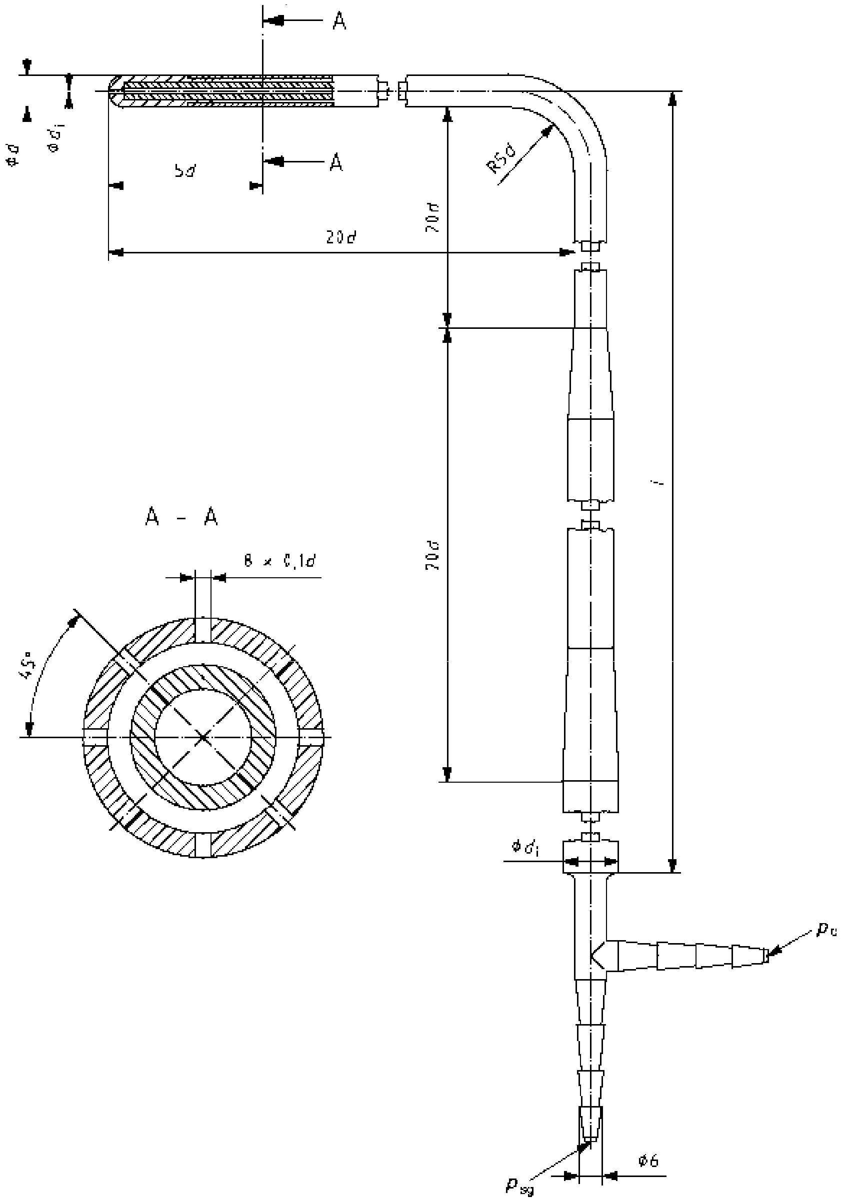
[a] Mean radius of curved option.

b) NPL type with modified ellipsoidal nose



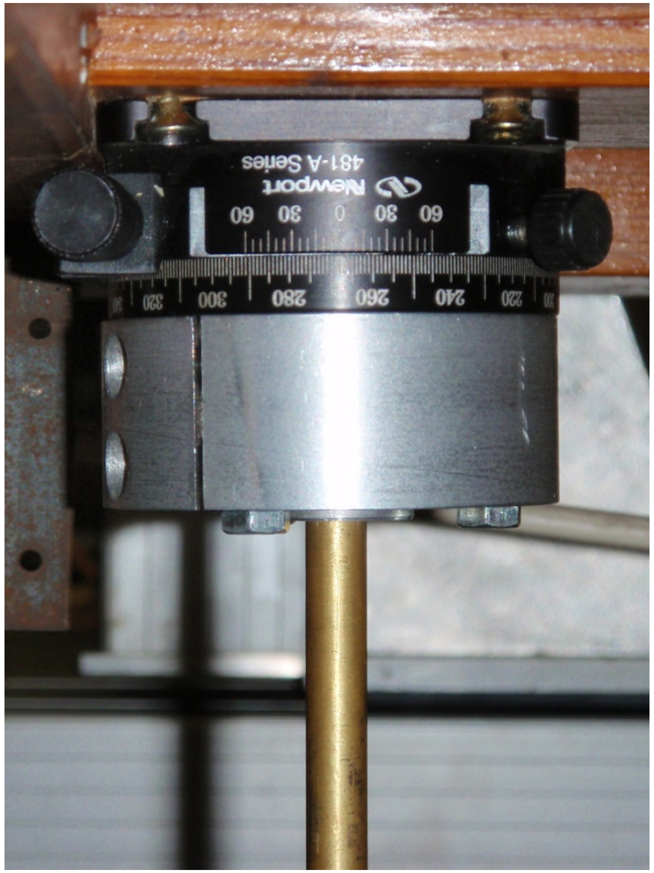
NOTE Static pressure taps may be limited to those indicated on section A-A, in which case section A-A shall be placed at 6*d* from the tube tip.

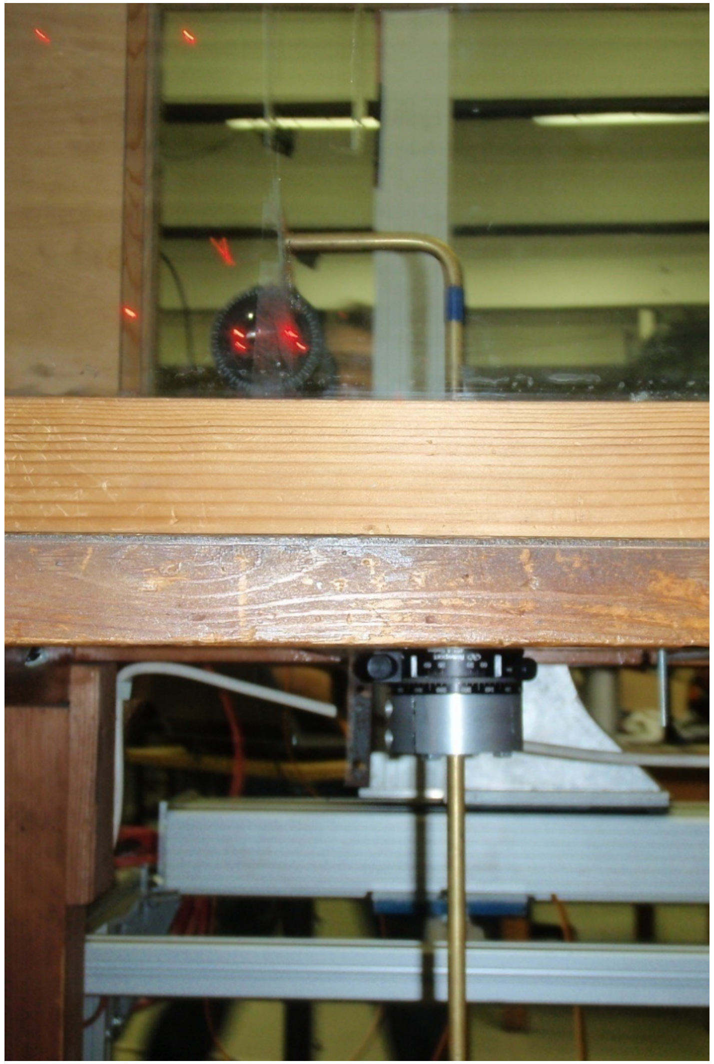
c) CETIAT type

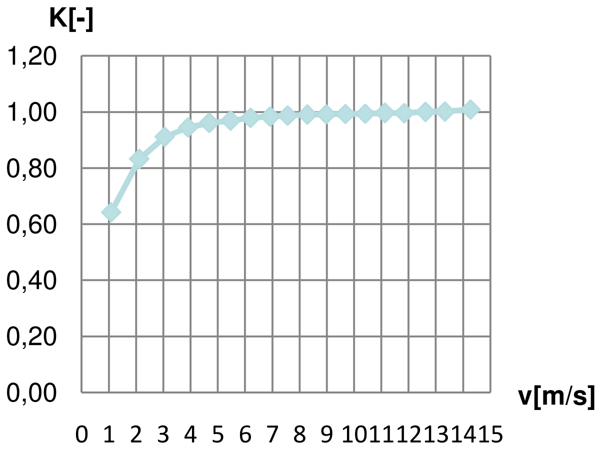


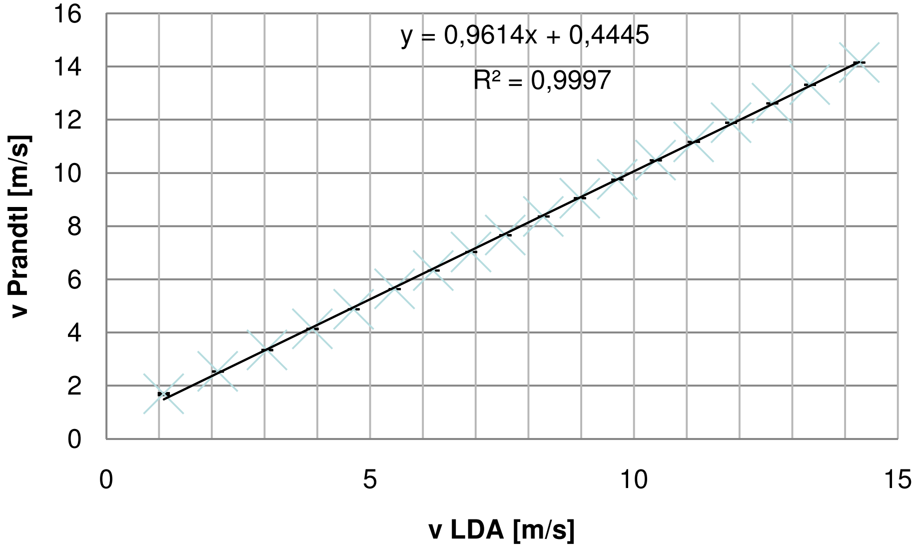
d) DLR type

Calibration of an AMCA type probe


Newport
481-A Series

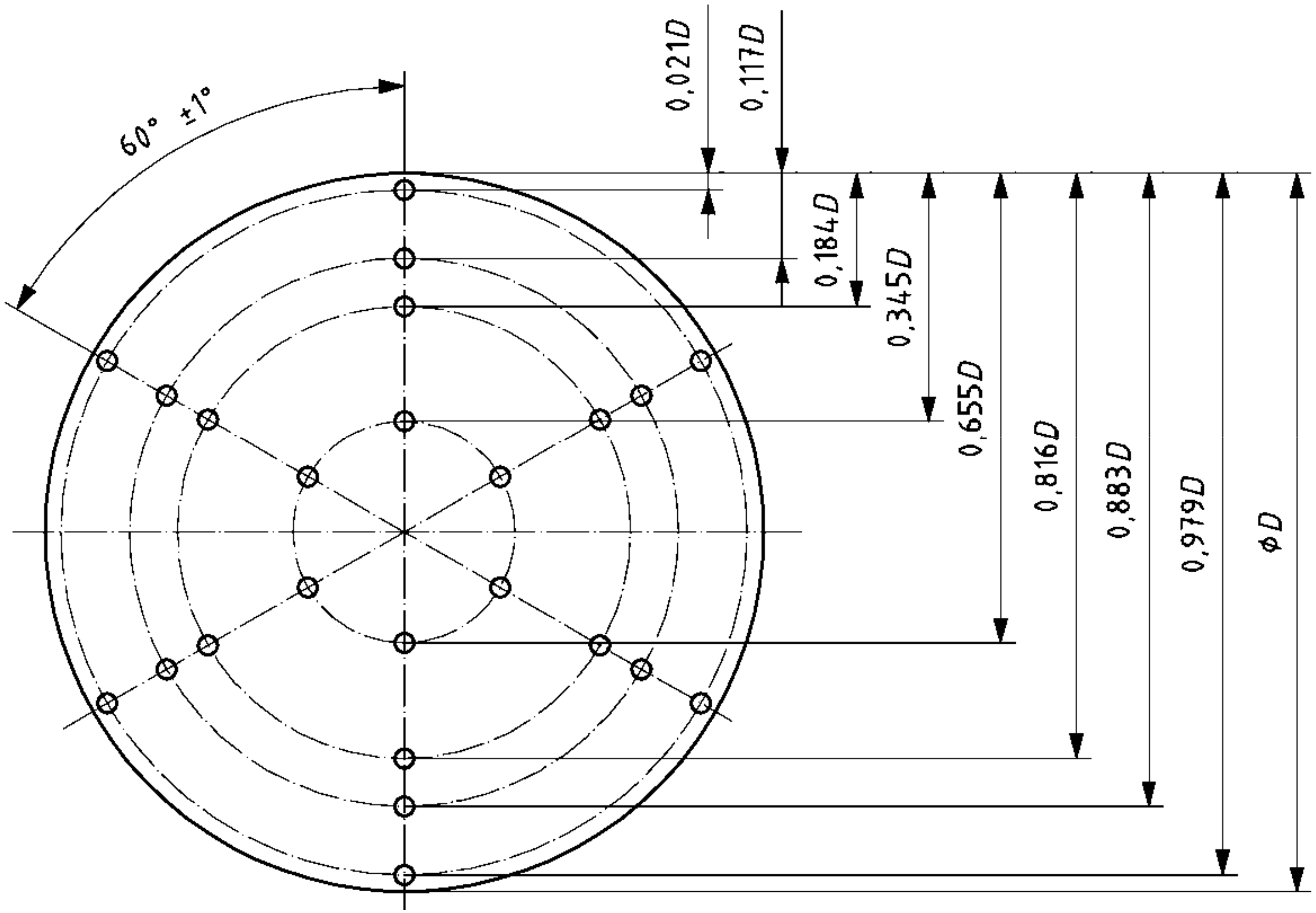






- **Velocity magnitude within +/- 1 % at higher velocities;**
- **For this uncertainty: directional insensitivity within +/- 5 deg**

The centre of the nose of the Pitot-static tube shall be located successively at not less than 24 measurement points spaced along three symmetrically disposed diameters of the airway, as shown in Figure 25.

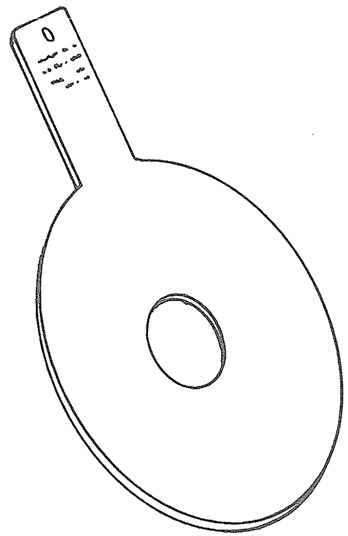


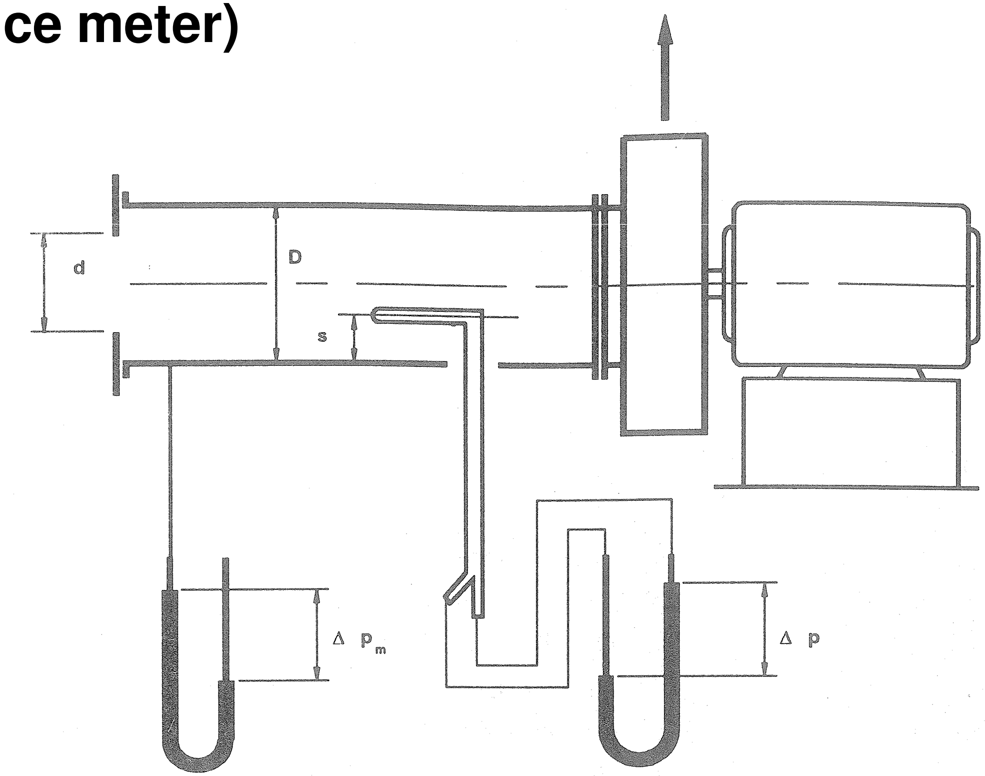
11.2. Volume flow rate measurements using contraction elements

11.2.1. Application example

11.2.2. Principle and layouts

•**Inlet orifice plate (inlet orifice meter)**





Assumption of ideal fluid: inviscid, incompressible flow

$$p_0 = p + \rho \frac{v^2}{2} \qquad v = \sqrt{\frac{2}{\rho}(p_0 - p)} = \sqrt{\frac{2}{\rho} \Delta p_m}$$

$$q_V = \frac{d^2 \pi}{4} v = \frac{d^2 \pi}{4} \sqrt{\frac{2}{\rho} \Delta p_m}$$

Reality: viscous, compressible flow

A/ Effect of viscosity

flow coefficient α

dependence on d/d_in, Re

for the inlet orifice meter: α = 0.6

$$q_V = \alpha \, \varepsilon \frac{d^2 \pi}{4} \sqrt{\frac{2}{\rho} \Delta p_m}$$

B/ Effect of compressibility

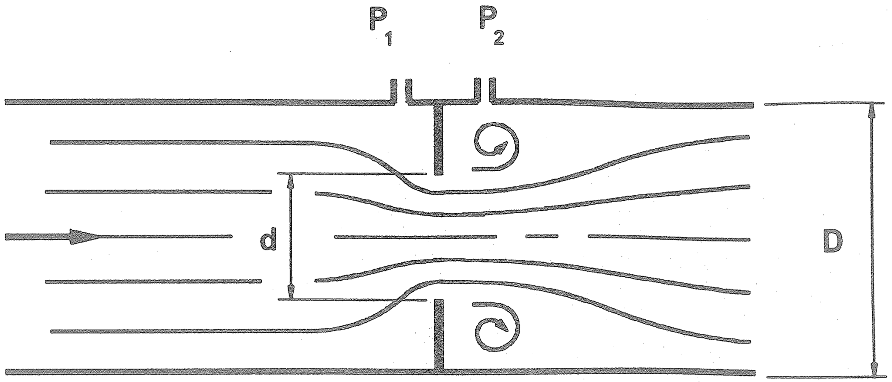
expansion coefficient ε

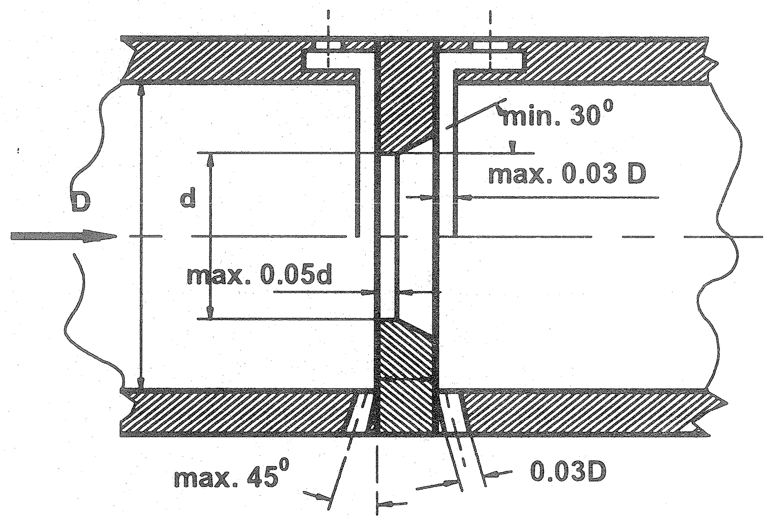
dependence on d/d_in, Δp, p_in, κ

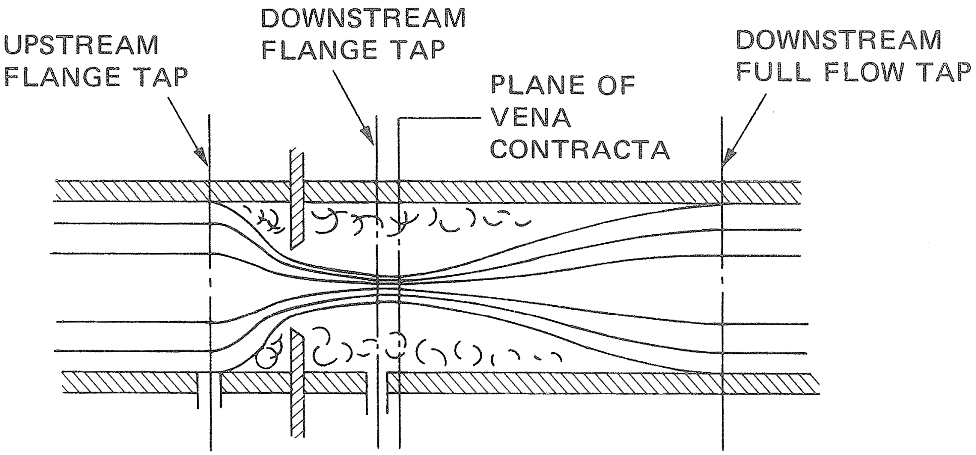
for the inlet orifice meter: ε = 1

•Through-flow orifice plate (through-flow orifice meter)

Standard in effect:
ISO 5167 / 2003







Standard in effect: Measurement of fluid flow by means of pressure differential devices inserted in circular cross-sections running full ISO 5167 (2003)

Table 3 — Required straight lengths between orifice plates and fittings without flow conditioners

Values expressed as multiples of internal diameter, D

Diameter ratio β	Upstream (inlet) side of orifice plate																									Downstream (outlet) side of the orifice plate	
	Single 90° bend Two 90° bends in any plane ($S > 30D$)[a]		Two 90° bends in the same plane: S-configuration ($30D \geq S > 10D$)[a]		Two 90° bends in the same plane: S-configuration ($10D \geq S$)[a]		Two 90° bends in perpendicular planes ($30D \geq S \geq 5D$)[a]		Two 90° bends in perpendicular planes ($5D > S$)[a,b]		Single 90° tee with or without an extension Mitre 90° bend		Single 45° bend Two 45° bends in the same plane: S-configuration ($S \geq 2D$)[a]		Concentric reducer 2D to D over a length of 1,5D to 3D		Concentric expander 0,5D to D over a length of D to 2D		Full bore ball valve or gate valve fully open		Abrupt symmetrical reduction		Thermometer pocket or well[c] of diameter $\leq 0{,}03D$[d]		Fittings (columns 2 to 11) and the densitometer pocket	
1	2		3		4		5		6		7		8		9		10		11		12		13		14	
—	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]	A[e]	B[f]
≤0,20	6	3	10	9	10	9	19	18	34	17	3	9	7	9	5	9	6	9	12	6	30	15	5	3	4	2
0,40	16	3	10	9	10	9	44	18	50	25	9	3	30	9	5	9	12	8	12	6	30	15	5	3	6	3
0,50	22	9	18	10	22	10	44	18	75	34	19	9	30	18	8	5	20	9	12	6	30	15	5	3	6	3
0,60	42	13	30	18	42	18	44	18	65[h]	25	29	18	30	18	9	5	26	11	14	7	30	15	5	3	7	3,5
0,67	44	20	44	18	44	20	44	20	60	18	36	18	44	18	12	6	28	14	18	9	30	15	5	3	7	3,5
0,75	44	20	44	18	44	22	44	20	75	18	44	18	44	18	13	8	36	18	24	12	30	15	5	3	8	4

NOTE 1 The minimum straight lengths required are the lengths between various fittings located upstream or downstream of the orifice plate and the orifice plate itself. Straight lengths shall be measured from the downstream end of the curved portion of the nearest (or only) bend or of the tee or the downstream end of the curved or conical portion of the reducer or the expander.

NOTE 2 Most of the bends on which the lengths in this table are based had a radius of curvature equal to 1,5D.

[a] S is the separation between the two bends measured from the downstream end of the curved portion of the upstream bend to the upstream end of the curved portion of the downstream bend.

[b] This is not a good upstream installation; a flow conditioner should be used where possible.

[c] The installation of thermometer pockets or wells will not alter the required minimum upstream straight lengths for the other fittings.

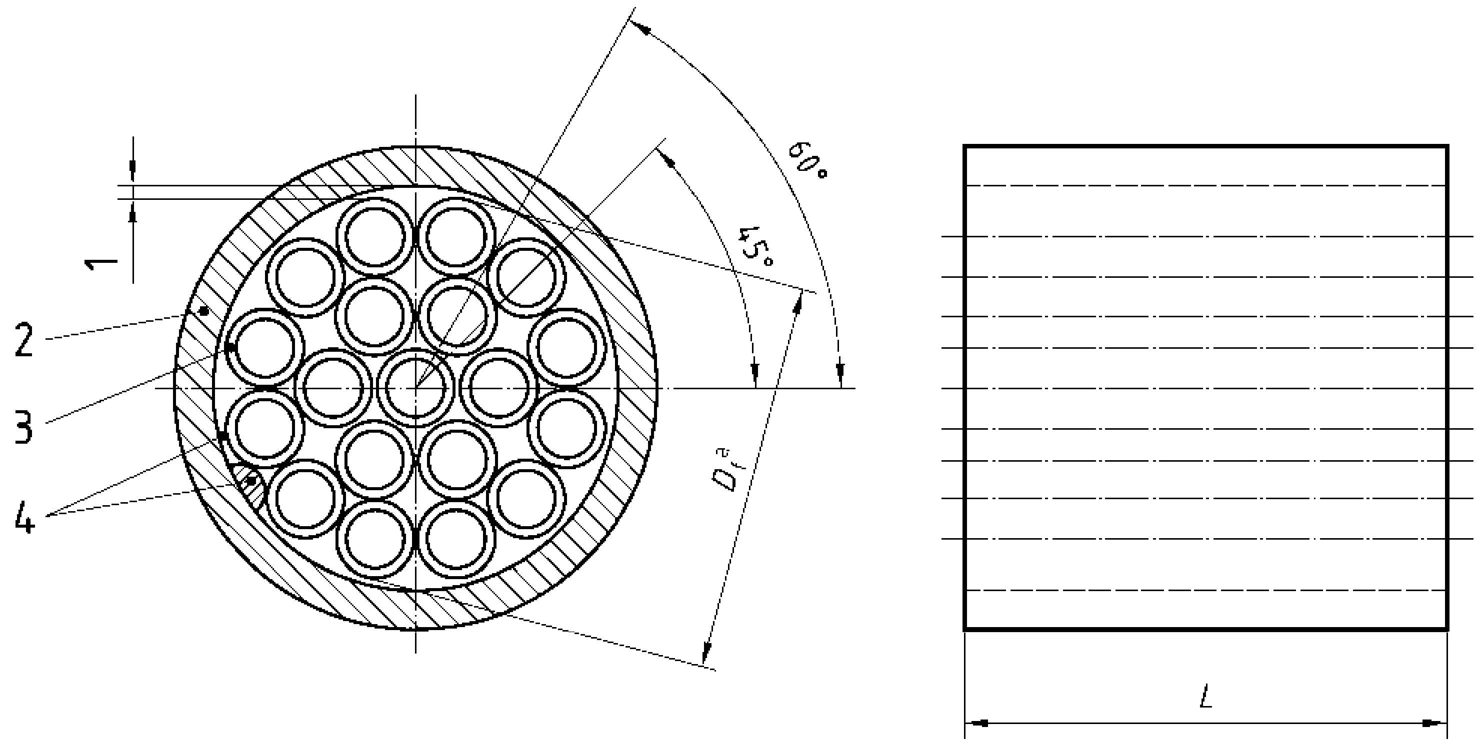
[d] A thermometer pocket or well of diameter between 0,03D and 0,13D may be installed provided that the values in Columns A and B are increased to 20 and 10 respectively. Such an installation is not, however, recommended.

[e] Column A for each fitting gives lengths corresponding to "zero additional uncertainty" values (see 6.2.3).

[f] Column B for each fitting gives lengths corresponding to "0,5 % additional uncertainty" values (see 6.2.4).

[g] The straight length in Column A gives zero additional uncertainty; data are not available for shorter straight lengths which could be used to give the required straight lengths for Column B.

[h] 95D is required for $Re_D > 2 \times 10^6$ if $S < 2D$.



Key

1 minimized gap

2 pipe wall

3 tube wall thickness

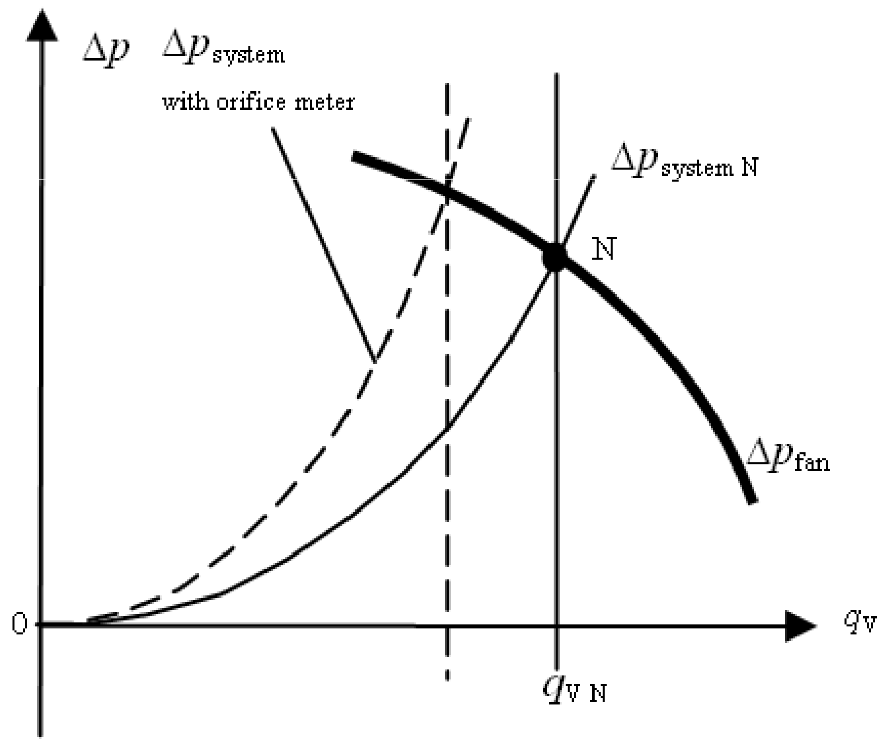
4 centring spacer options (typically four places)

a D_f is the flow straightener outside diameter.

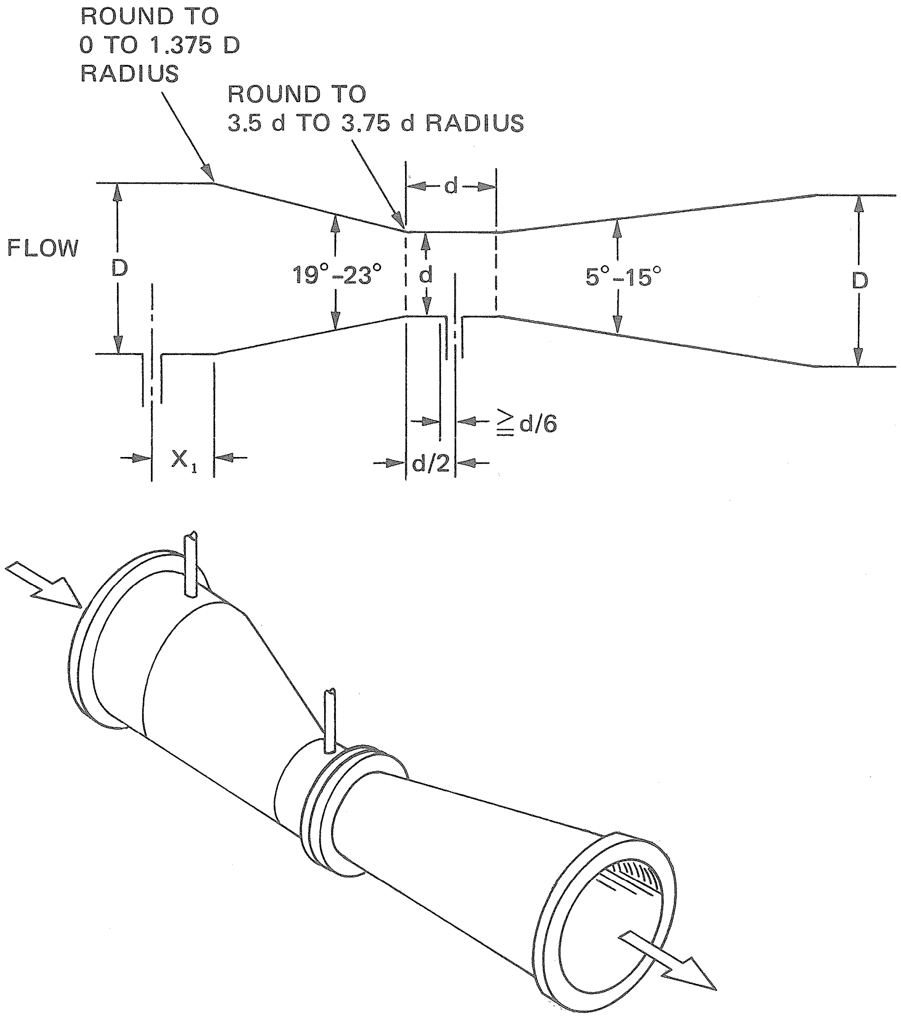
19-tube bundle flow straightener (1998)

- *Geometry*
- α, ε
- *Installation – Examples*
- *Accuracy – Examples*
- *Problems*

$$q_V = \alpha\, \varepsilon \frac{d^2 \pi}{4} \sqrt{\frac{2}{\rho} \Delta p_m}$$



•Venturi meter ISO 5167

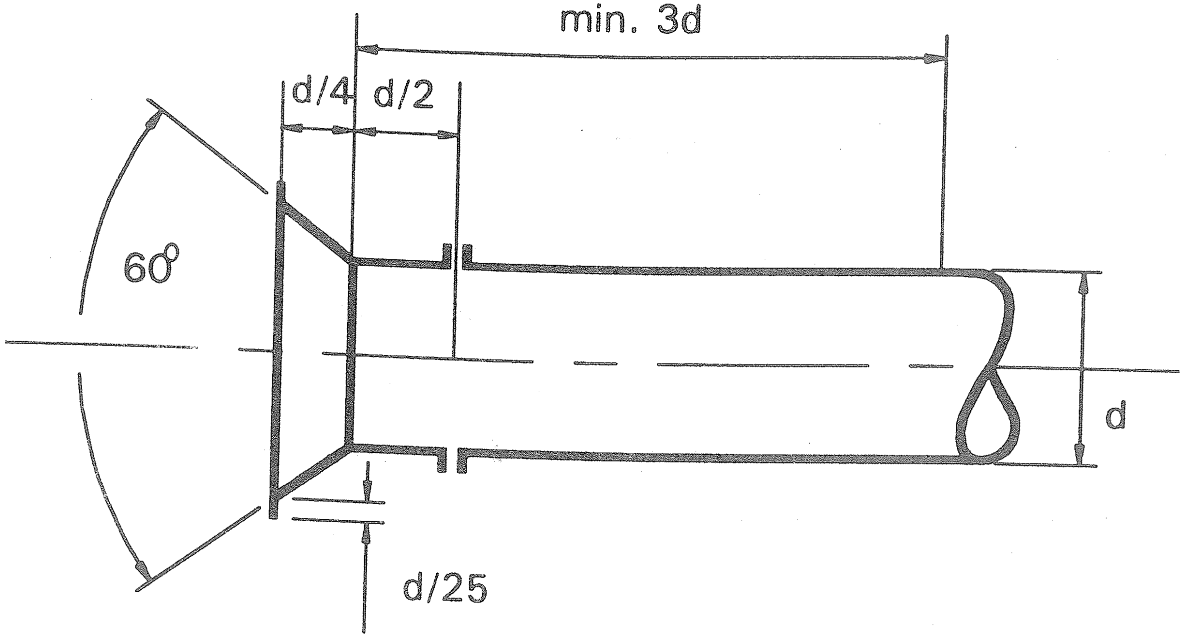


•**Inlet cone** ISO 5221-1984 (E)

$$\mathrm{Re} = \frac{4q_V}{\pi \rho d \nu}$$

$$(\alpha\varepsilon) = 0.955 \pm 0.020 \quad if \quad 2 \cdot 10^5 < \mathrm{Re} < 3 \cdot 10^5$$

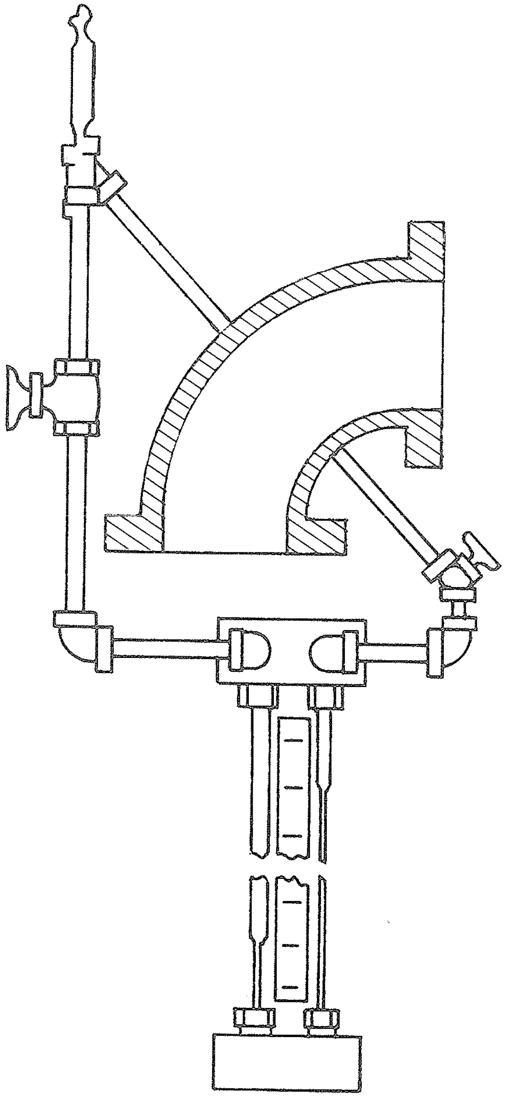
$$(\alpha\varepsilon) = 0.960 \pm 0.015 \quad if \quad \mathrm{Re} \geq 3 \cdot 10^5$$



11.3. Other types of traditional flowmeters

Example:

•Elbow meter



11.4. Comparison between volume flow rate measurement deduced from velocity data (VEL) and using contraction elements (CON)

ASPECT	CON	VEL
1/ Intrusiveness	"–" Introduces considerable losses ⇒ the operating state may be modified ⇔ to be included already in the system design state	"+" Negligible intrusiveness (wall bores)
2/ Following temporal changes in the operational state	"+" Follows unsteady flow rate continuously	"–" Does not follow (surface integration) (⇔ correction..?)
3/ Requirements	"–" Strict (manufacturing, installation, system is to be stopped…)	"+" Moderate (no requirements, only recommendations, system may run continuously…)

4/ Expenses	"–" High (manufacturing, installation, operation: losses to be covered)	"+" Moderate
5/ Accuracy	"+" High (limited uncertainty, guaranteed by the standard) Legally defensible!	"–" Moderate (limits of uncertainty are not guaranteed) Legally assailable!

CON: high-precision, continuous, legally defensible measurements (e.g. accounting, process control, etc.)
VEL: occasional (case study) measurements, brief estimation (e.g. fault diagnostics)