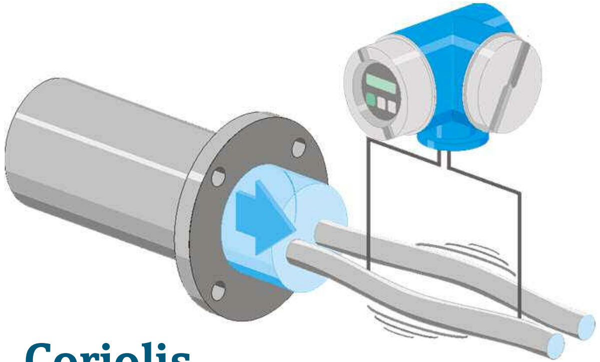
Gas Flow Measurement

Endress+Hauser
People for Process Automation

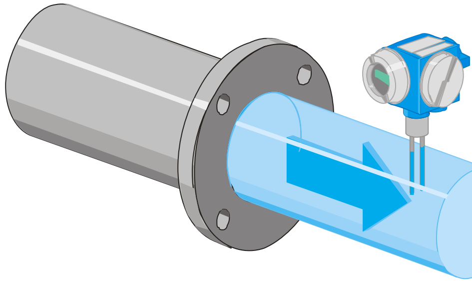
What will you experience with gas rig?

- Response time
- Low flow limitation
- Impact of energy and pressure loss
- Impact on flowmeters installation
- Impact of the flow profile
- Impact of moisture
- Pressure and temperature simulation
- Impact of setting errors

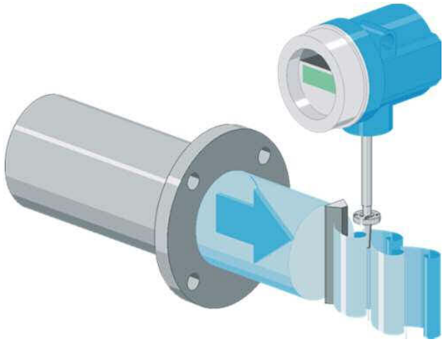
Measuring Principles for Gas Measurement



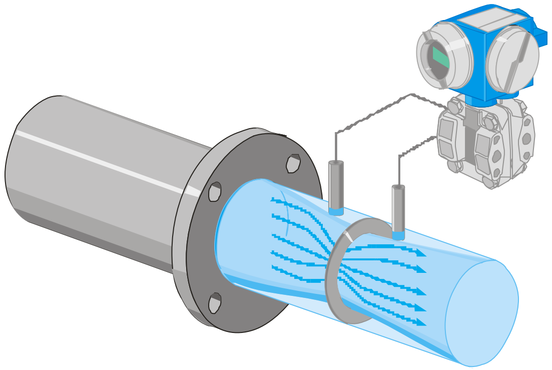
Coriolis
Nominal diameters: DN 1 to 350 (1/24 to 14")



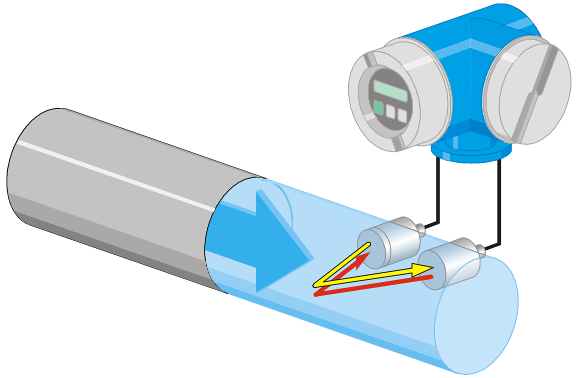
Thermal Mass
Nominal diameters: DN 15 to 1500 (1/2 to 60")



Vortex
Nominal diameters: DN 15 to 300 (1/2 to 12”)



Differential Pressure
Nominal diameters: DN 10 to >DN1000



Ultrasonic (Biogas only)
Nominal diameters: DN 50 to 200 (2 to 8”)

Conversion of Volume Flow to Mass Flow

- Simple Ideal Gas Equation:

$$m = \rho . V$$

- Real Gas Equation:

$$m = \rho . V = \frac{p}{p_{ref}} . \frac{T_{ref}}{T} . \frac{Z_{ref}}{Z} . \rho_{ref} . V$$

m	= mass flow
p	= pressure
p_{ref}	= reference pressure (typically 1013 mbar or 14.696 psi)
T	= temperature
T_{ref}	= reference temperature (typically 0 °C or 70 °F)
Z	= compressibility
Z_{ref}	= compressibility at reference conditions
ρ_{ref}	= density at reference conditions
V	= volume

Real Gas Compressibility Factor - Z

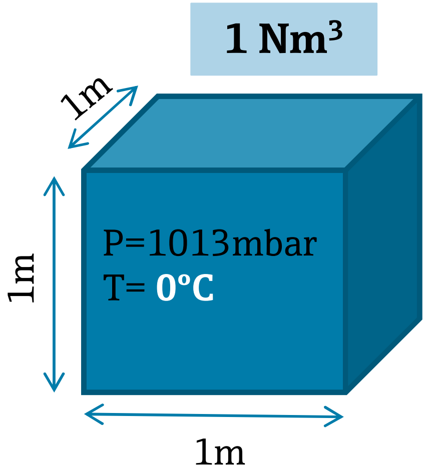
	1 bar a	5 bar a	10 bar a	20 bar a	40 bar a
Air @ 20 °C	0.9997	0.9986	0.9972	0.9944	0.9889
Air @ 100 °C	1.0001	1.0007	1.0013	1.0027	1.0053
CO2 @ 20 °C	0.9945	0.9727	0.9453	0.8906	-
CO2 @ 100 °C	0.9978	0.9892	0.9785	0.9570	0.9140
He @ 20 °C	1.0002	1.0012	1.0024	1.0048	1.0096
He @ 100 °C	1.0002	1.0009	1.0019	1.0038	1.0076
Ammonia @ 100°C	0.9959	0.9797	0.9593	0.9187	0.8374
Chlorine @ 100 °C	0.9939	0.9697	0.9395	0.8789	-
Argon @ 20 °C	0.9993	0.9966	0.9933	0.9866	0.9731

Corrected Volume – Nm^3 or Sm^3??

- Normal cubic meter (Nm^3) and Standard cubic meter (Sm^3) both are corrected volume term

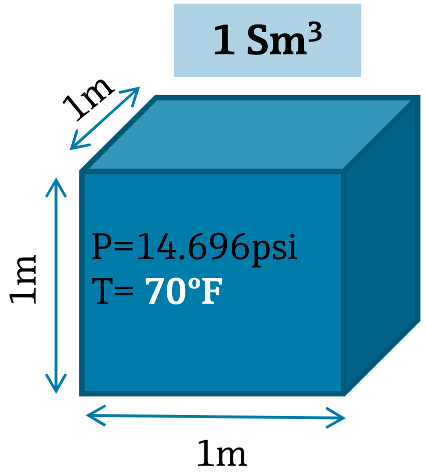
$$Corrected\ Volume, v_{ref} = \frac{Mass, m}{Reference\ Density, \rho_{ref}}$$

- Corrected volume is **NOT** a volume term, but a mass term
- They refer to the same reference pressure but to ***different reference temperatures***



Examples:

Air = 1.293 kg
Hydrogen= 0.089 kg
Chlorine= 3.220 kg



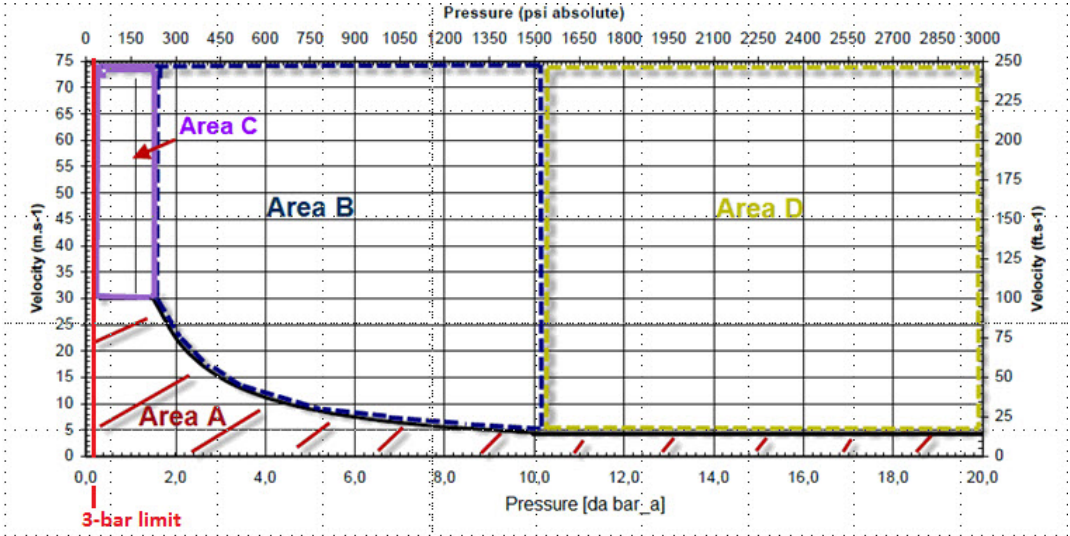
Examples:

Air = 1.199 kg
Hydrogen= 0.083 kg
Chlorine= 2.936 kg

Deviation 6-10%!!!!

Special Application: Oxygen

1. Wetted part material. Note: Titanium and Zicronium should be avoided



Area A: Stainless steel
Area: B+C: Alloy C22
Area: D: Copper /Brass

2. Cleaning – All oxygen equipment must be cleaned from oil & grease

Endress+Hauser

Traceability chain of Endress+Hauses

±0,000001%

Standard Kilo at (BIPM) Paris

Measuring uncertainty = +/- 0.000001%
+/- 10 microgram

±0,0001%

National Standard Kilo of METAS

Measuring uncertainty = +/- 0.0001%
+/- 0.5g/500 kg, duplicate No 38

±0,0016%

Gravimetric scale of E+H Flowtec

Traceable weights of OIML class F2
+/- 0.8g/50 kg = 0.0016%

±0,015%

PremiumCal rigs in Reinach and Greenwood

Measuring Uncertainty +/- 0.015%
accredited acc. to ISO 17025

±0,05%

Meter accuracy

Promass 83/84F DN 08 – 400

Premium Calibration +/-0.05%

11

Calibration

- Calibration with Air
- Repeatable and stable ambient conditions
- Controlled temperature (24°C +/- 0.5°C) and humidity (40% Rel)
- Undisturbed, fully developed flow profile
- Automated positioning of the Device Under Test
- Mass flow range: 0.05kg/h … 10’000kg/h
- Measurement uncertainty ±0.3 % o.r.
- **DIN17025 and ISO/IEC 17025 accredited**

Calibration with Water for Gas Application?

- PTB Custody Transfer Approval mentioned if a gas device is calibrated with Water:

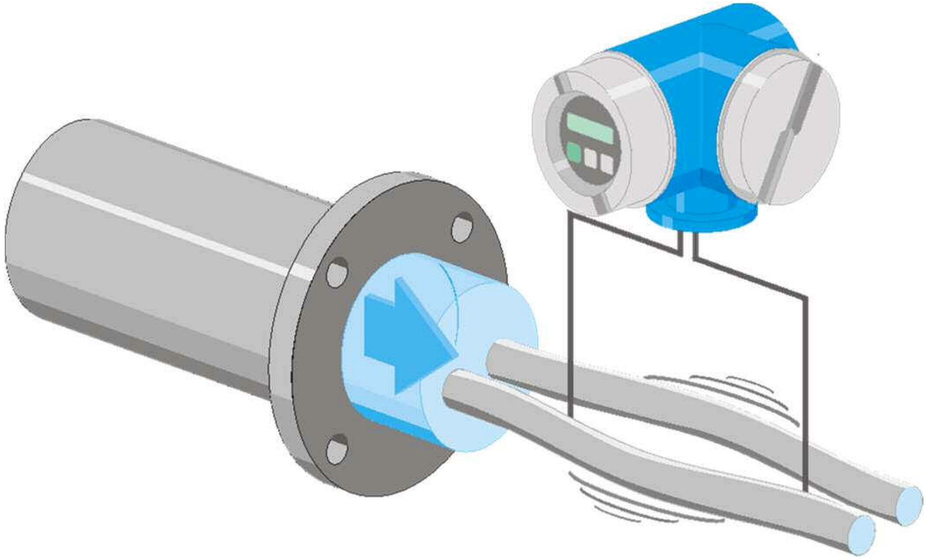
Bei der Prüfung eines Gerätes mit Wasser betragen die zulässigen Fehlergrenzen:
If a device is tested with water, the maximum permissible errors are:

-	± 1 %	für / *for*	Q_{min}	≤	Q	<	Q_t
-	± 0,3 %	für / for	Q_t	≤	Q	≤	Q_{max}.

- External 3rd Party tested with different condition and different fluid the measuring performance is within the measuring error limit for both calibration with gas and water (Refer to White paper)

Coriolis

Coriolis Measuring Principle



$\Delta\varphi \sim m$

$f_R \sim \rho$

$\Omega \sim T$

- $\Delta\varphi$ = **Phase shift**
- **m** = **Mass flow**
- f_R = **Resonance frequency**
- ρ = **Density**
- Ω = **Resistance (PT1000)**
- **T** = **Temperature**

Overview of calculated values

- **V = Volume flow**
  V = m/ρ

- **V_N = Standard volume flow = Volume flow at fixed p and T**
  V_N = m/ρ_N (note: ρ_N is a fixed value for each fluid)

- **c = Concentration**
  Concentration can be calculated from density
- **μ,η = Viscosity**
  Viscosity can be calculated from oscillation damping. Viscosity measurement is only available with the Promass 83I.

Installation Guidelines

- Coriolis flowmeters **DO NOT** require straight inlet or outlet runs
- Elbow, valves or pumps upstream do not affect the performance of coriolis

Sizing of Coriolis Flowmeter

Sizing is the compromise of:

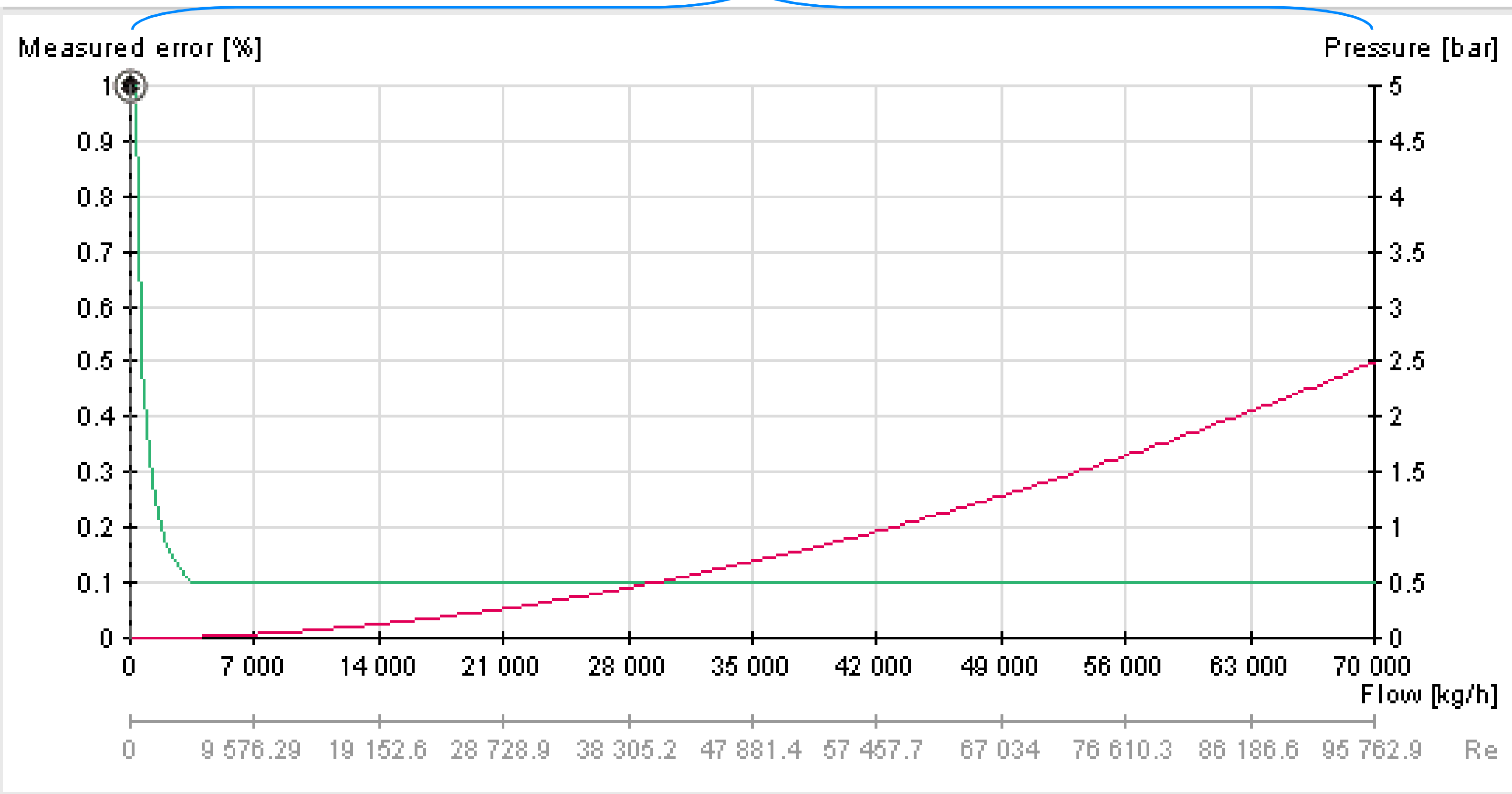
Accuracy at minimum flow rate
vs.
Pressure loss at maximum flow rate

For a reliable sizing the following information must be available:

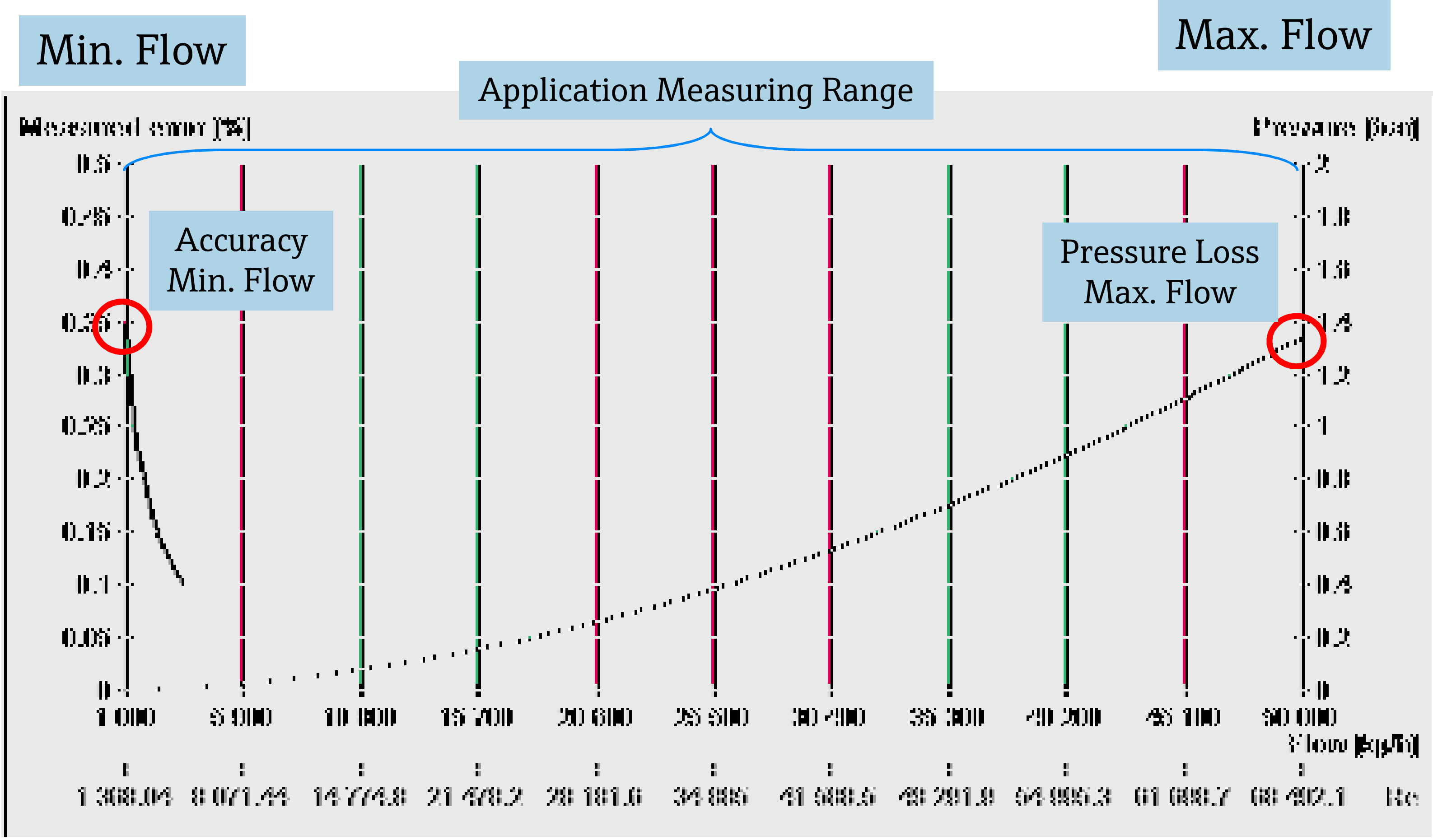
- The measured fluid
- Flowmeter model to be sized
- Minimum and maximum flow rate to be measured
- The process condition (min. and max. pressure / temperature)
- Observe possible velocity limitations

Accuracy vs. Pressure Loss Promass 83F DN50

Full Flowmeter Measuring Range

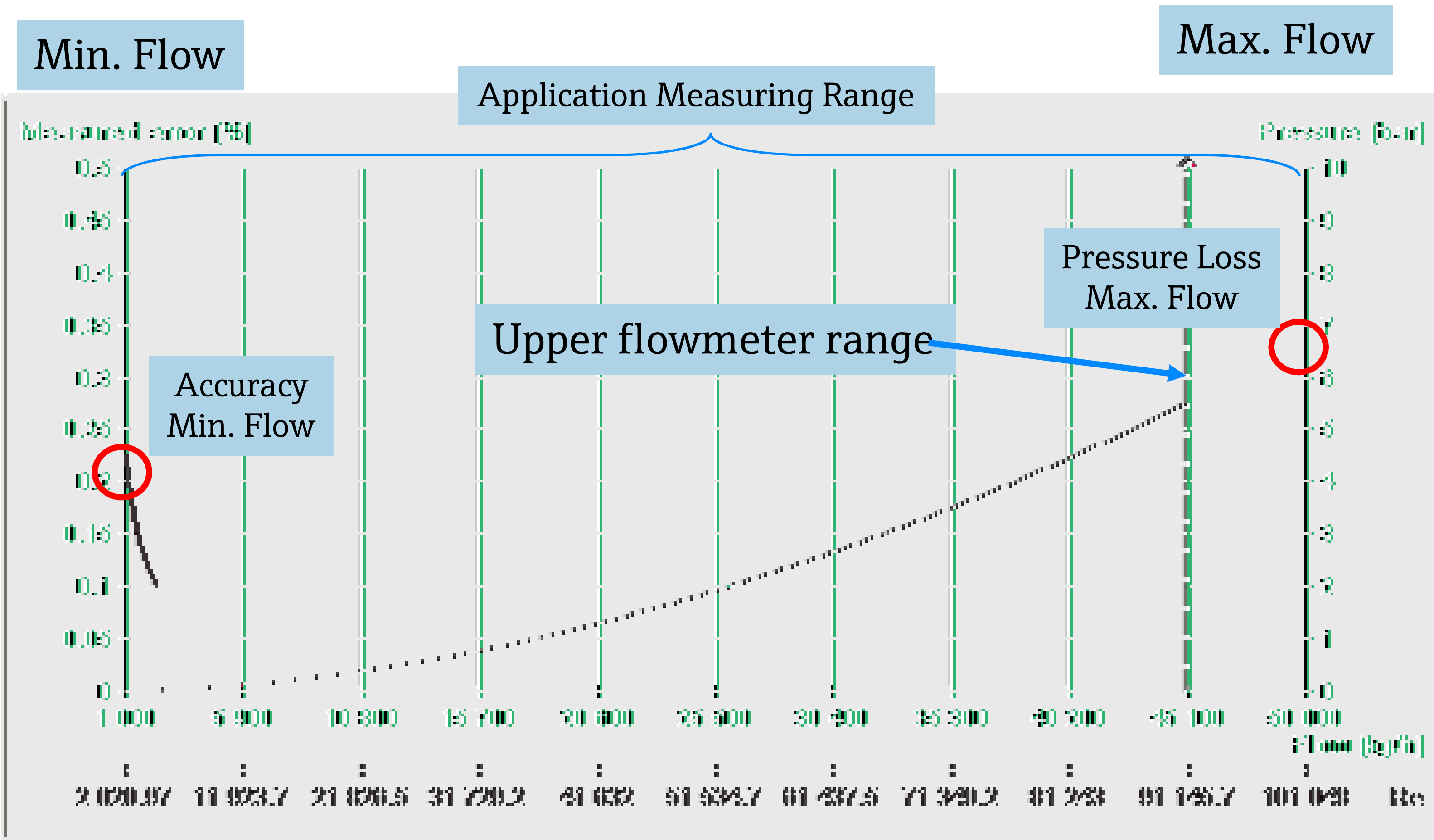


Accuracy vs. Pressure Loss for Ideal DN



Best compromise solution

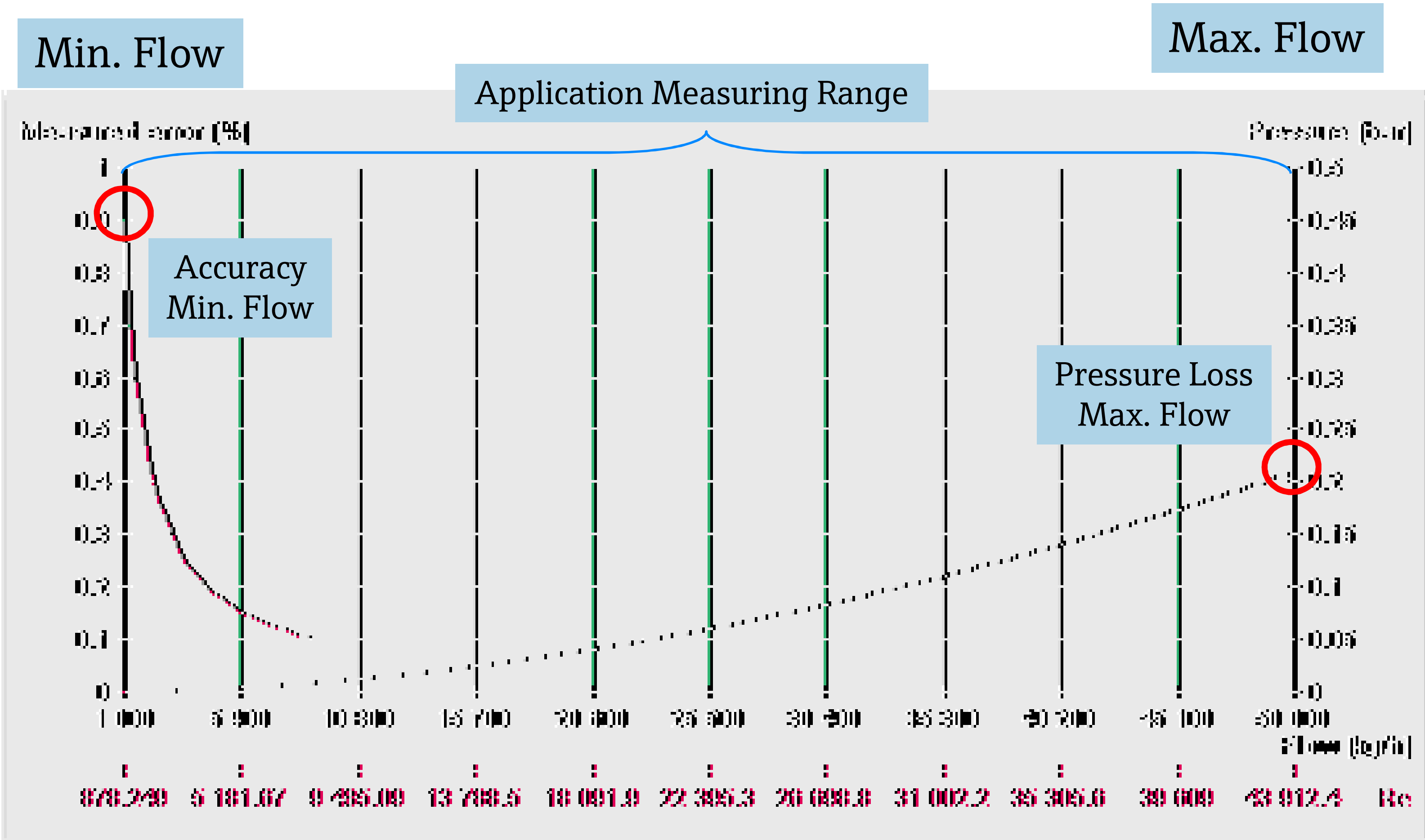
Accuracy vs. Pressure Loss for DN 40



Optimized solution for high accuracy

Endress+Hauser

Accuracy vs. Pressure Loss for DN 80



Optimized solution for low pressure loss

Advantages and Limitations

Advantages

- Direct massflow measurement
- Independent of gas properties
- Independent of process conditions
- Independent of installation

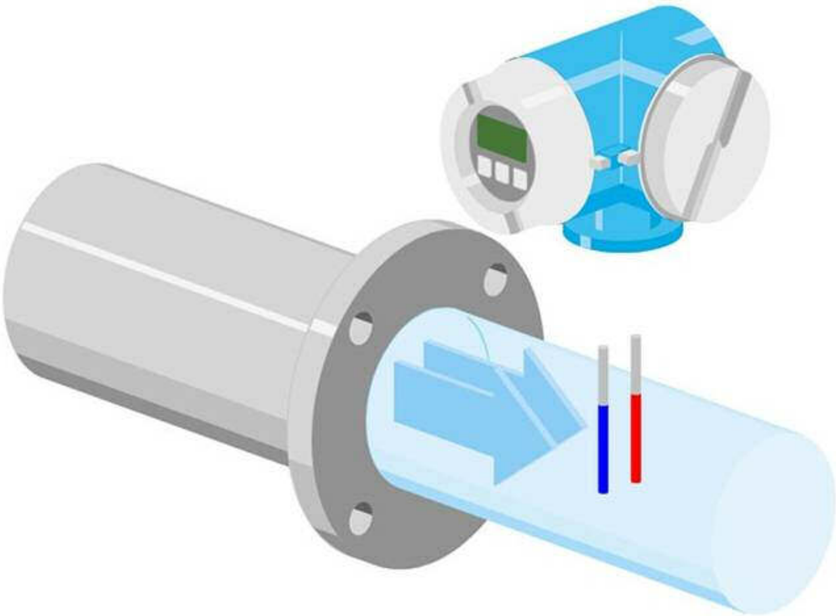
Limitation

- Pressure loss
- Size max DN 350

Thermal Mass Flow

Endress+Hauser
People for Process Automation

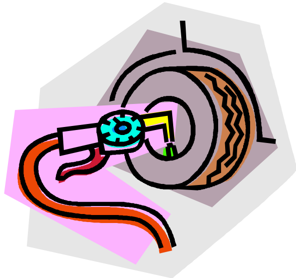
Thermal Mass Flowmeter Measuring Principle



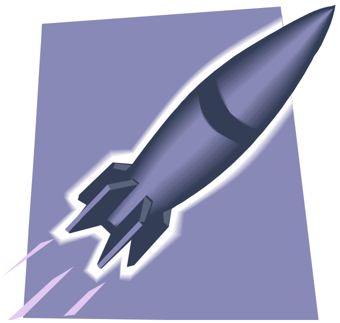
- Mass flow measurement base on thermal dispersion
- A heated body in a flowing gas stream gives off heat to the flowing gas due to the cooling affect of the gas molecules and mass velocity
- The amount of heat convected away by the *gas* is directly related to the mass flow rate
- Direct mass flow measurement

What influences the cooling rate of sensor?

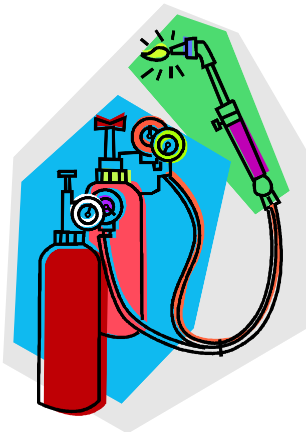
Pressure
Temperature = Density



Velocity



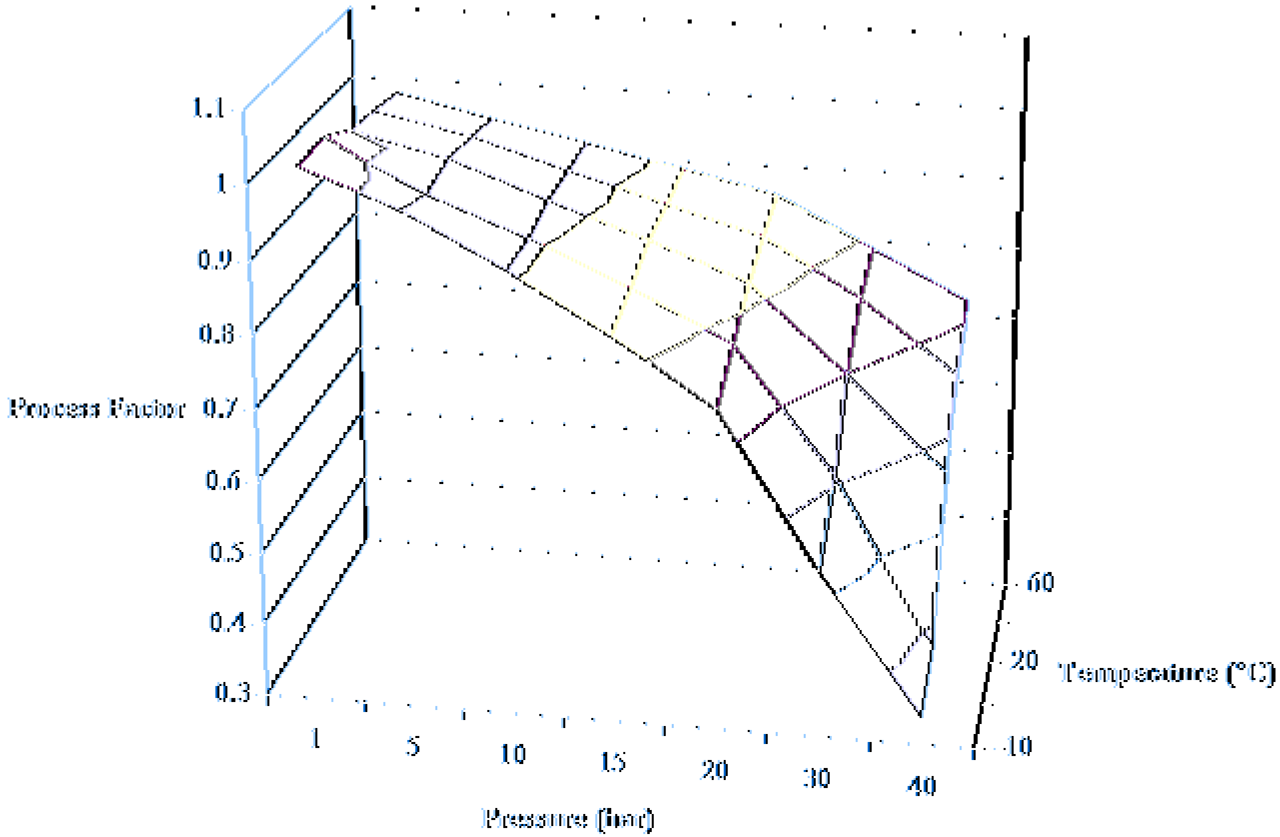
Gas Properties



Influence of Pressure and Temperature

- The thermal properties of gases changes as pressure and temperature changes
- The influence is different for different gases
- i.e. Air is more temperature depending where CO_2 is more affected by changing pressure
- The influence can be compensated for by applying a correction factor

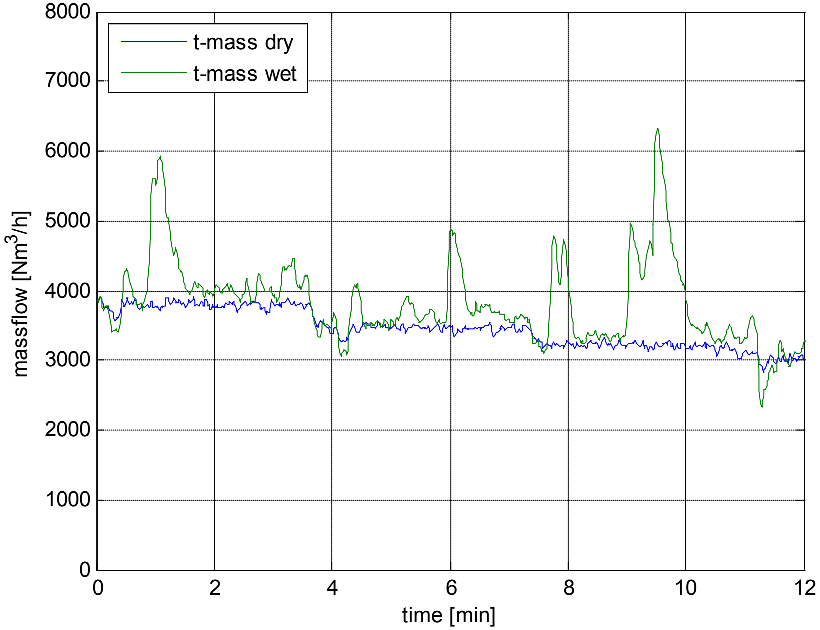
Pressure and Temperature influence of CO_2



As the process pressure increases the gas shows an increased specific heat absorption. To compensate for this effect the output must be corrected by applying a multiplication factor

Influence of Moisture

- Moist gas will increase the cooling effect on the sensors
- This influence is minimal as long as condensation is avoided
- In case of condensation the influence is NOT predictable
- Typically the meter will read 30 to 50% too much if the gas is condensing



t-mass for Industrial Gases Measurement

t-mass 150

- Measures Compressed Air, Nitrogen, Carbon Dioxide & Argon
- Measuring accuracy up to ± 3.0% o.r.

t-mass 65

- Integrated Gas Engine with list of 20 gases. Specific gas mixtures can be programmed up to 8 components
- Measuring accuracy up to ± 1.5% o.r.

Fits everywhere

In-line version

Insertion version
Cost-efficient gas flow measurement in large diameter pipes.

Insertion version with optional 'Hot Tap' mounting tool
For inserting or removing the device under process condition

What gas can be measured with t-mass?

Application recommended within the range of t-mass specification

Air	
Oxygen	O_2
Nitrogen	N_2
Carbon Dioxide	CO_2
Argon	Ar
Methane	CH_4

Biogas	
Natural gas	
Hydrogen	H_2
Helium	He
Butane	CH_3CH_2
Propane	C_3H_8

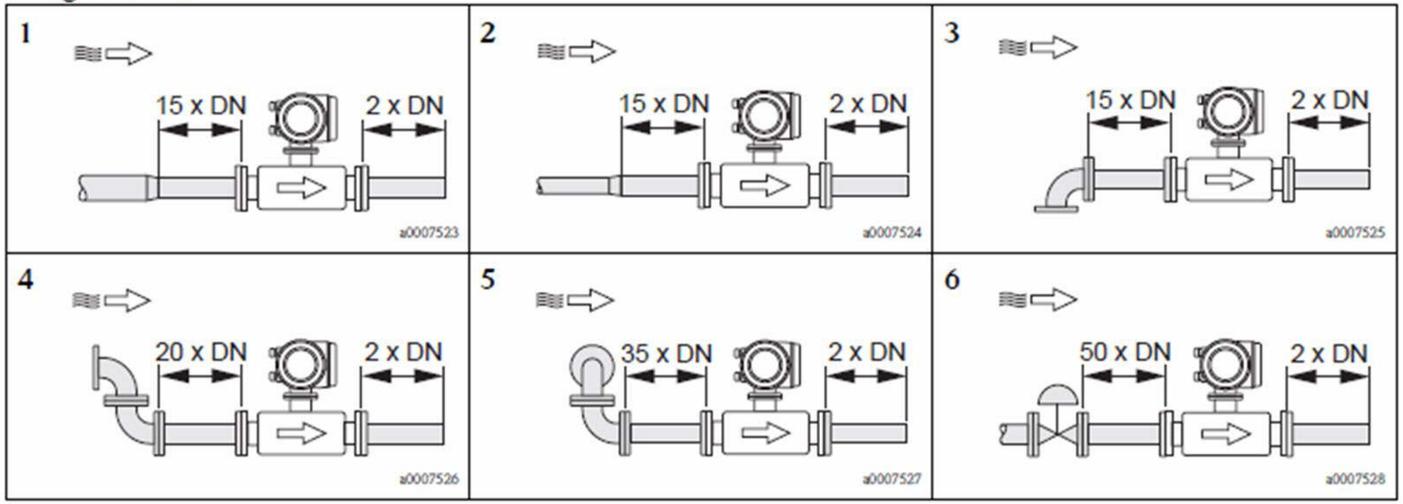
Care should be exercised, check;
Pressure
Temperature
Composition
Moisture
Flow rates
Customer expectations

Other gases:
i.e. Ammonia
Chlorine

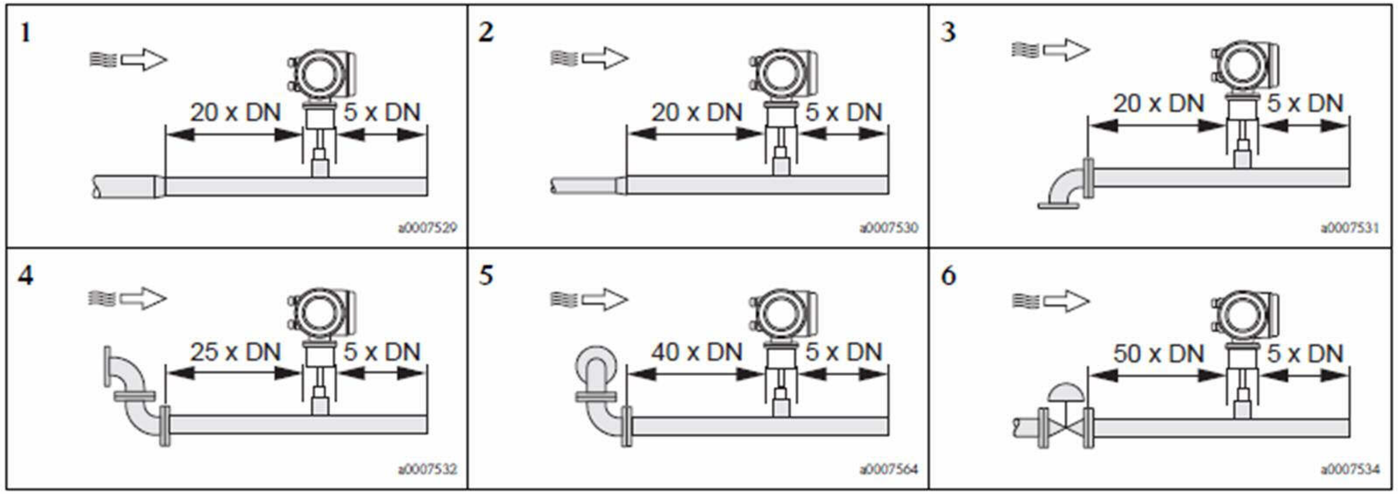
Get expert support for all gases not listed above!

Installation requirement

Flanged sensor



Insertion sensor

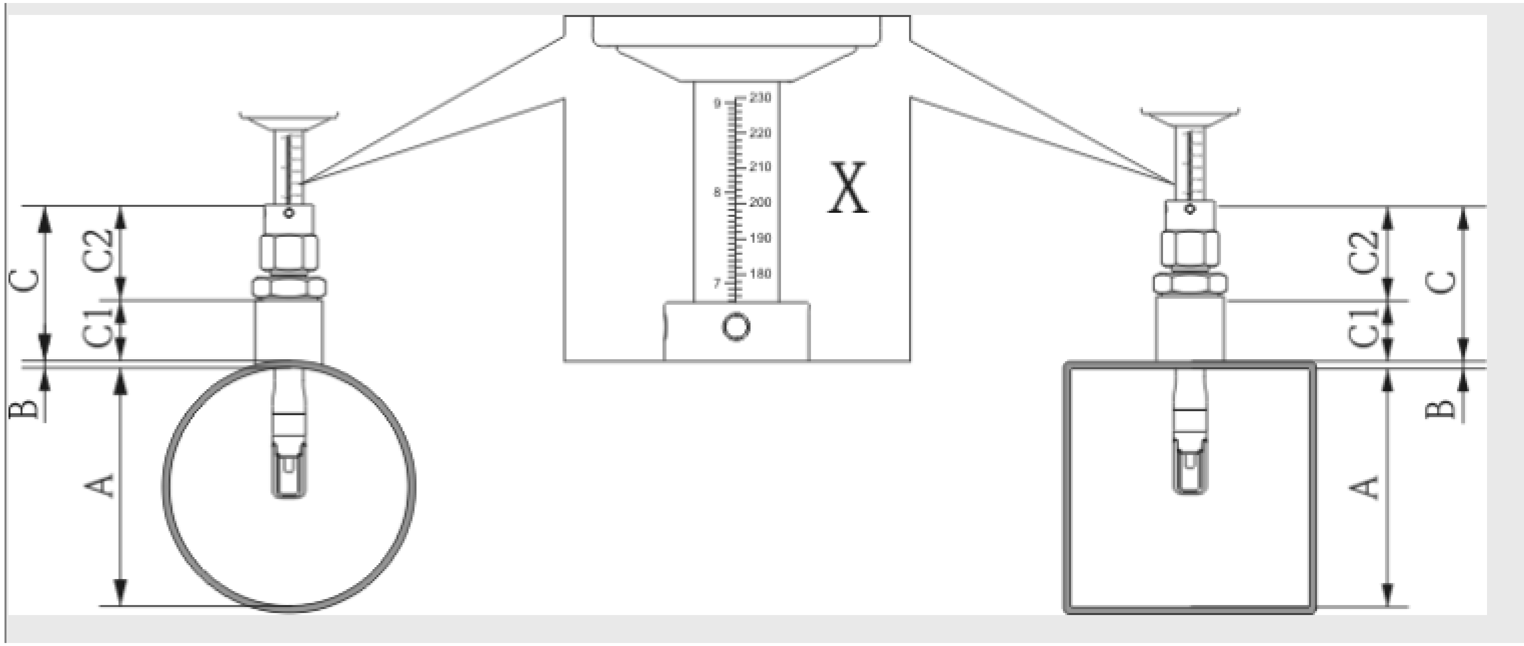


t-mass Insertion Installation Guide

Duct Installation		
Horizontal assembly	◉	
Vertical mount	○	
Wall thickness	2	mm
Accessory Selection		
Accessory	E+H Mounting boss, enclosed	
Process connection	G 1 A Thread (Fitting)	
Dimension information		
Height process conn. C1	60	mm
Height sensor conn. C2	39	mm
Total height C	99	mm

Calculated results		
Insertion depth X	131	mm
Insertion tube length	235	mm

Reset



Advantages and Limitations

Advantages

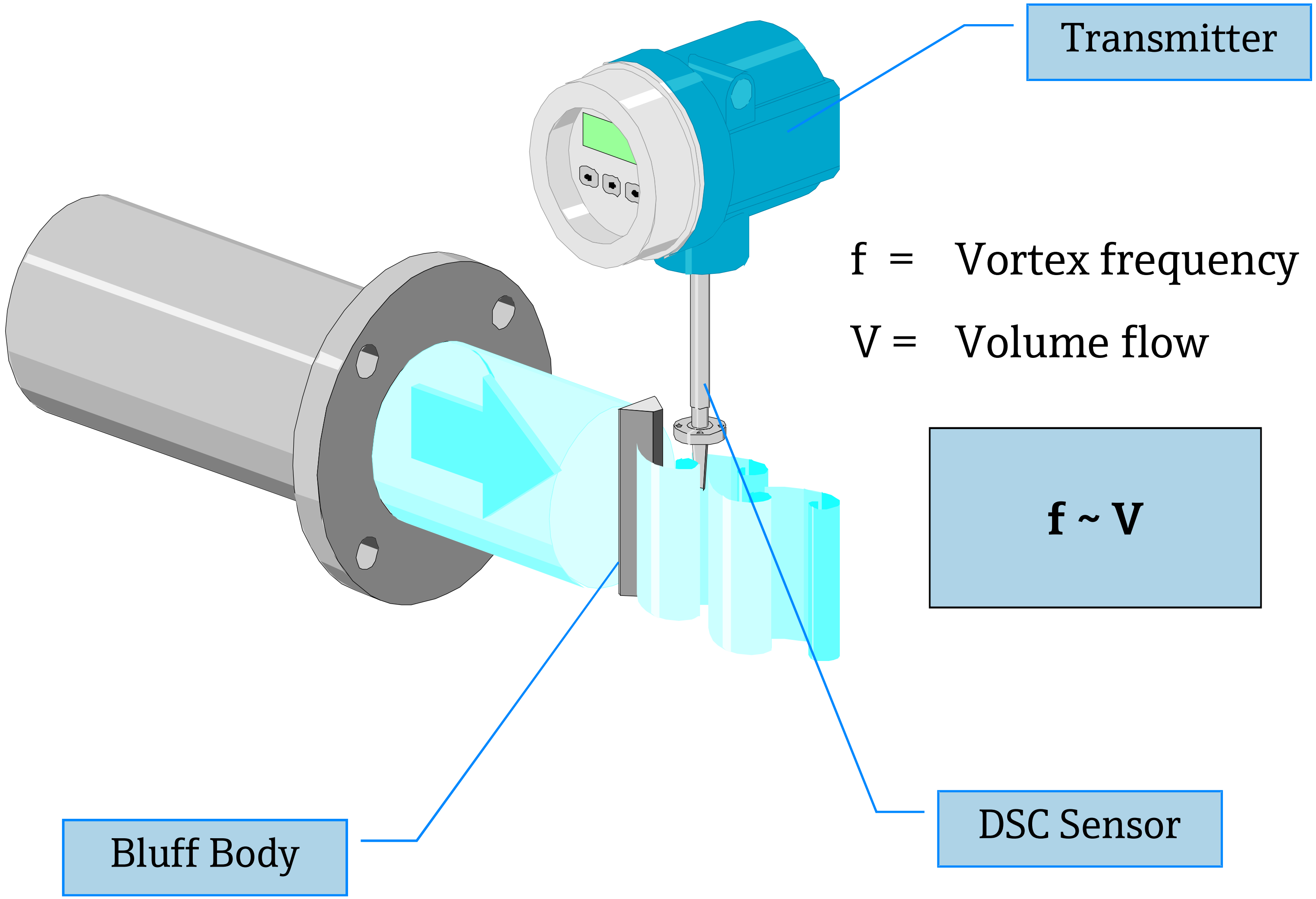
- Wide turndown ratio, 100:1
- Very low pressure loss (<2 mbar)
- Direct mass flow measurement

Limitations

- Not suitable for undefined gas mixtures
- Not recommended for condensate and dirty gases

Vortex

Vortex Measuring Principle

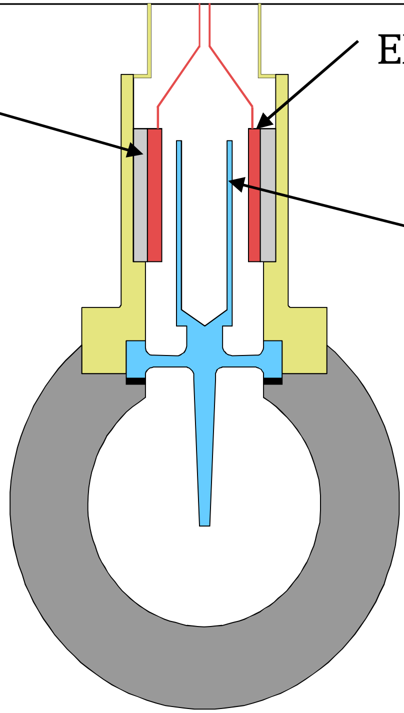


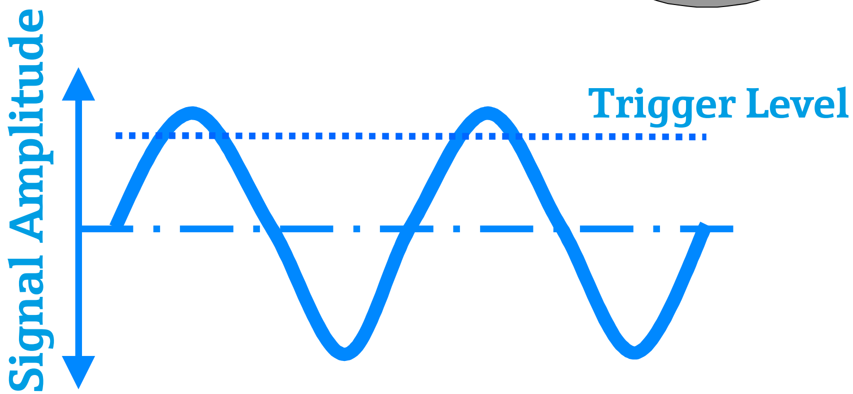
f = Vortex frequency

V = Volume flow

f ~ V

Differential Switched Capacitor Sensor





The movement of the paddle generates sinusidal voltage change between Electrode 1 and 2

Minimum flow requirement

- Physical limits based on principle (→ Karman street)
- 1) Depending on **density**

Prowirl 200 Standard

Example: Water

$$V_{min} = \frac{6}{\sqrt{\rho}} = \frac{6}{\sqrt{1000}} = 0.19 m/s$$

Example: Air @ 0°C, 1.013 bara

$$V_{min} = \frac{6}{\sqrt{\rho}} = \frac{6}{\sqrt{1.3}} = 5.3 m/s$$

Minimum flow requirement

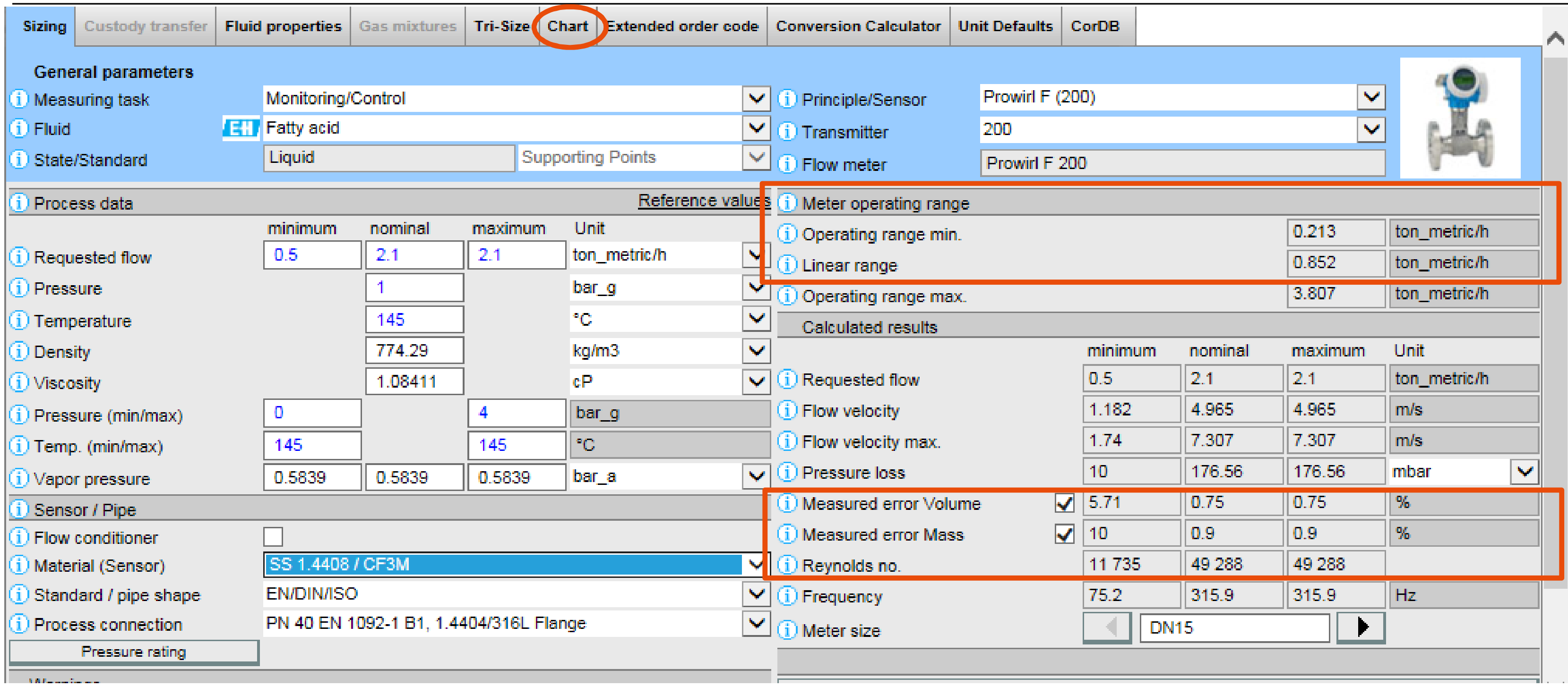
- 2) Depending on **Reynolds-Number**

$$Re = \frac{4 \cdot \dot{V} \cdot \rho}{\pi \cdot d_I \cdot \mu} \geq 5000$$

$\dot{V}$: Volume flow [m^3/s]
ρ : Density [kg/m^3]
d_I : Diameter [m]
μ : kinematic viscosity [$Pa \cdot s$]

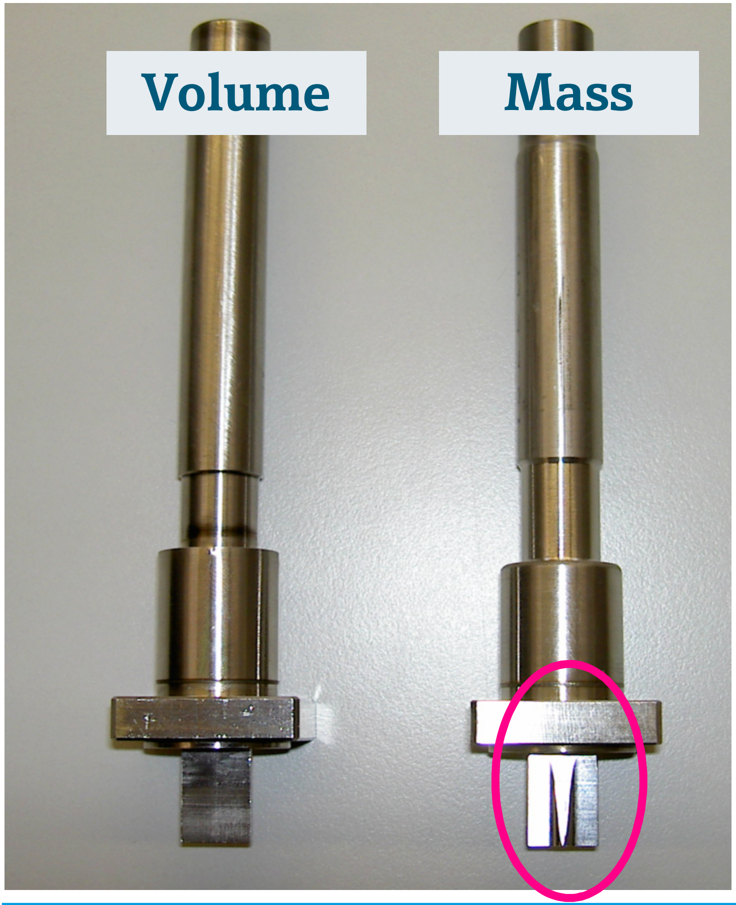
- Question: What happens with the min. flow if the fluid viscosity is increasing? Min. flow decrease (-) or increase (+)?
- NOTE: linear measuring range starts at Re=20'000!

Applicator Sizing does the job



- Operating range – Vortex starts to measures at Reynolds number 5,000 and above
- Linear Range - Reynolds Number 20,000 and above with measuring uncertainty ±0.75% o.r.

Prowirl Sensor: Volume or Mass



Integrated Temperature Sensor

The same type of sensor is used for all meter sizes means cost reduction of spare part handling

Prowirl 200 with "Gas Engine"

Prowirl 200 features recognised calculation methods for gas parameters to enable an accurate gas flow measurement!

Customer specific settings
(gases/mixtures, reference conditions...)

"Gas Engine"

20 gases available, gas mixtures from up to 8 components

Accurate calculation of...

- Operating density
- Reference/standard density
- Energy
- Viscosity

Result

- Gas parameters for all process conditions
- Gas parameter for reference/standard conditions

Accurate measurement of gases (esp. Natural gas) and gas mixtures

Process parameters
(temperature, pressure)

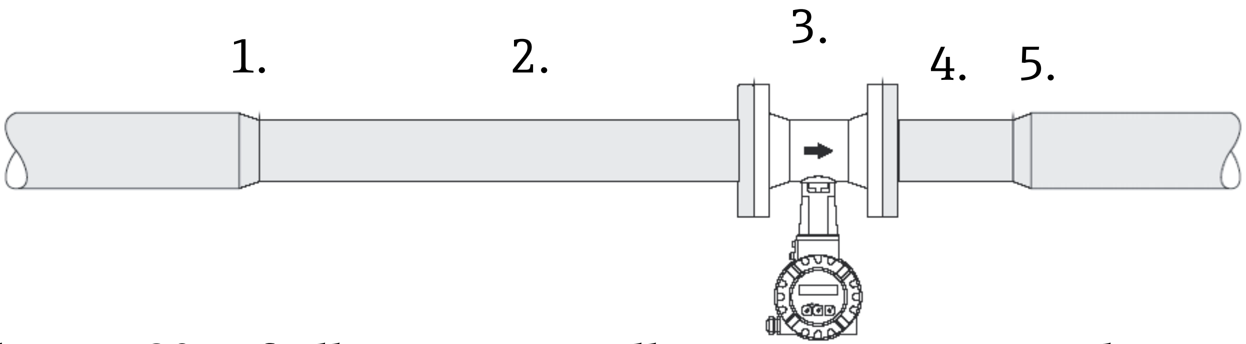
← Prowirl 200 features integrated **temperature measurement** and **current input** for easy wiring of a pressure transmitter

Prowirl 200 offers multivariable solutions!

World's first vortex flowmeter **with current input** enables fully compensated mass-/standard volume flow or delta heat measurement

Only available with "Mass flow" option

Common Vortex Installation



About 70% of all vortex installations require a reduction of line size, including:

1. reducer
2. min. 15 DN straight run (inlet)
3. Vortex
4. min. 5 DN straight run (outlet)
5. expander

All of this is replaced now – by one flow meter! with the same specifications…

DN100 to DN50

Prowirl R 200 sensor DN100/4” S Style
super reduced by two line sizes to DN50/2”

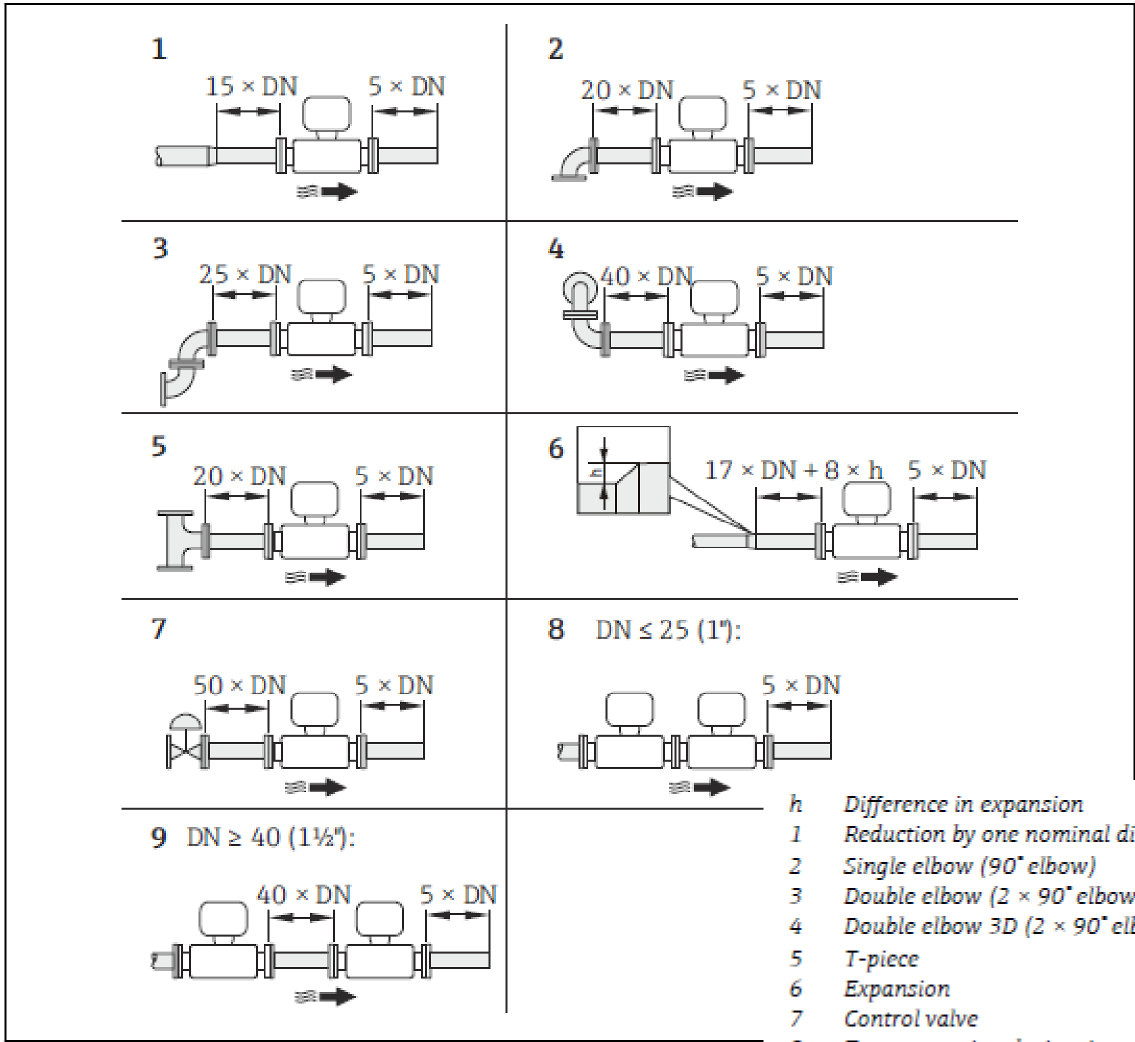
DN100 to DN80

Prowirl F sensor DN100/4” R Style
reduced by one line size to DN80/3”

DN100

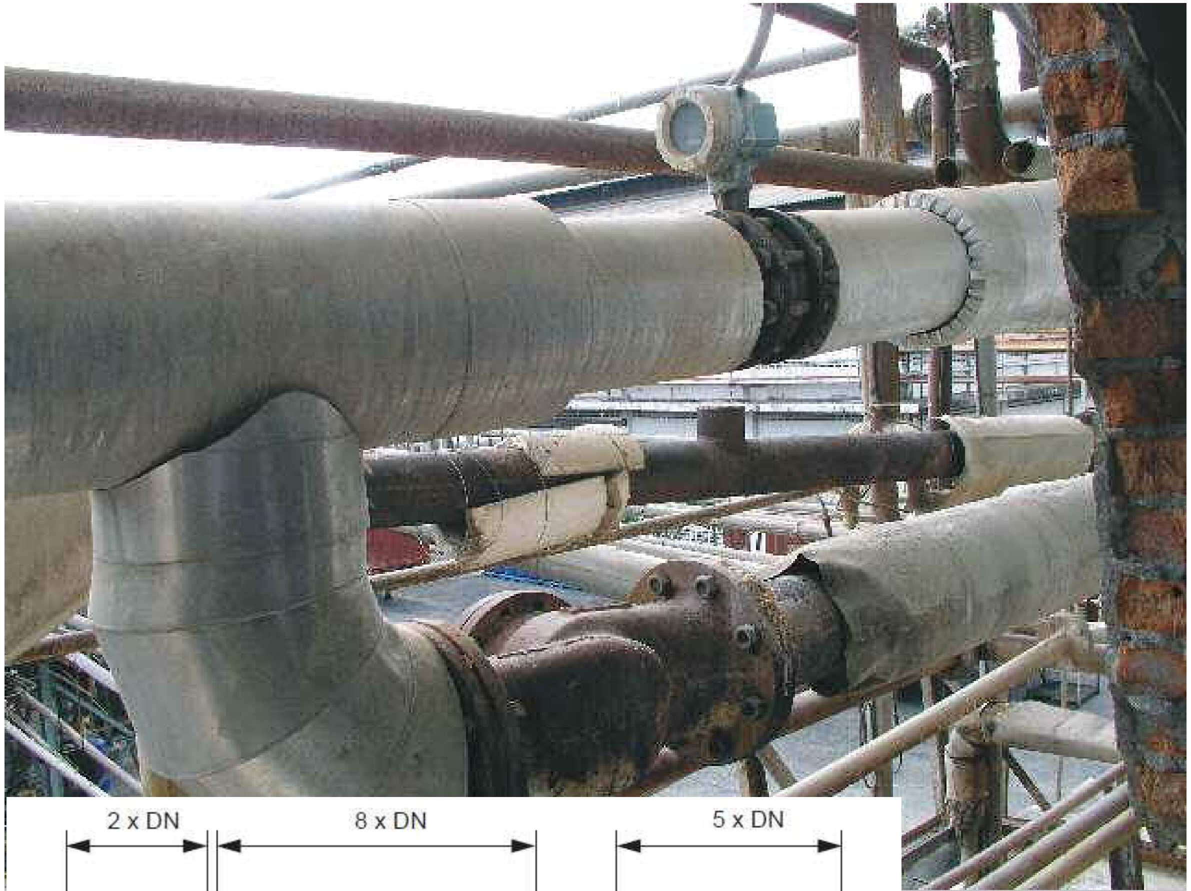
Prowirl F sensor DN100/4” standard

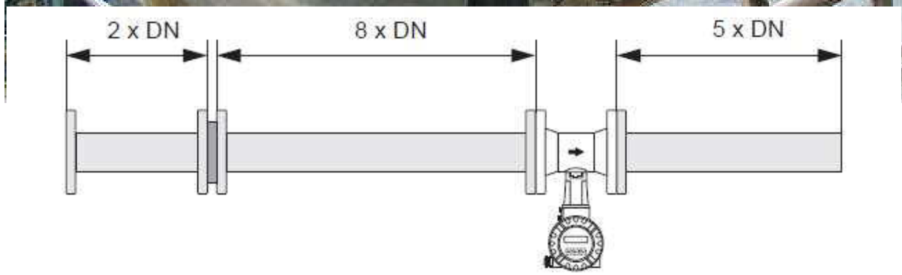
Installation requirement

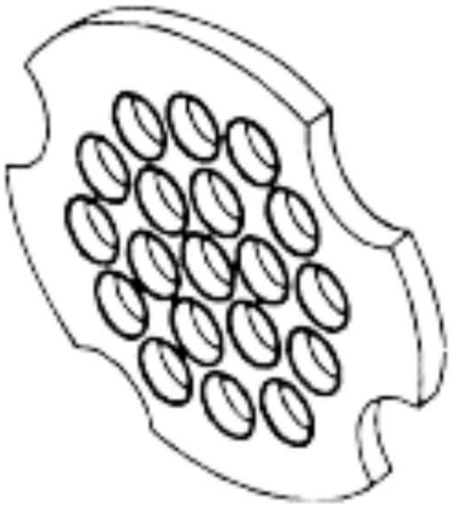


h *Difference in expansion*
1 *Reduction by one nominal diameter size*
2 *Single elbow (90° elbow)*
3 *Double elbow (2 × 90° elbows, opposite)*
4 *Double elbow 3D (2 × 90° elbows, opposite, not on one plane)*
5 *T-piece*
6 *Expansion*
7 *Control valve*
8 *Two measuring devices in a row where DN ≤ 25 (1"): directly flange on flange*
9 *Two measuring devices in a row where DN ≥ 40 (1½"): for spacing, see graphic*

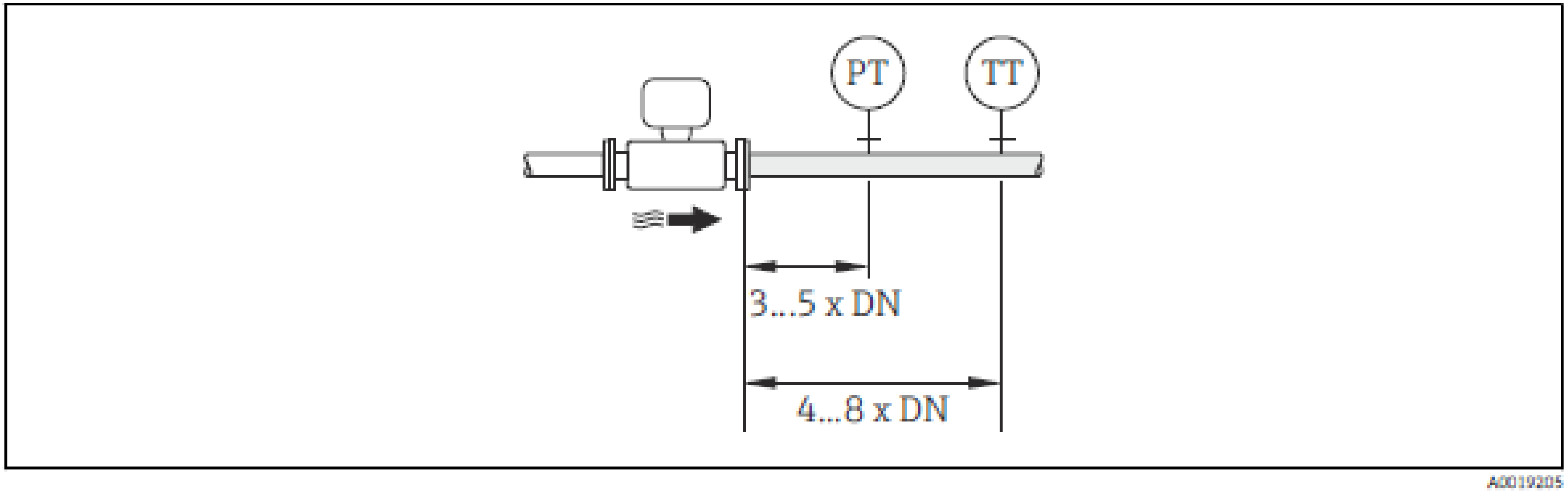
Flow conditioner to reduce inlet run





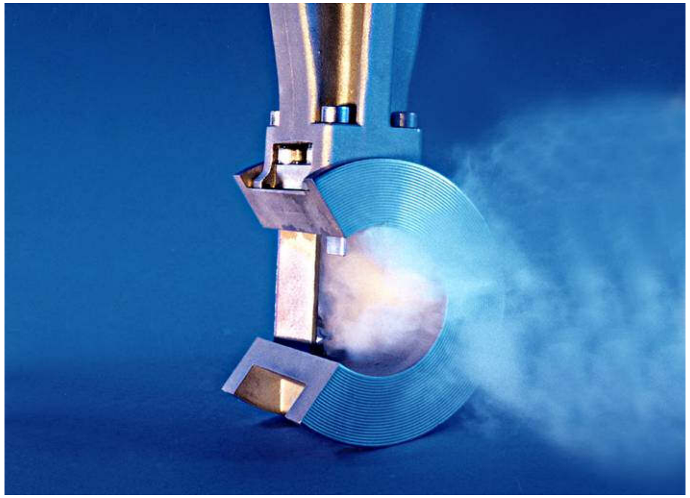


Vortex Installation with Pressure & Temperature Compensation



PT *Pressure transmitter*
TT *Temperature transmitter*

Advantages and Limitation



Advantages

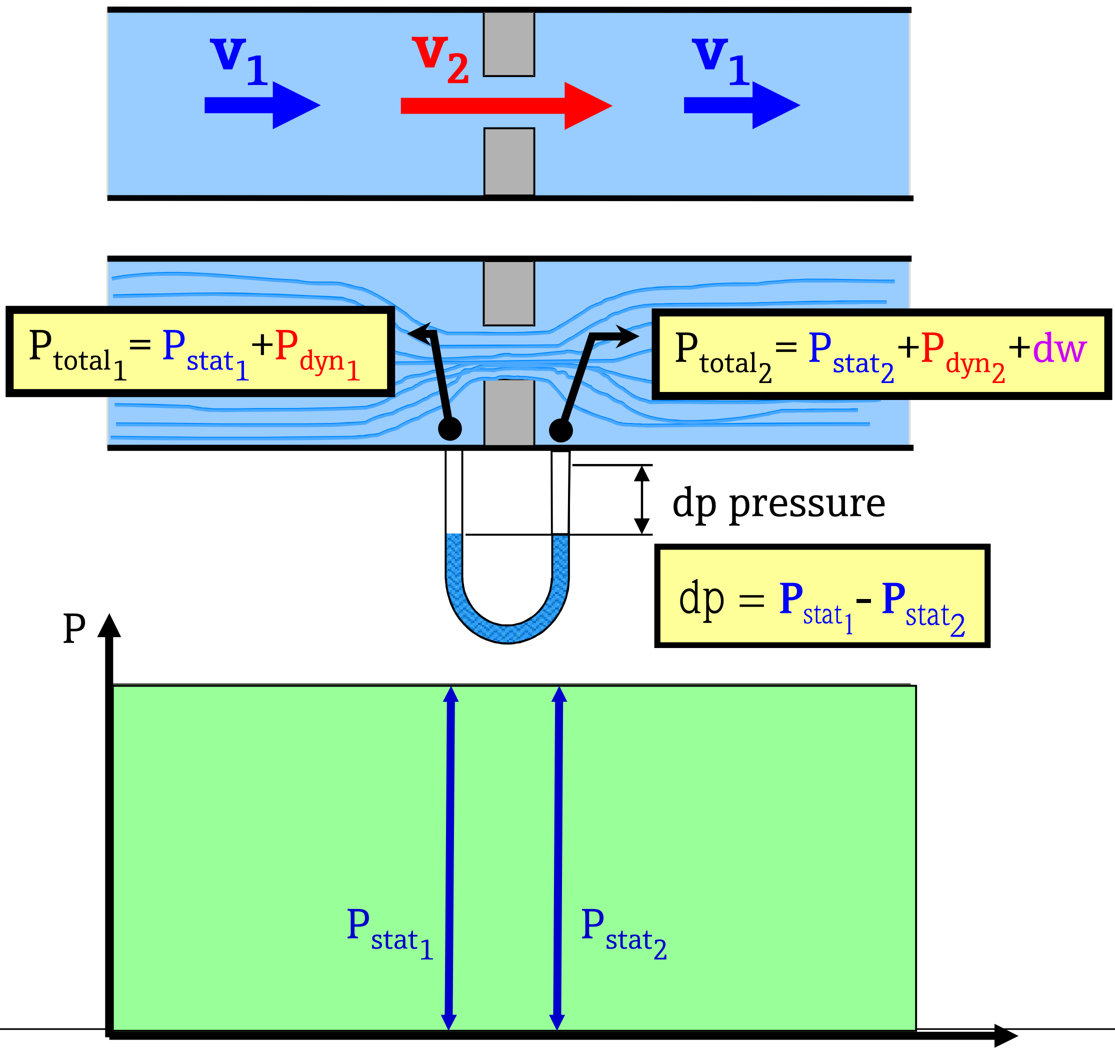
- High pressure range
- Suitable for gas, steam and liquids
- High temperature range
- Independent of gas properties

Limitations

- Volumetric measurement
- Sizes max. DN 300
- Min. flow limitation

Differential Pressure

Principle - Restriction Type Primary Elements



Flow Equation

$$Q_m = \left[0.5961 + 0.0261 \cdot \beta^2 - 0.216 \cdot \beta^8 + 0.000521 \cdot \left(\frac{10^6 \cdot \beta}{\mathrm{Re}_{xxx}} \right)^{0.7} + \left(0.0188 + 0.0063 \cdot \left(\frac{19000 \cdot \beta}{\mathrm{Re}_{xxx}} \right)^{0.8} \right) \cdot \beta^{3.5} \cdot \left(\frac{10^6}{\mathrm{Re}_{xxx}} \right)^{0.3} \right.$$

$$+ \left(0.043 + 0.08 \cdot e^{-10 \cdot L_1} - 0.123 \cdot e^{-7 \cdot L_1} \right) \cdot \left(1 - 0.11 \cdot \left(\frac{19000 \cdot \beta}{\mathrm{Re}_{xxx}} \right)^{0.8} \right) \cdot \frac{\beta^4}{1 - \beta^4}$$

$$\left. - 0.031 \cdot \left(\frac{2 \cdot L_2}{1 - \beta} - 0.8 \cdot \left(\frac{2 \cdot L_2}{1 - \beta} \right)^{1.1} \right) \cdot \beta^{1.3} + X_{\beta 2} \left[0{,}011 (0{,}75 - \beta) \left(2{,}8 - \frac{D}{0{,}0254} \right) \right] \right]$$

$$\cdot \left[1 - \left(0{,}351 + 0{,}256\, \beta^4 + 0{,}93\, \beta^8 \right) \cdot \left[1 - \left(\frac{p_{r\_nom} - \Delta p_{r\_\max}}{p_{r\_nom}} \right)^{1/\kappa} \right] \right]^{X_{\beta 1}} \cdot \frac{\pi}{4} \cdot \frac{(D \cdot \beta)^2}{\sqrt{1 - \beta^4}} \cdot \sqrt{2 \cdot \Delta p_{r\_\max} \cdot \rho_{nom}}$$

$$Q_m = C \cdot \varepsilon \cdot \frac{d^2 \pi}{4} \cdot \frac{1}{\sqrt{1 - \beta^4}} \cdot \sqrt{2 \cdot \Delta p \cdot \rho_{nom}}$$

$$Q_m = K \cdot \sqrt{2 \cdot \Delta p \cdot \rho_{nom}}$$

$$Q \approx \sqrt{\Delta p}$$

Simplified flow equation

$$Q \approx \sqrt{\Delta p}$$

$$\approx \neq =$$

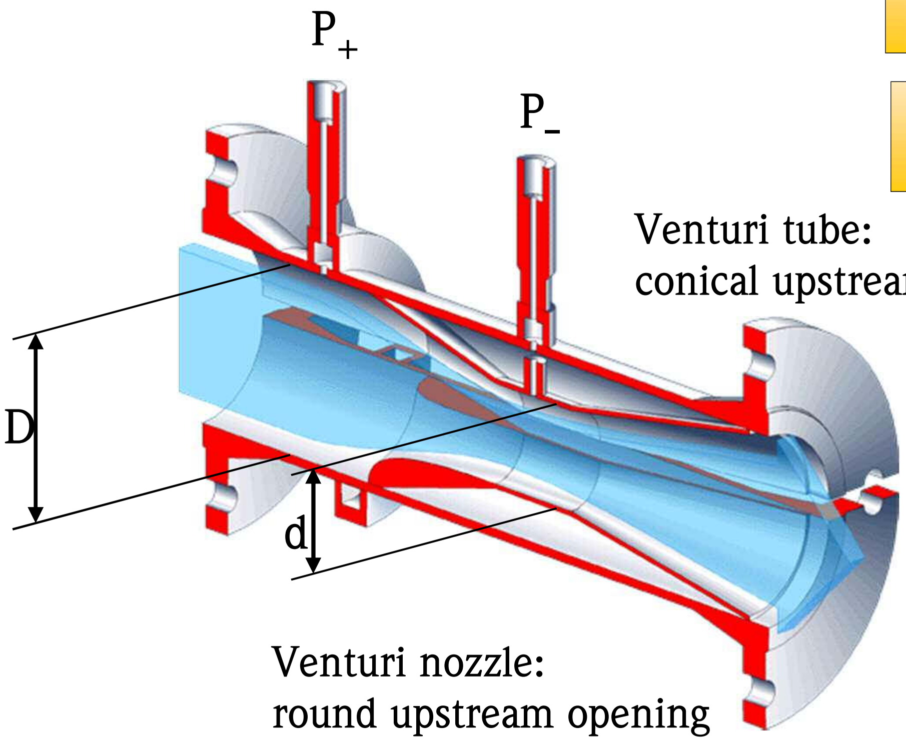
Flow measurement with primary devices

ISO 5167-4: Venturi tube and Venturi nozzle

$$\Delta p = p_+ - p_-$$

$$q_m = K_{(\beta)} \cdot \sqrt{2 \cdot \Delta p \cdot \rho}$$

$$q_v = K_{(\beta)} \cdot \sqrt{2 \cdot \Delta p \cdot 1/\rho}$$



Venturi tube:
conical upstream opening

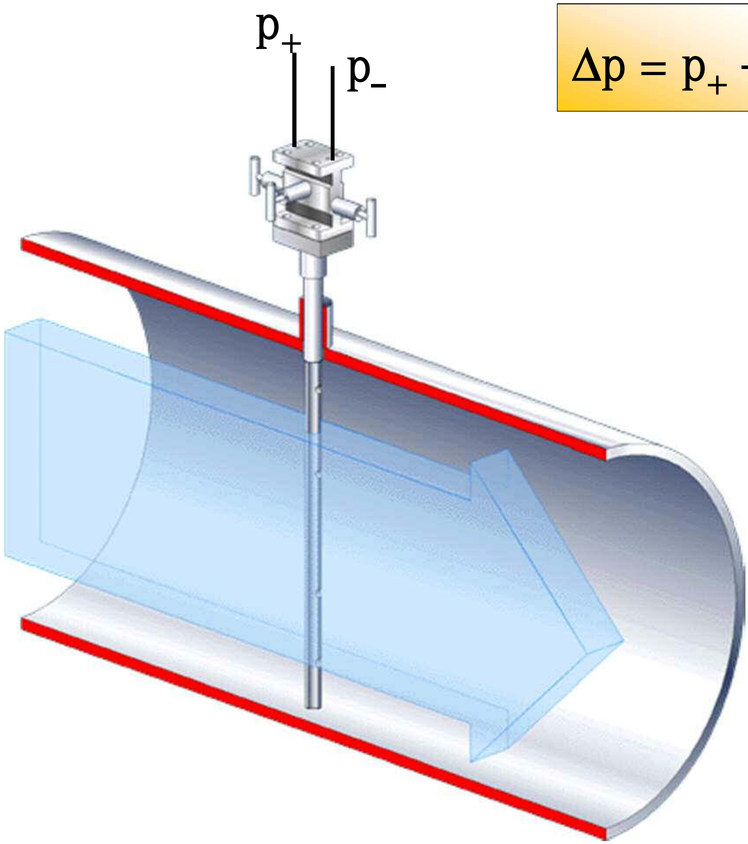
Venturi nozzle:
round upstream opening

Diameter ratio of the primary device:

$$\beta = \frac{d}{D}$$

Flow measurement with primary devices

Pitot tube



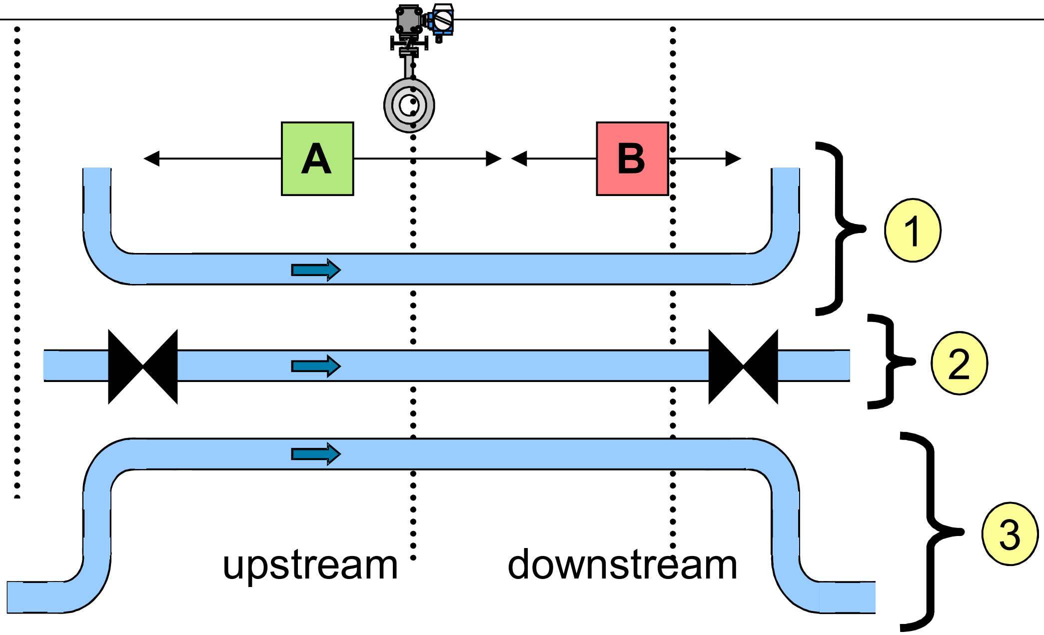
$$\Delta p = p_+ - p_-$$

$$q_m = K \cdot \sqrt{2 \cdot \Delta p \cdot \rho}$$

$$q_v = K \cdot \sqrt{2 \cdot \Delta p \cdot 1/\rho}$$

According to calculations of manufacturer or sample calibration

Installation: Inlet/Outlet Run – How long?



	Pitot tube A	Pitot tube B	Orifice (β = 0,2 ... 0,8) A	Orifice (β = 0,2 ... 0,8) B
1	7 * D	3 * D	(10 ... 16) * D	(4 ... 8) * D
2	30 * D	4 * D	(18 ... 44) * D	(4 ... 8) * D
3	9 * D	3 * D	(14 ... 50) * D	(4 ... 8) * D

Factor 1/2 if additional uncertainty of e_K = 0,5 % is accepted!

D = inner pipe diameter

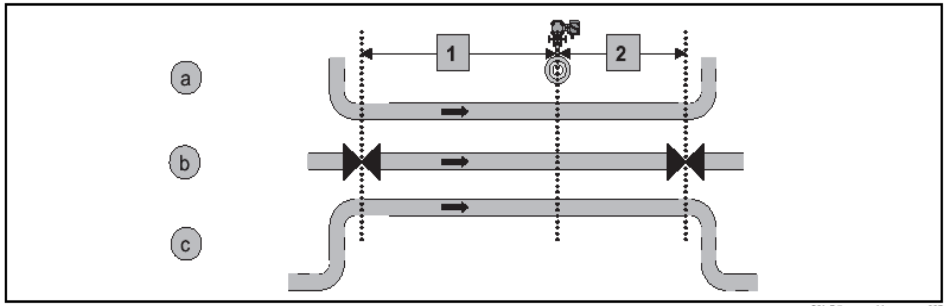
dp Flow : Compensation according to ISO 5167

Temperature and pressure compensation

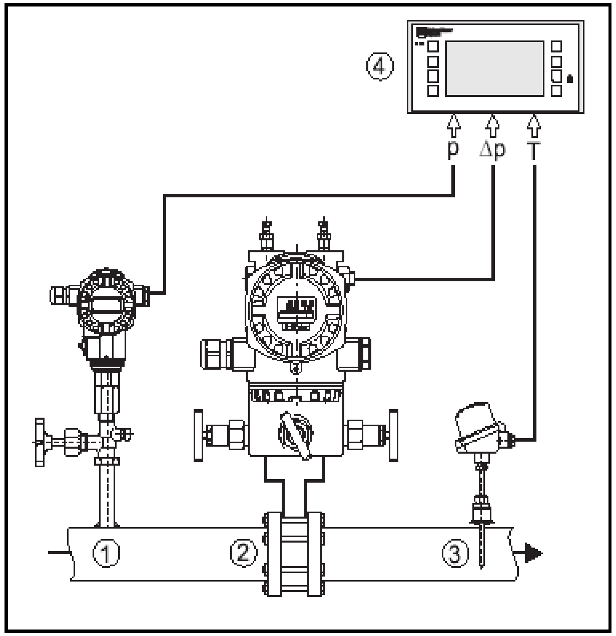
Separate process connections

Two additional probes are required for temperature and pressure compensation:

- **An absolute pressure sensor**
  According to ISO 5167, this probe must always be mounted on the upstream side of the orifice.
- **A temperature probe**
  In order to avoid disturbances of the flow profile, this probe must be mounted on the downstream side of the orifice.



1: *upstream length;* **2:** *downstream length;*
a: *90° bend;* **b:** *valve, open;* **c:** *2x90° bend*



1: *Absolute pressure sensor*
2: *orifice and differential pressure transmitter*
3: *temperature probe*
4: *evaluation unit*

Advantages and Limitations

Advantages

- Tradition and experience
- Wide application area
- Low cost for large DN

Limitations

- Low turndown
- High maintenance required

Ultrasonic (Biogas)

Prosonic B200 for Biogas Measurement

Why Measure Biogas?

- Rate of gas produced by the digester is an indicator of the health of the digester. Decreasing output is a warning of a failing process.
- Rate of gas as input into engines, boilers or for diversion to storage
- Totalization of biogas diverted to flare
- Totalization of biogas production for accounting purposes

Prosonic B200

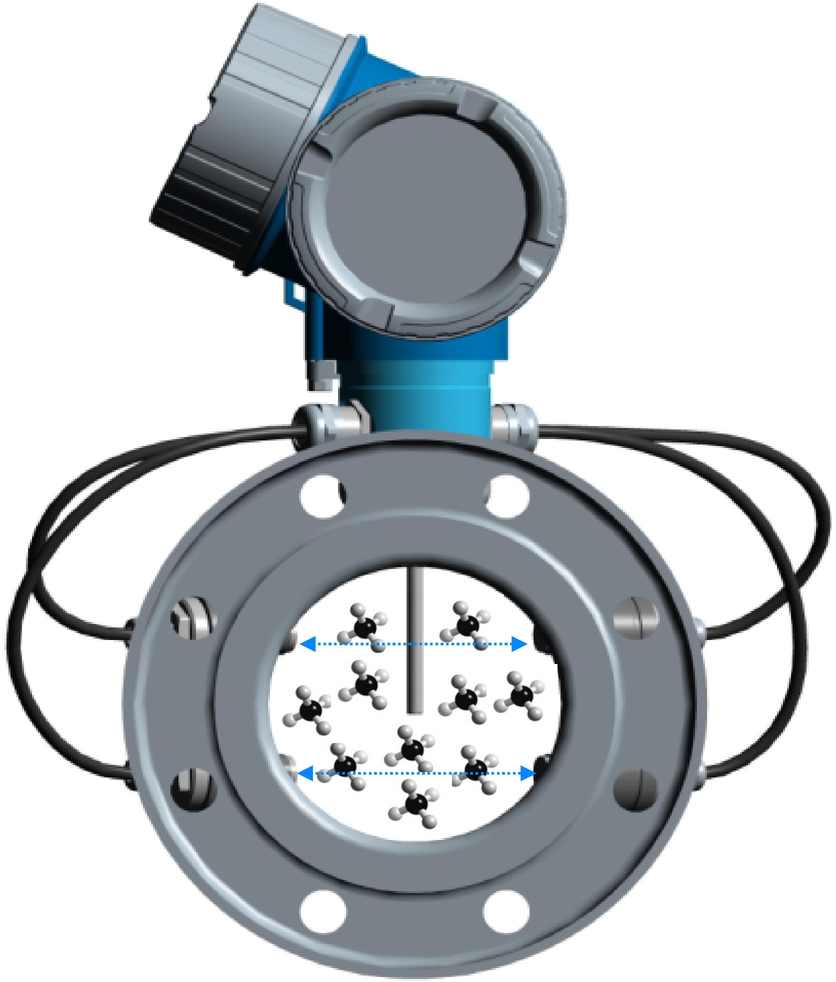
- For wet biogas, landfill or digester gas
- Direct measurement of the methane content (CH4) in the pipe
- Process Temperature: 0 to +80°C
- Nominal diameters: DN 50 to 200 (2” to 8")
- High accuracy: ±1.5% o.r.

How does Prosonic B200 Measure Methane?

- The Prosonic B 200 measures the time taken for the ultrasonic pulse to travel through the gas.
- As the path length is know the speed of sound in the gas can be accurately determined. As the speed of sound in a gas is dependent on the gas composition the B 200 can use the sound speed to calculate the methane content of the biogas.

Endress+Hauser

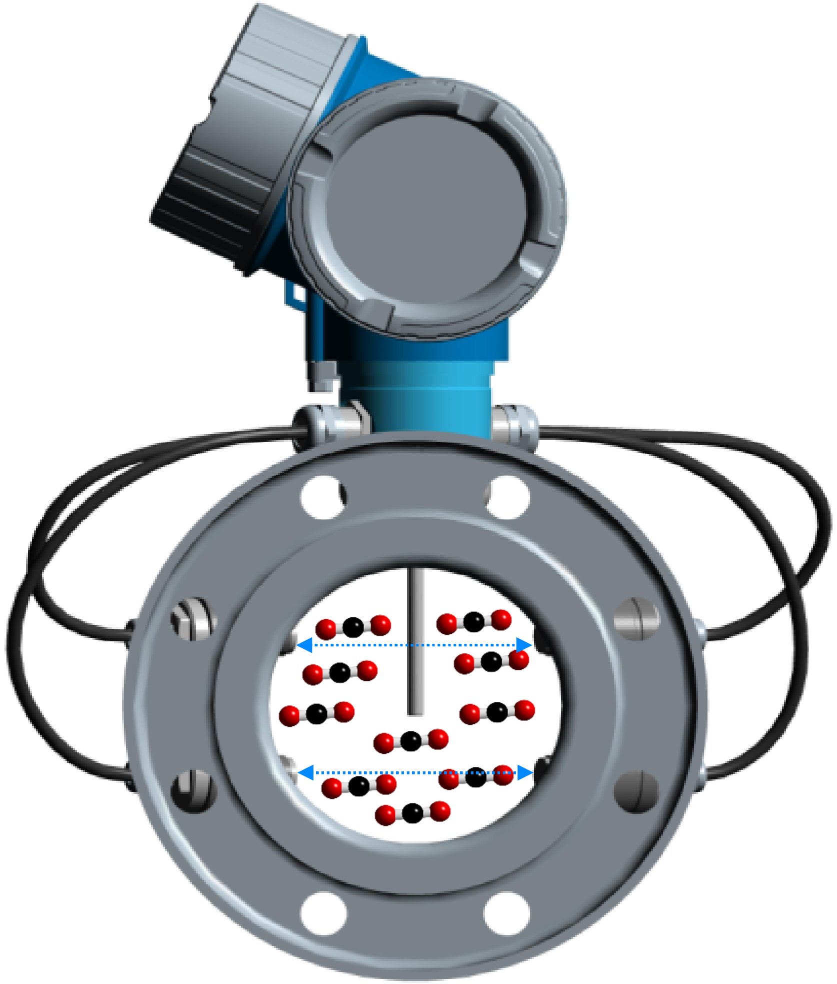
100% CH_4 @ 40 °C



The speed of sound in 100% Methane at 40 °C is 458.5 m/s

Temperature	Methane	Carbon dioxide	Speed of sound
°C	CH_4	CO_2	m/s
40	0.0%	100.0%	**274.7**
40	10.0%	90.0%	**284.1**
40	20.0%	80.0%	**294.5**
40	30.0%	70.0%	**306.0**
40	40.0%	60.0%	**319.0**
40	50.0%	50.0%	**333.8**
40	60.0%	40.0%	**350.8**
40	70.0%	30.0%	**370.7**
40	80.0%	20.0%	**394.2**
40	90.0%	10.0%	**422.8**
40	100.0%	0.0%	**458.5**

100% CO_2 @ 40 °C



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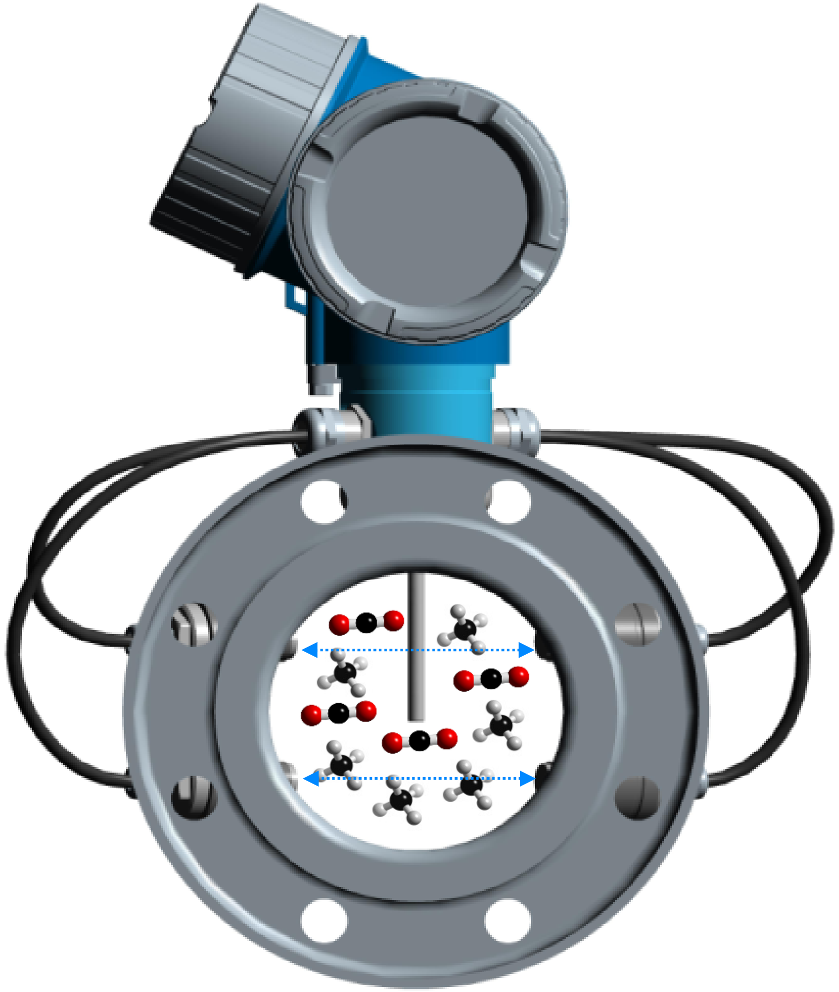
40	100.0%	0.0%	**458.5**

Endress+Hauser

Biogas 60% CH_4 40% CO_2 @ 40 °C



The speed of sound in biogas (60% CH_4 40% CO_2) at 40 °C is 350.8 m/s

Temperature	Methane	Carbon dioxide	Speed of sound
°C	CH_4	CO_2	m/s
40	0.0%	100.0%	**274.7**
40	10.0%	90.0%	**284.1**
40	20.0%	80.0%	**294.5**
40	30.0%	70.0%	**306.0**
40	40.0%	60.0%	**319.0**
40	50.0%	50.0%	**333.8**
40	60.0%	40.0%	**350.8**
40	70.0%	30.0%	**370.7**
40	80.0%	20.0%	**394.2**
40	90.0%	10.0%	**422.8**
40	100.0%	0.0%	**458.5**

Field trial – Agrikracht NV BE

Methane measurement

- Pronova SSM 600 is a gas analyzer designed specifically for biogas applications.
- The methane concentration is measured using infra-red technology, the manufactures state the accuracy to be 0.1%Vol.

- The B 200’s methane measurement differs by only 0.39%

Application of Prosonic B200 in Malaysia

Installation Location:
Poultry farm biogas plant at Negeri Sembilan, Malaysia

Prosonic B200 Features:

- Wet biogas measurement
- Direct measurement of methane, CH_4 content in the pipe

Prosonic B200 Benefits:

- Continuous, around-the-clock monitoring of gas quantity and quality
- Fast and targeted reaction in case of interference in the fermentation process

Best Fit for Gas Measurement?

Consider:

- Installation requirement
- Measuring accuracy
- Pressure loss
- Turndown
- Influence of moisture
- Changing pressure
- Changing temperature

Turndown

Measuring Principle	Turndown
Thermal	100: 1
Coriolis	15:1
Vortex	13:1
DP	6:1

- For DP, the turndown can be increased by using the split-range functionality of RMC621.

Pressure Loss

Instrument	Measuring Principle	Pressure loss
Deltatop Orificeplate DN50	Differential Pressure	95 mbar
Promass 83F DN50	Coriolis	45 mbar
Prowirl 72F DN50	Vortex	25 mbar
t-mass 65F DN50	Thermal	<2 mbar

Any Question

Thank you very much for your attention

Endress+Hauser
People for Process Automation