
ABB MEASUREMENT & ANALYTICS

Industrial flow measurement

Basics and practice



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Industrial Flow Measurement Basics and Practice

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Introduction

In the recent decades, the market for the products of the industrial process industries has changed greatly. The manufacture of mass products has shifted to locations where raw materials are available economically. Competitive pressures have forced a swing to specialization as well as to an ability to adapt to customers desires. The systems are designed so that the economic data, such as raw material properties, raw material costs, batch sizes, are quickly integrated into the processes. An important consideration is the assurance and improvement of product quality.

The operation of such systems requires a high degree of automation. With the assistance of process technology the control of the procedures can be optimized and personnel requirements minimized. The process control technology assures that process cycles are documented so that the quality of the product is always traceable.

The most important prerequisite for automation is knowledge of the actual process parameters, which can be ascertained utilizing measurement instruments. If the actions dependent on the measurements are to be realized then the specifications must naturally be qualitatively high. Therefore, the measurement instrument requires:

- high accuracy
- easily understandable functionality
- easy operation and maintenance
- testability even without a test bench
- self monitoring
- error signalling / self-diagnostics
- communication ability

The planner of an industrial process system assumes in advance that the measurement error limits will be satisfied. However, it is not always possible to divorce oneself from the problems associated with the measuring point.

This publication for industrial flow measurement aims at supporting practitioners in solving their versatile and demanding tasks. At the same time, it is intended to provide a vivid overview of the basic measuring principles and their limitations to interested newcomers.

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We hope you will enjoy reading this publications and take advantage of its practical use. We would like to thank all authors who have contributed to creating this publication. Any suggestions and comments from your side are welcome and will flow into the development process of new technological solutions.

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List of Symbols

A	Area, cross-section (mm ² , m ²)
B	Magnetic flux density, induction (T)
b	Width (mm, m)
C	Flow coefficient (1)
c	Resistance coefficient (1) (see Electromagnetic Flowmeters)
c	Sound velocity (m/s)
c	Specific heat (J/K · kg)
D, d	Diameter (mm, m)
E	Velocity of approach factor (1) (see Differential Pressure Measurement)
E	Energy (J, KWh)
e	Energy level (kinetic energy expressed as liquid level) (m)
F	Force (N, kg · m/s ²)
f	Frequency (s ⁻¹)
g	Acceleration due to gravity = 9.81 m/s ²
H	Energy level (kinetic energy expressed as liquid level) (m)
h	Height, elevation, level (mm, m)
J	Electrical current (A)
k	Surface roughness (mm)
l	Length (mm, m)
m	Mass (g, kg)
m	Area ratio d ² /D ² (1) (see Differential Pressure Measurement)
p	Pressure (Pa, bar), P _{dyn} = dynamic pressure
Δp	Differential pressure (Pa, bar)
q _m	Mass flow, mass flow rate (g/s, kg/h)
q _Q	Heat flow, heat flow rate (J/s)
q _v	Volume flow, volume flow rate (l/s, m ³ /h)
T	Temperature (K, °C)
T	Time constant (s)

t	Time (s)
U	Electrical voltage (V)
V	Volume (mm^3 , m^3 , l)
v	Velocity (m/s)
W	Weighting factor (1) (see Electromagnetic Flowmeters)
β	Diameter ratio $d/D ; 1 <$ (see Differential Pressure Measurement)
γ	Thermal volume expansion coefficient (K^{-1})
Δ	Difference, spec. differential pressure Δp
ε	Expansion coefficient (1)
η	Dynamic viscosity (Pa · s)
χ	Electrical conductivity (S/cm)
λ	Resistance coefficient, coefficient of friction (1) (see Free Surface Measurements)
μ	Flow coefficient (1), (see Weir)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3 , g/cm^3)
Φ	Magnetic flux (Wb, Vs)
ω	Angular velocity (s^{-1})
Fr	Froude number (1)
Re	Reynolds number (1)
St	Strouhal number (1)
VUZ	Viscosity Influence Number (1)

Content	Page
1 Introduction to the Physics of Flow Rate and Total Flow Measurements	13
1.1 Measured Variables	13
1.2 Fluid Mechanics Concepts	15
1.2.1 Viscosity	15
1.2.2 Reynolds Number	15
1.2.3 Flow Regimes	16
1.2.4 Flow Separation	17
1.2.5 Energy Equations and Flow Rate	19
1.2.6 Channel Hydraulics	23
2 Flow Rate and Total Flow Measurement of Gases and Liquids	29
2.1 Volume Totalizers	30
2.1.1 Oval Gear Totalizers	30
2.1.2 Oscillating Piston Totalizers	33
2.1.3 Lobed Impeller Gas Totalizers	36
2.1.4 Turbine Totalizers	38
2.1.5 Vortex Flowmeters	45
2.1.6 Swirl Flowmeters	57
2.2 Flowmeters	67
2.2.1 Flowmeters for Differential Pressure Measurement	67
2.2.2 Compact Orifice Flowmeters	78
2.2.3 Wedge Meters for Critical Applications	79
2.2.4 Pitot Flowmeters	82
2.2.5 Variable Area Flowmeters	85
2.2.6 Electromagnetic Flowmeters	102
2.2.7 Ultrasonic Flowmeters	137
2.2.8 Coriolis Mass Flowmeters	140
2.2.9 Thermal Mass Flowmeters for Gases	151
2.3 Flow in Open Channels and Free Surface Pipelines	157
2.3.1 Flow Measurement in Open Channels	157
2.3.2 Flow Measurement in Free Surface Pipelines	165
3 Regulations and Requirements Regarding Quality, Environment, Safety and Data Protection	173
3.1 Integrated Management System	173
3.2 Degrees of Protection per EN 60529 (Excerpts from the Standard Sheet)	176
3.3 Requirements Regarding Interference Immunity (EMC)	179
3.4 Explosion Protection	182
3.4.1 International Orientation of Explosion Protection	183
3.4.2 Terms and Definitions	184
3.4.3 Types of Protection in Europe and North America	191
3.4.4 Approvals According to the FM Approval Standards	196
3.4.5 Approvals in Accordance with the CSA Standards	196
3.4.6 Free Movement of Goods Related to Explosion-Proof Electrical Devices .	197

3.4.7	Identification of Equipment	197
3.5	GOST Approvals for Flow Measurement	199
3.5.1	Russia	199
3.5.2	Belarus, Ukraine and Kazakhstan	205
3.6	SIL - Functional Safety Standards	207
3.7	Pressure Equipment Directive 97/23/EC	209
3.8	Corrosion	213
3.9	Data Transmission	214
3.9.1	Standardized Pneumatic Signal	214
3.9.2	Standardized Electrical Analog Signal	215
3.9.3	Switch Outputs	215
3.9.4	HART Protocol	216
3.9.5	Fieldbus in Process Automation	218
3.9.6	FOUNDATION Fieldbus	220
3.10	Calibration and Official Verification	221
3.10.1	Why Calibrate?	221
3.10.2	Terms and Definitions	221
3.10.3	Methods of Flow Calibration	222
3.10.4	Test Bench for Liquid Flow Measurement	223
3.10.5	Test Bench for Gas Flow Measurement	225
3.10.6	Approvals of Test Benches and Products	227
3.10.7	Calibration Possibilities at ABB	230
3.10.8	Measuring Instruments Directive (MID)	233
3.10.9	OIML (Organisation Internationale de Métrologie Légale)	234
4	Device Selection Criteria	235
4.1	Flowmeters for Closed Pipings	236
4.1.1	Influences of the Measuring Medium Properties	240
4.1.2	Flow Regime Effects	244
4.1.3	Ranges of Application and Technical Limit Values	248
4.1.4	Performance Specifications and Properties of the Flowmeters	252
4.1.5	Installation and Maintenance	258
4.2	Flowmeters for Channels and Free Surface Pipings	262
4.2.1	Solids in the Measuring Medium	263
4.2.2	Gas Content	263
4.2.3	Flow Regime Effects	264
5	Overview of the Outstanding Meter Features	269
5.1	Oval Gear Meters, Oscillating Piston Meters	269
5.2	Lobed Impeller Meters	269
5.3	Turbine Meters	270
5.4	Vortex Flowmeters	270
5.5	Swirl Flowmeters	271
5.6	Differential Pressure Flowmeters	271
5.7	Variable Area Flowmeters	272
5.8	Electromagnetic Flowmeters	272

5.9	Ultrasonic Flowmeters	273
5.10	Coriolis Mass Flowmeters	274
5.11	Thermal Mass Flowmeters	274
5.12	Weirs	275
5.13	Venturi Flumes	275
5.14	Electromagnetic Flowmeters in Culverts	276
5.15	Electromagnetic Flowmeter FXP4000 for Partially Full Pipelines	276
6	Keywords for the Operating Conditions and Requirements on the Measuring Point	277
7	Standards and Regulations	279
8	Materials, Corrosion Resistance Tables	281
9	References	289

1 Introduction to the Physics of Flow Rate and Total Flow Measurements

1.1 Measured Variables

Measurement technology provides the tools for optimizing production processes and dosing operations. In addition to pressure and temperature, the flow rate is one of the most important measured variables. The quantitative determination of amount, volume, and flow rate allows production processes to be optimized through control and regulation.

The most important basic values are mass and volume:

Mass with the symbol m measured in kg or g

Volume with the symbol V measured in m³, dm³ or cm³

As a ratio of mass to volume the density defines the relationship between both values:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} : \rho = \frac{m}{V} \left[\frac{\text{kg}}{\text{dm}^3}, \frac{\text{kg}}{\text{m}^3}, \frac{\text{g}}{\text{cm}^3} \right]$$

Since the majority of production systems operate continuously, the measured values must be representative of the instantaneous conditions or indicate the instantaneous values. Therefore, a time dependent value is necessary: the flow rate. Using the two basic units, mass and volume, a distinction is made between the mass flow rate q_m and the volume flow rate q_v:

$$\text{Mass flow rate} = \frac{\text{Mass}}{\text{Time}} : q_m = \frac{m}{t} \left[\frac{\text{kg}}{\text{s}}, \frac{\text{g}}{\text{s}}, \frac{\text{kg}}{\text{h}} \right]$$

$$\text{Volume flow rate} = \frac{\text{Volume}}{\text{Time}} : q_v = \frac{V}{t} \left[\frac{\text{m}^3}{\text{s}}, \frac{\text{l}}{\text{s}}, \frac{\text{m}^3}{\text{h}} \right]$$

Mass flow rate is the ideal measurement value because it is independent of pressure and temperature, although volume flow rate is usually technically more convenient to measure and, therefore, is preferred.

The volumes of the incompressible liquids are never affected by the pressure in the ranges normally encountered. Temperature changes, however, result in volume changes which in some cases require correction measures.

The corrected volume V_2 is:

$$V_2 = V_1 (1 + \gamma \cdot \Delta T) \quad (1.1)$$

$\gamma [K^{-1}]$: thermal volume expansion coefficient

$T [K]$: (specific fluid property) temperature

Modern flowmeters incorporate amplifiers which can apply calculated corrections to the flow rate analogous to V_2 . The effects of temperature and pressure are appreciably greater for gas measurements. It is for this reason that these absolute measurements are usually based on normal conditions, namely $p_n = 101325 \text{ Pa}$ or 1.01325 bar and $T_n = 273 \text{ K}$. These absolute measurements at normal conditions (p_n, T_n) also in some regions called standard conditions (p_s, T_s). This may confuse sometimes.

The normal volume V_n is:

$$V_n = V \cdot \frac{273}{273 + T} \cdot \frac{1.013 + p}{1.013} \quad (1.2)$$

V = operating volume in m^3

T = operating temperature in $^{\circ}\text{C}$

p = operating pressure in bar

The conversion from volume flowrate to the volume flow rate under normal conditions ($q_v)_n$, can be calculated by the appropriate computer components.

The flow rate, which is a time dependent value, furnishes information regarding the instantaneous conditions in the piping. It does not provide any information about the mass or volume delivered, i.e. the total quantity. In order to determine these values, an integration is required:

$$V = \int_{t_1}^{t_2} q_v \cdot dt \quad (1.3a)$$

or

$$m = \int_{t_1}^{t_2} q_m \cdot dt \quad (1.3b)$$

The flow rate represents the present while the volume or mass total represents the past.

1.2 Fluid Mechanics Concepts

1.2.1 Viscosity

The viscosity of a fluid characterizes its ability to resist shape changes and is defined as its resistance to shear forces. This is a result of the internal friction in the fluid caused by the forces between the molecules. Since the molecular movement is related to the temperature, the viscosity is also a function of the temperature. The absolute viscosity η in Pa·s (Pascal-second) is defined as follows: 1 Pascal-second is the absolute viscosity of the laminar flow of a homogeneous fluid between two flat parallel layers spaced 1 meter apart with a velocity difference of 1 m/s and in which a shear force of 1 Pascal exists.

The kinematic viscosity ν is a density related viscosity and has units of m²/s:

$$\nu = \frac{\eta}{\rho} \left[\frac{\text{Pa} \cdot \text{s} \cdot \text{m}^3}{\text{kg}} = \frac{\text{m}^2}{\text{s}} \right] \quad (1.4)$$

This fluid property, viscosity, also exists in gases. The values are appreciably smaller than for liquids and increase with temperature. For liquids the viscosity reduces with increasing temperature.

1.2.2 Reynolds Number

The Reynolds Number Re is a characteristic number utilized in similarity techniques. With it, it is possible to project values measured with a particular flowing fluid to another fluid with different viscosity and density values, but with similar geometric relationships:

$$Re = \frac{d \cdot v}{\nu} [1] \quad (1.5)$$

d: pipe diameter in m

v: average flow velocity in m/s:

\nu: kinematic viscosity in m²/s

1.2.3 Flow Regimes

At low velocities and high viscosities the fluid flows in layers, meaning that the fluid particles move in well ordered adjacent sliding layers. This is known as laminar flow in which the layers do not mix with one another.

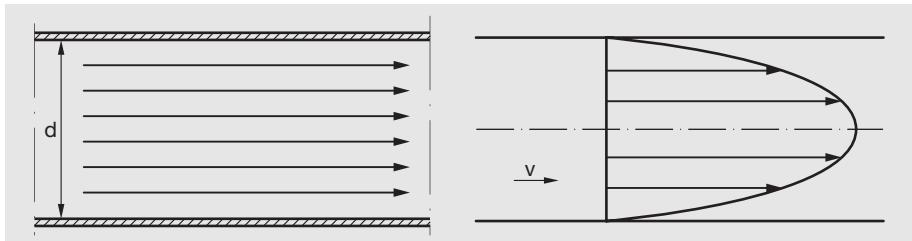


Fig. 1-1: Laminar Flow

Velocity Profile

The velocity distribution shows that the frictional forces at the stationary pipe wall exert the highest retarding force and that from layer to layer the velocity increases to its maximum value, which occurs in the middle of the pipe.

If the velocity increases or the viscosity decreases an additional motion is superimposed on the axially oriented movement throughout the flow stream which moves in all directions in a random manner and affects the flow streamlines in such a way that a uniform velocity profile results. This is known as a turbulent flow. A boundary layer is formed in the vicinity of the wall in which the velocity must accelerate from zero to v , because of its adhesion at the wall. Therefore, the velocity profile in the outer region is not steady.

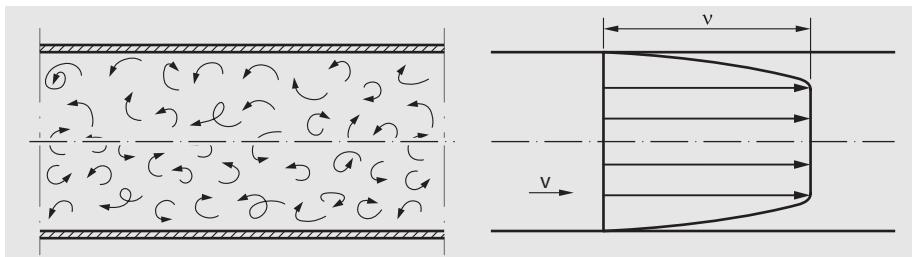


Fig. 1-2: Turbulent Flow

Velocity Profile

The evaluation-criterion for the kind of flow is the value of the Reynolds Number Re , since it takes into consideration the essential factors v and v .

The critical Reynolds number Re_{cr} defines with reasonable accuracy the transition point:

$$Re_{cr} \sim 2300$$

Kind of flow	$Re < 2300$	$Re > 2300$
Kind of flow	laminar	turbulent
Pressure drop in piping, measuring device	small	appreciable
Velocity profile	parabolic	approx. rectangular
Relationship of the average value of the flow velocity to the maximum velocity at the center of the pipe	0.5	0.8...0.9

Tab. 1-1: Flow Effects

Under ideal conditions the transition can occur at higher Reynolds numbers. This unstable condition changes immediately to the stable turbulent condition at the slightest stimulus, e.g. due to a flow disturbance.

Almost all flowmeters operate at flow velocities in the turbulent range. In specific cases may transitional flow as a mixture of laminar and turbulent flow, with e. g. turbulence in the center of the pipe, and laminar flow near the edges appear.

1.2.4 Flow Separation

As already mentioned, there exists at the wall of the flow conduit a boundary layer in which the flow velocity increases from zero to v . A projecting obstruction at the wall extends the length of the boundary layer and restrains the fluid even more in the vicinity of the wall so that downstream of this restriction a dead zone with a slightly negative pressure exists. The fluid flows from the region of higher velocity into this dead zone and creates vortices.

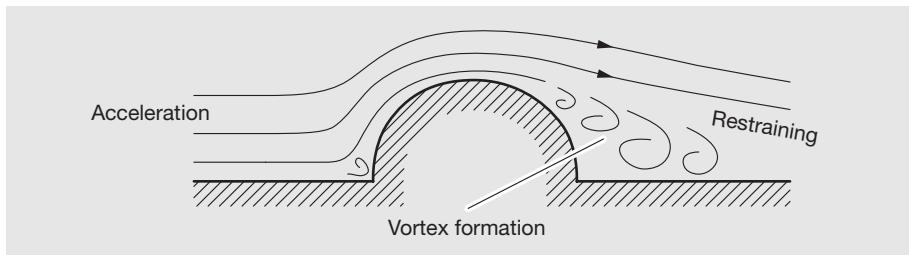


Fig. 1-3: Dead Zone with Vortex Formation

The flow separates from the surface of the wall. Examples are shown in Fig. 1-4 and Fig. 1-5. Vortices are undesirable for measurements because they consume energy which is removed from the flow stream resulting in pressure drops. Furthermore, they change the velocity profile to such a degree that many measuring methods will not function.

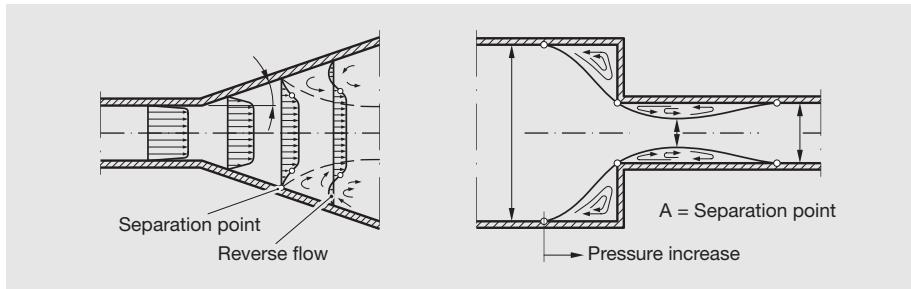


Fig. 1-4: Flow Separations and Flow Profiles at a Continuous Expansion

Fig. 1-5: Flow Separation and Flow Profiles at a Step Restriction

Fig. 1-6 and Fig. 1-7 show the flow profiles after flow disturbances.

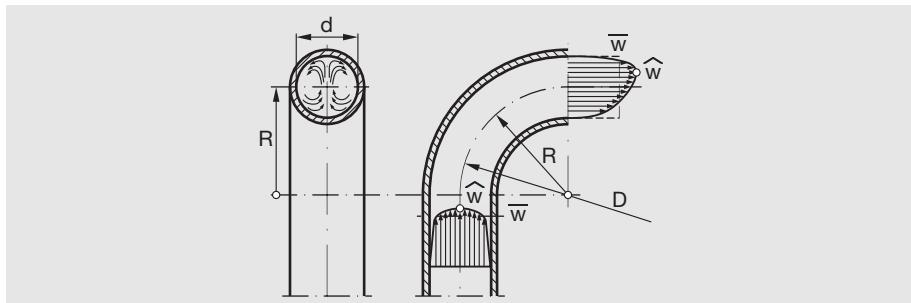


Fig. 1-6: Flow Separations and Flow Profiles in a Curved Pipe

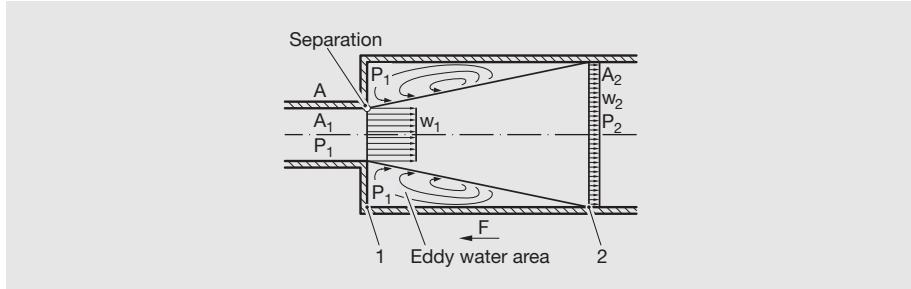


Fig. 1-7: Flow Separation and Flow Profiles at a Step Expansion

When a body is placed in the middle of a media flow, separation occurs and vortices are formed on both sides if velocity or R_e is above a certain value. It is interesting to note, that after a vortex has formed on one side a similar vortex forms on the other side which causes the first one to be shed.

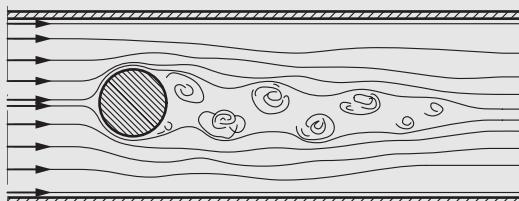


Fig. 1-8: Karman Vortex Street

That periodic vortices are shed from each side alternately was discovered by Karman after whom the vortex street is named. These usually undesirable vortices are utilized as the basis for the measurement in vortex flowmeters.

1.2.5 Energy Equations and Flow Rate

The following energy types exist in a flowing liquid or gaseous medium:

Potential energy < Position energy
Kinetic energy < Pressure energy

(Other energy types, e. g. electrical or chemical energy, are of no importance in this context.)

There are:

Position energy:

$$m \cdot g \cdot h$$

m = mass

g = gravity

h = height

Pressure energy:

$$m \cdot \frac{p}{\rho}$$

p = static pressure

ρ = density

Kinetic energy:

$$m \cdot \frac{v^2}{2}$$

v = flow velocity

Their sum is:

$$E = m \cdot g \cdot h + m \cdot \frac{p}{\rho} + m \cdot \frac{v^2}{2} \quad (1.6)$$

The Bernoulli law of conservation of energy states that the sum of the energy at every location in the flow passage must remain constant (expansion must be considered for compressible gases), when energy is neither externally added nor removed. Based on the mass flow q_m this yields:

$$g \cdot h + \frac{p}{\rho} + \frac{v^2}{2} = \text{constant} \quad (1.7)$$

This equation can be simplified because there are only minor position changes in a piping so that the potential energy can be neglected:

$$\frac{p}{\rho} + \frac{v^2}{2} = \text{constant} \quad (1.8)$$

Or, when comparing two reference points (Fig. 1-9):

$$\frac{p_1}{\rho} + \frac{v_{1^2}}{2} = \frac{p_2}{\rho} + \frac{v_{2^2}}{2} \quad (1.9)$$

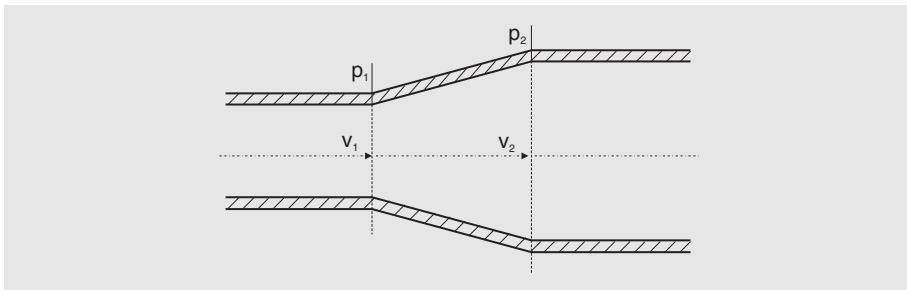


Fig. 1-9: Piping Expansion

Rearranging equation (1.9), the basic equation for the pressure drop becomes:

$$\Delta p = p_1 - p_2 = \frac{\rho}{2} (v_{2^2} - v_{1^2}) \quad (1.10)$$

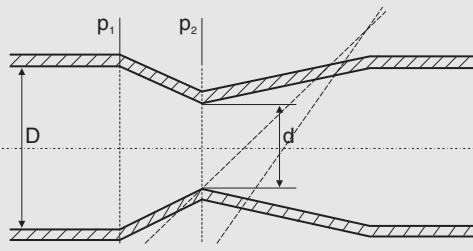


Fig. 1-10: Piping Restriction

The piping restriction shown in Fig. 1-10 presents two different cross sections, with diameters D and d , to the flow q_v .

$$q_v = v \frac{D^2 \pi}{4} = v \cdot A \quad (1.11)$$

Based on the laws of continuity, the same mass flows through each cross section at the same time, which means the same flow rate for incompressible fluids:

$$q_v = v_1 \cdot A_1 = v_2 \cdot A_2$$

$$q_v = v_1 \frac{D^2 \pi}{4} = v_2 \cdot \frac{d^2 \pi}{4} \quad (1.12)$$

$$\frac{v_1}{v_2} = \left(\frac{d}{D} \right)^2$$

The area ratio m , a new term introduced here, thus results in:

$$m = \left(\frac{d}{D} \right)^2 \quad (1.13a)$$

$$m = \frac{v_1}{v_2} \quad (1.13b)$$

$$v_1 = m \cdot v_2$$

which when inserted in Equation (1.10):

$$\Delta p = \frac{\rho}{2} (v_2^2 - m^2 v_2^2) = \frac{\rho}{2} v_2^2 (1 - m^2) \quad (1.14)$$

Replacing v_2 with:

$$v_2 = \frac{q_v}{A_2} \quad \text{from (1.11)}$$

$$\Delta p = \frac{q_v^2}{A_2^2} \cdot \frac{\rho}{2} (1 - m^2) \quad (1.15)$$

From this results the flow rate:

$$q_v = A_2 \sqrt{\frac{2 \cdot \Delta p}{\rho(1 - m^2)}} \quad (1.16)$$

A restriction of the flow cross section thus increases the flow velocity and reduces the static pressure. This pressure drop is the differential pressure Δp , which is proportional to the square of the flow rate.

$$qv^2 \sim \Delta p$$
$$qv \sim \sqrt{\Delta p} \quad (1.17)$$

When the flow velocity is reduced to zero at an obstruction (bluff body), a pressure increase occurs at this location because the kinetic energy is converted to pressure.

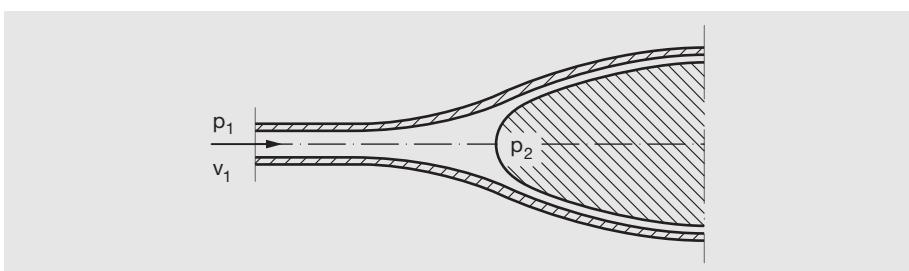


Fig. 1-11: Flow Obstruction

At the center of the obstruction, at the stagnation point, the velocity is: $v_2 = 0$

It follows from Equation (1.9):

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{0^2}{2} \quad (1.18)$$

$$p_2 = p_1 + \frac{\rho}{2} \cdot v_1^2$$

The total pressure p_2 at the stagnation point is thus the total of the static pressure p_1 and the converted dynamic pressure:

$$P_{dyn} = \frac{\rho}{2} \cdot v_1^2.$$

Therefore, if both of these pressure values are known, then the flow velocity and thus the pressure can be calculated from:

$$v = \sqrt{\frac{2}{\rho} (p_2 - p_1)} \quad (1.19)$$

This relationship is used to determine the flow velocity for stagnation pressure measurements.

1.2.6 Channel Hydraulics

Flow in Open Channels

The elevation h , pressure p and velocity v energies are additive for a flow (Fig. 1-12) in the cross section A according to the energy relationships of Bernoulli for a uniform velocity distribution when the friction losses are neglected.

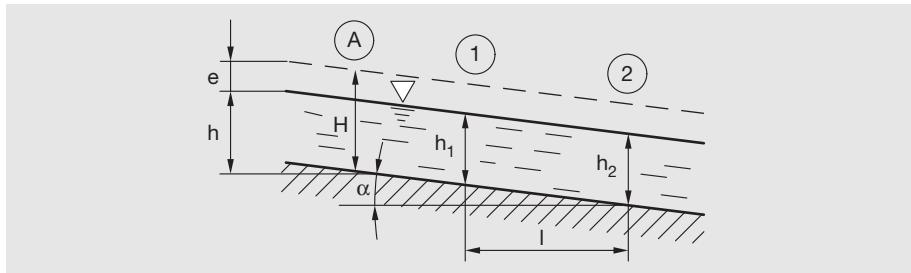


Fig. 1-12: Sloped Open Channel

$$E = m \cdot g \cdot h + m \cdot \frac{p}{\rho} + m \cdot \frac{v^2}{2} \quad (1.6)$$

Neglecting the atmospheric pressure which is constant and does not influence this discussion and expressing the energy values as fluid heights the equation can be written as:

$$H = h + \frac{v^2}{2g} = h + e \quad (1.20)$$

The expression:

$$e = \frac{v^2}{2g}$$

symbolizes the conversion of the kinetic energy into potential energy expressed as a fluid elevation. The curve e is the energy line.

Based on the laws of continuity, the energy contents at points 1 and 2 must be the same:

$$h_1 + \frac{v_{1^2}}{2g} = h_2 + \frac{v_{2^2}}{2g} \quad (1.21)$$

To investigate the flow conditions for different slopes, the elevation difference is included:

$$h_1 + l \cdot \tan \alpha + \frac{v_{1^2}}{2g} = h_2 + \frac{v_{2^2}}{2g} \quad (1.22a)$$

$$h_2 - h_1 - \frac{v_{1^2} - v_{2^2}}{2g} = l \cdot \tan \alpha \quad (1.22b)$$

After simplification and algebraic rearrangement, the expression for the slope of the upper water surface for rectangular cross sections is:

$$\frac{h_2 - h_1}{l} \approx \frac{\tan \alpha}{1 - \frac{v^2}{g \cdot h}} \quad (1.23)$$

Substituting $v = \sqrt{g \cdot h}$ a noteworthy limiting velocity v_{lim} is reached, the wave propagation velocity. It is identical to the propagation velocity of flat waves. In Equation 1.23 at v_{lim} , the term is:

$$1 - \frac{v^2}{g \cdot h} = 0$$

For the slope:

$$\frac{h_2 - h_1}{l} = \infty$$

this means that, under ideal conditions (e.g. frictionless operation) the slope is infinite. The defining criterion is the Froude number Fr:

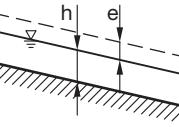
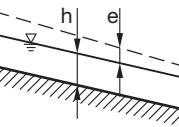
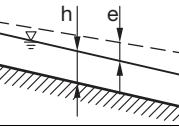
$$Fr = \frac{v}{\sqrt{g \cdot h}} \quad (1.24)$$

(Fr symbolizes the relationship between inertial and gravitational forces. Equation 1.24 applies to a special case: a rectangular cross section).

At wave propagation velocity v_{lim} the value of Fr is 1. In the wave propagation velocity condition a standing wave occurs which cannot move, neither upstream nor downstream.

If the velocity is smaller than v_{lim} , the flow regime is known as subcritical. Waves can propagate upstream and obstructions (e.g built-in items) in the flow stream can produce effects upstream of their location.

For velocities greater than v_{lim} the flow regime is known as supercritical. In this case obstructions have an effect on the downstream flow and waves cannot propagate upstream.

Flow Regime	$e = \frac{v^2}{2g}$	Discharge	Froude Number	Velocity	Kinetic Energy
Critical		uniform	Fr = 1	$v = \sqrt{g \cdot h}$	$\frac{v^2}{2g} \Rightarrow \text{constant}$
Subcritical		retarded	Fr < 1	$v < \sqrt{g \cdot h}$	$\frac{v^2}{2g} \Rightarrow \text{decreasing}$
Supercritical		accelerated	Fr > 1	$v > \sqrt{g \cdot h}$	$\frac{v^2}{2g} \Rightarrow \text{increasing}$

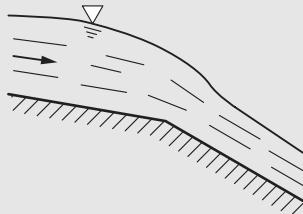
Tab. 1-2: Flow Regime and Slopes

Transition from Subcritical to Supercritical

When a subcritical flow is accelerated it may become supercritical, a condition which may be desirable in order to eliminate backflowing waves. This is the case in a Venturi flume, for example.

Fig. 1-13 shows two examples:

The slope becomes steeper, the kinetic energy increases, the flow changes from subcritical to supercritical.



Damming upstream of a gate, the potential energy increases, the velocity downstream of the gate is so large that the flow becomes supercritical. The same effect is achieved by a lateral restriction.

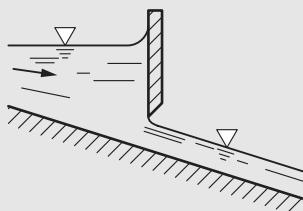


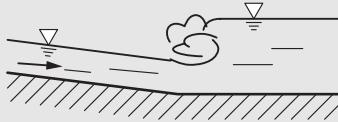
Fig. 1-13: Accelerating Transition

Transition from Supercritical to Subcritical

A large portion of the kinetic energy of a supercritical flow must be decreased if subcritical flow is to be achieved. The flow velocity decreases and the water level increases. In the subcritical flow regime a wave which moves upstream is produced which converts a great deal of energy into heat.

Finally, when the velocities of the supercritical flow and the wave propagation are the same, the wave moving at propagation velocity stands. This phenomenon is known as a hydraulic jump which occurs often and becomes stabilized at a disturbance.

The slope decreases suddenly, the liquid level rises, and in the transition a hydraulic jump occurs with an energy-absorbing rolling wave.



A similar effect occurs when a positive step is encountered which in itself requires additional energy.



A special case is the backflow after a gate when the level downstream is high. The wave is formed as an invisible hydraulic jump.

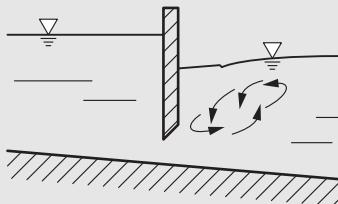


Fig. 1-14: Hydraulic Jump

Discharge from Large Openings or Rectangular Weirs

Rectangular Weir

According to Bernoulli the entire available energy is converted to kinetic energy for frictionless discharge from an open vessel.

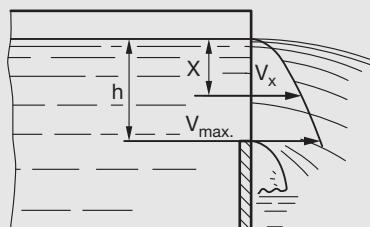
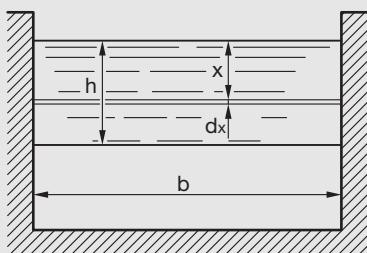


Fig. 1-15: Rectangular Weir

At a depth x there is the discharge velocity:

$$v_x = \sqrt{2g \cdot x}$$

Through the area $A_x = b \cdot dx$ the flow $q_{vx} = A_x \cdot v_x$ comes out:

$$q_{vx} = b \cdot dx \cdot \sqrt{2g \cdot x} \quad (1.25)$$

The following is valid for the entire opening:

$$q_v = \int_0^h b \cdot \sqrt{2g \cdot x} \, dx \quad (1.26a)$$

$$q_v = \frac{2}{3} \cdot b \cdot h \cdot \sqrt{2g \cdot h} \quad (1.26b)$$

$$q_v = \frac{2}{3} \cdot b \cdot \sqrt{2g} \cdot h^{3/2}$$

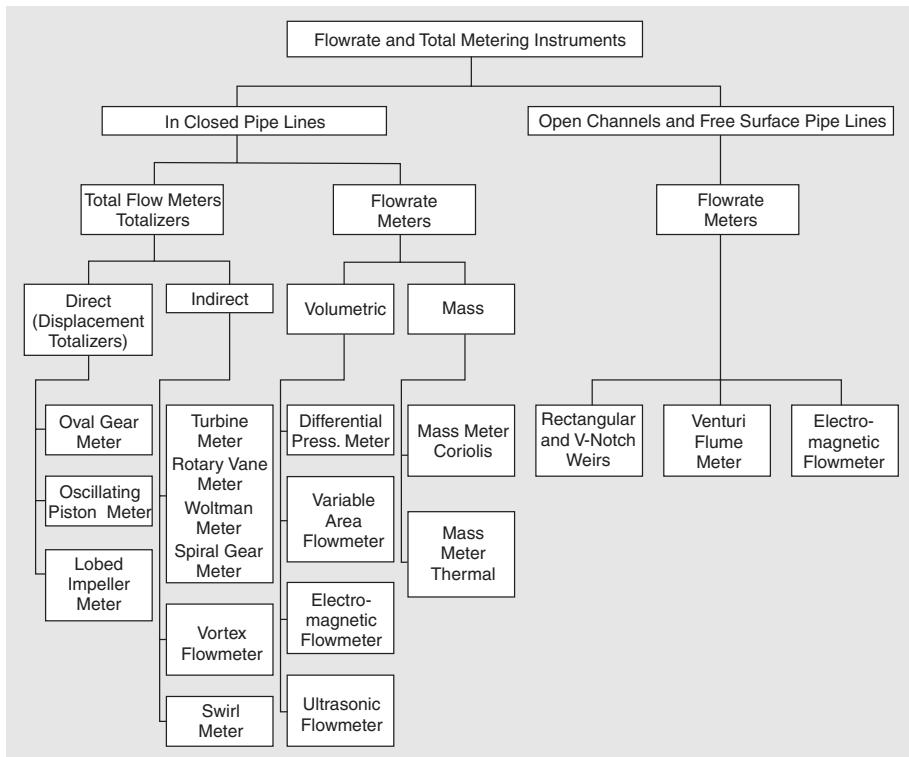
Losses actually occur in the discharge which are incorporated in the discharge coefficient μ :

$$q_v = \frac{2}{3} \mu \cdot b \cdot \sqrt{2g} \cdot h^{3/2} \quad (1.27)$$

This equation forms the basis of the measurement calculation for meter tubes and measuring channels.

2 Flow Rate and Total Flow Measurement of Gases and Liquids

There are various different methods for measuring the flow rate and the total flow. Each method has its own specific characteristics which are directed toward individual installation requirements. In the following, the most important measuring principles existing in the market place are described and compared to each other.



In the illustration above for the measurement in closed piping a distinction is made between total flow meters (totalizers) and flow rate meters (flowmeters). So, what are the characteristics of these two variants?

Total flow meters, usually volume totalizers, are devices filled with a defined volume which is then measured and integrated to determine the total flow volume. Direct volume totalizers have movable measuring chambers with a defined volume (comparable to a line of buckets). Indirect volume totalizers, on the contrary, do not have closed measuring chambers, but work either mechanically using rotary vanes and transporting partial volumes between the vanes, or electrically with pulses that are proportional to the volume.

Flowmeters also use the direct method for measured value acquisition. They measure either the flow velocity or the kinetic energy of the flow.

The user faces the difficult task of selecting the technically best and most cost effective measuring device for his application. The following device descriptions and selection criteria are intended to assist in that choice.

2.1 Volume Totalizers

Volume totalizers with moving measuring chambers driven by the measuring medium are also known as displacement meters. They are suitable for both gases and liquids. They are direct volume totalizers since they transport the measuring medium in chambers with defined, geometrically limited volumes.

Among the direct volume totalizers are those with measuring vanes – also called turbine totalizers – and volume totalizers with forced flow changes. In this method a pulse total is generated which represents a specific – not geometrically bounded – volume, for example the quantity which produces one complete revolution of a rotary vane totalizer.

2.1.1 Oval Gear Totalizers

The measuring element of an oval gear totalizer consists of two oval gears.

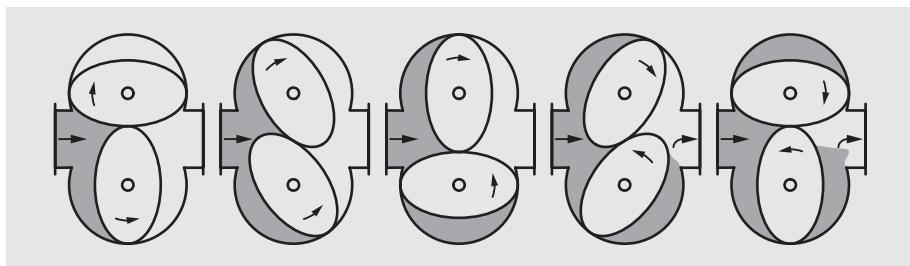


Fig. 2-1: Method of Operation of an Oval Gear Totalizer

The driving liquid produces the required torque, which varies as a function of the gear position, to rotate the gears.

For example, the torques on the lower gear in the left side of Fig. 2-1 cancel each other while the torque on the upper gear is one sided and actually causes the rotation. Around the upper gear a bounded crescent like volume exists which is pushed towards the outlet of the meter. Each rotation of the pair of oval gears transports a defined liquid volume.

The number of rotations is therefore an exact measure of the quantity of liquid which has flowed through the meter. The precision teeth assure a good seal between the two gears. The clearance between the oval gears and the walls of the measuring chambers is so small that the leakage flow (gap loss) is negligible.



Fig. 2-2: Oval Gear Totalizer for Industrial Liquids, Design with Counter

The rotations of the pair of oval gears are transmitted without a stuffing box to an indicator either by a permanent magnet coupling or by a feedback-free magnetic field controlled pulse transmitter.

The gears and bearings are subject to mechanical wear. Through selection of materials for the housing, oval gears, and bearings as well as by design consideration of expansions due to high temperatures, oval gear totalizers are suitable for almost all operating conditions.

The error limits shown in Fig. 2-3 represent the relationship to the measuring medium, especially as a function of its viscosity. For low viscosities and a given accuracy the span is appreciably smaller than for higher viscosities.

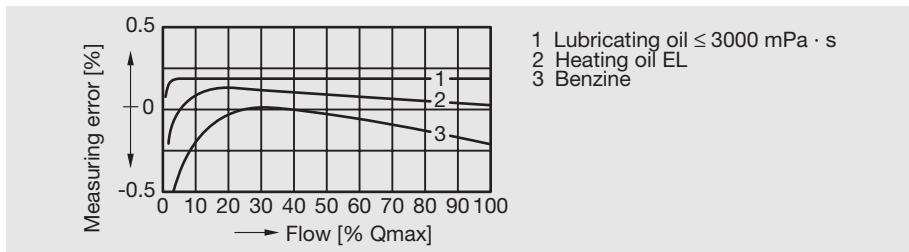


Fig. 2-3: Representation of the Error Limits as a Function of the Measuring Medium

It is comprehensible that the pressure drop increases with increasing viscosity. The pressure drop curves (Fig. 2-4) include the meter size as an additional parameter.

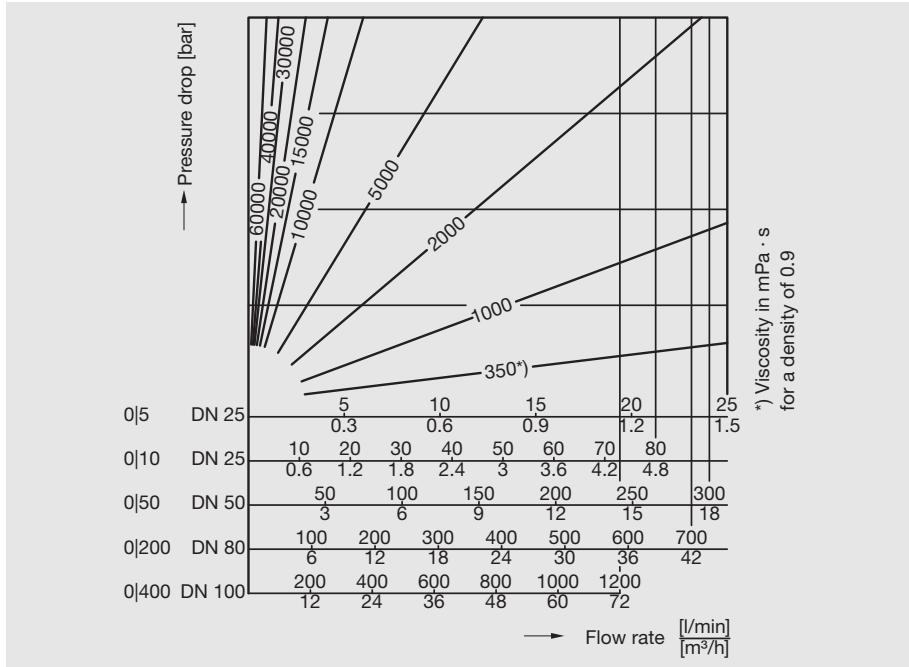


Fig. 2-4: Pressure Drop as a Function of Viscosity

Specifications	
Nominal diameters	DN 6...DN 400
Max. possible flow rate	$1200 \text{ m}^2/\text{h}$
Viscosity	$0.3 \dots 1 \cdot 10^5 \text{ mPa} \cdot \text{s}$
Max. permissible pressure	100 bar
Max. permissible temperature	290 °C
Approved for official verification	

2.1.2 Oscillating Piston Totalizers

In a cylindrical housing a hollow cylinder, the oscillating piston, oscillates eccentrically. In this manner it transports defined volumes. The method of operation is shown in Fig. 2-5.

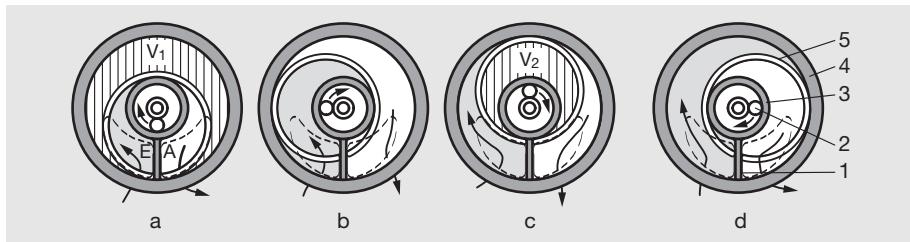


Fig. 2-5: Method of Operation of the Oscillating Piston Totalizer

The stationary outer cylinder (4) is also the housing, in which a dividing wall (1) and a guide ring (3) are mounted. The dividing wall on the bottom of the housing provides the boundary between the inlet (E) and outlet (A) openings. The bearing for the oscillating piston (5) is mounted in the sleeve (2) and is guided along the dividing wall. Openings for filling and draining are located in its base. In positions (a) and (b) the oscillating piston volume V_2 is filled. The liquid forces the oscillating piston away so that the housing volume V_1 can be filled. At the same time the force from the piston causes the portion of the liquid volume V_1 in the right side to be discharged. When position (d) is reached, the volume V_1 has been completely discharged once and refilled, the volume V_2 begins its discharge phase. One rotation of the oscillating piston encompasses both volumes, V_1 and V_2 .



Fig. 2-6: Oscillating Piston Totalizer for Water (Type RONDO DIRECT) with Various Nominal Diameters

The movement of the piston bearing (2) is transmitted to an indicator using a magnet and follower arrangement. A magnetic coupling is not utilized in the RONDO DIRECT Oscillating Piston Totalizer. The rotary motion of the piston is transmitted directly from the piston to the totalizer.

Since the oscillating piston wears rapidly, proper material selection is very important. Various materials are available such as gray cast iron, bronze, hard rubber, carbon and plastics. For high temperature operation an intermediate spacer is used to provide additional separation from the totalizer. Oscillating piston totalizers are especially used for water and oil measurement.

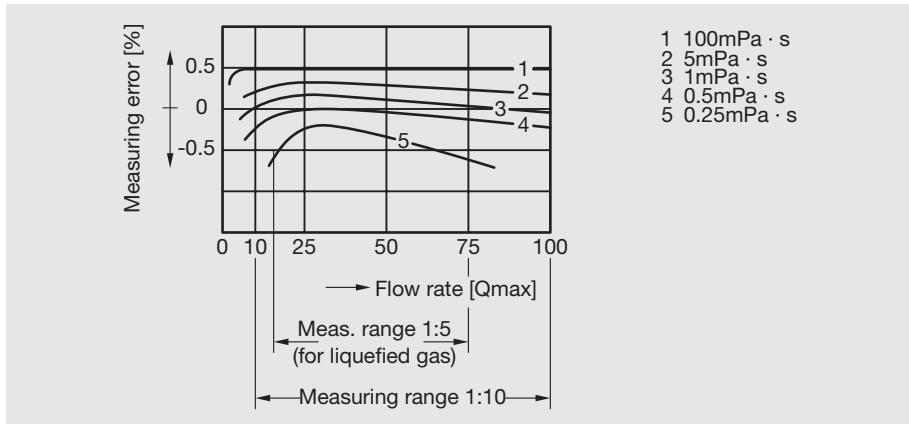


Fig. 2-7: Representation of the Measuring Error as a Function of the Viscosity

The error curves in Fig. 2-7 indicate the high accuracy attainable at high viscosity due to a decrease in leakage losses (gap losses). The oscillating piston totalizers are still operational at viscosities as high as 10,000 mPa·s.

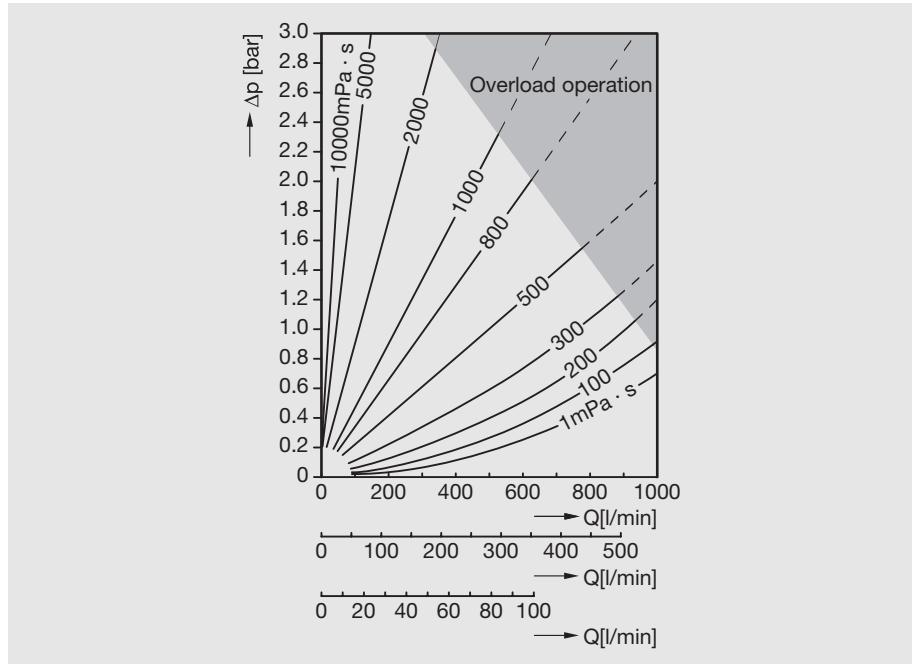


Fig. 2-8: Pressure Drop as a Function of Viscosity at DN 80

Fig. 2-8 shows that the pressure drop increases with increasing viscosity. For large differential pressures the material used for the oscillating piston must be checked for sufficient mechanical strength.

Specifications	
Nominal diameters	DN 15...DN 80
Max. possible flow rate	1000 m ³ /h
Viscosity	0.3...2 · 10 ⁴ mPa·s
Max. permissible pressure	PN 100
Max. permissible temperature	300 °C
Approved for official verification	

2.1.3 Lobed Impeller Gas Totalizers

Two rotating impellers, designed with a figure eight cross section, rotate in opposite directions due to the forces exerted by the gas being measured. The shape of the impellers prevents contact while the gap between them remains constant.

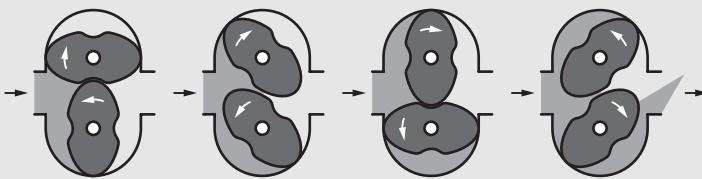


Fig. 2-9: Method of Operation of the Lobed Impeller Gas Totalizer

A gear drive external to the measuring chamber synchronizes the impellers. During each rotation four crescent shaped volumes are moved through the measuring chamber. The number of rotations is proportional to the gas flow. The rotation is coupled using an adjustable fine tooth gear train to the totalizer.

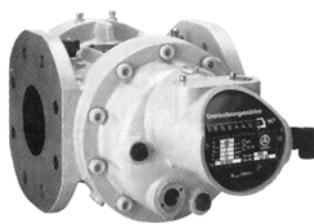


Fig. 2-10: Lobed Impeller Gas Totalizer

An unmeasured flow, which is a function of the pressure drop, flows through the gaps. The negative error is compensated by an adjustment. The viscosity of gases increases at high pressures and reduces the losses in the gaps which compensates for the higher losses which would otherwise exist due to the higher pressure difference.

The pulsations in the gas discharge can cause the pipe system connected to the meter to vibrate. If resonance should occur, loud noises and sudden pressure drops can result. This condition should not be allowed to occur; if necessary noise or pulsation dampers should be utilized.

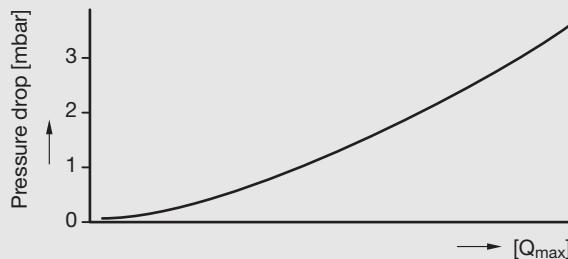


Fig. 2-11: Pressure Drop of the Lobed Impeller Gas Totalizer

The pressure drop results from the mechanical and dynamic resistances in the meter. The dynamic portion increases appreciably with increasing load.

Lobed impeller meters are very susceptible to contamination. Since contamination affects the pressure drop it must be monitored and the meter cleaned when required.

Specifications	
Nominal diameters	DN 40...DN 3000
Flow rate	between 3 m ³ /h and 6500 m ³ /h (gas at operating conditions)
Pressure rating	max. PN 25
Operating temperature	-10...40 °C
Span	up to 1:50
Error limit	within the permissible limits for official verification, i.e. < 1 %
Approved for official verification	

2.1.4 Turbine Totalizers

Turbine totalizers are indirect volume totalizers in which the flow causes a vaned rotor to revolve. The number of rotor revolutions is proportional to the total flow and the frequency of the revolutions to the flow rate.

The various designs are differentiated by the direction of the inflow and by the method utilized for measured value acquisition.

Rotary Vane Totalizer

The flow entry is tangential and causes the wheel to revolve in the rotary vane totalizer. A gear train is utilized to transmit the rotations of the wheel axle to the totalizer which, in wetted designs, is located in the measuring medium. Rotary vane totalizers are available as single jet (Fig. 2-12a) and as multijet designs (Fig. 2-12b).

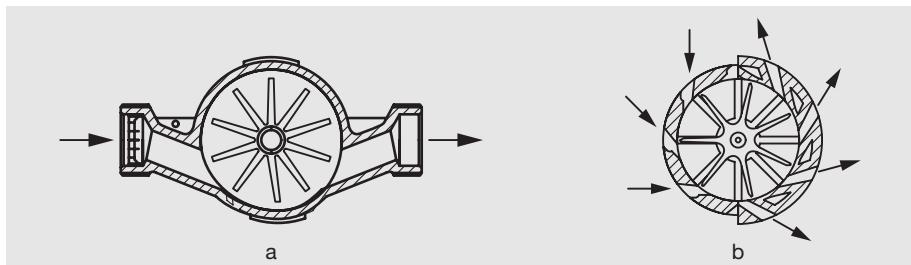


Fig. 2-12: Rotary Vane Totalizer

Dry design units separate the indicator chamber from the measuring chamber and transmit the rotation via a magnetic coupling. Rotary vane totalizers are used as domestic water meters and also, in hot water design, as volume measuring elements for smaller heat quantity totalizers.

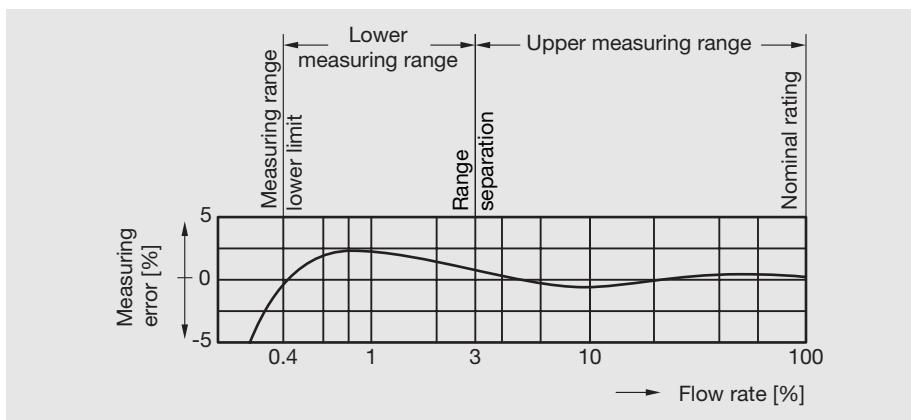


Fig. 2-13: Error Curve of a Multijet Rotary Vane Totalizer

Fig. 2-13 shows the error curve with reference to the limits specified in the German Verification Act, i.e. $\pm 2\%$ (cold water)/ $\pm 3\%$ (warm water) in the upper and lower measuring range.

Specifications

Nominal sizes (based on the flow rate)	0.6...15 m ³ /h
Smallest possible flow rate	12 l/h
Largest possible flow rate	30 m ³ /h
Viscosity limit	$\leq 5 \text{ mPa}\cdot\text{s}$
Approved for official verification	



Fig. 2-14: Cross Section of a Single Jet Totalizer (Type PICOFLUX)

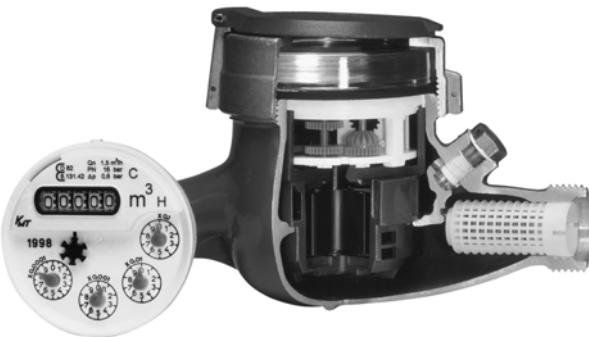


Fig. 2-15: Cross Section of a Multijet Totalizer (Type OPTIMA ARTIST)

Woltman Totalizer

The axle of a Woltman totalizer rotor is in parallel with the flow direction. This means the flow is axial to the turbine wheel. A low-friction gear train connects the axle to the totalizer via a magnetic coupling.

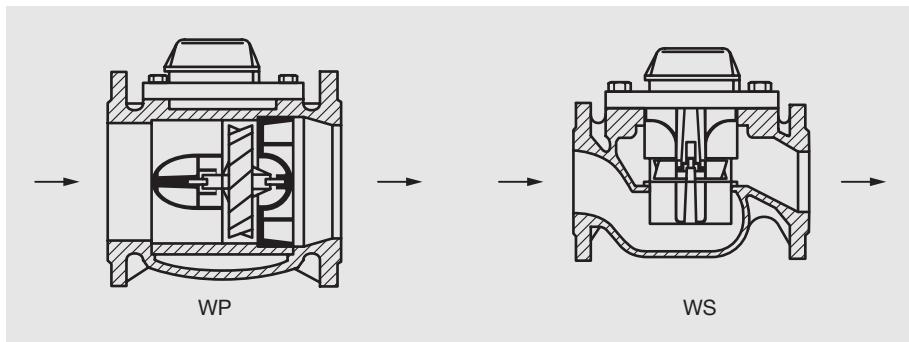


Fig. 2-16: Woltman-Zähler

There are two distinct designs, one with a horizontal turbine wheel "WP" and one with a vertical turbine wheel "WS". The vertical design offers the advantage of minimal bearing friction and therefore a higher sensitivity. The pressure drop however is appreciably higher because of the shape of the flow passage. The horizontal design allows the totalizer to be mounted in any orientation (e.g. vertical), a larger flow range and lower pressure drops.

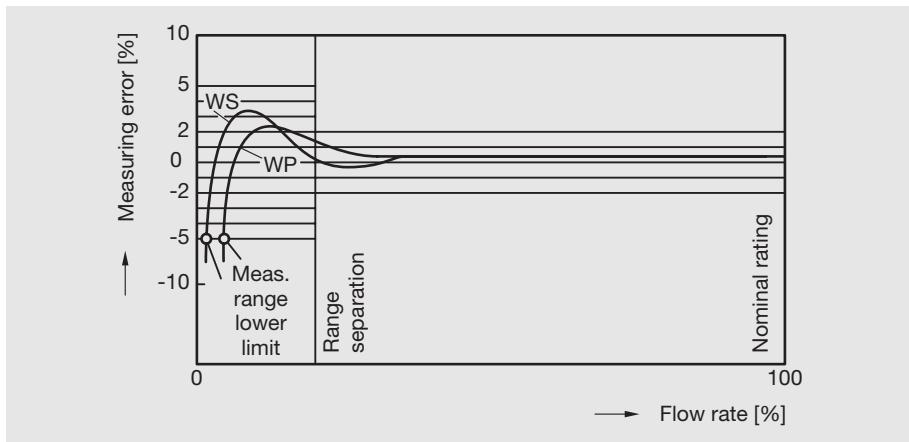


Fig. 2-17: Typical Error Curve of a Woltman Totalizer with Nominal Diameter DN 80

The error curve shown in Fig. 2-17 is related to the calibration error limits. The Woltman totalizer is used primarily as a water meter, but also as a volume measuring element for heat quantity totalizers.



Fig. 2-18: Cross Section of a “WP” Woltman Totalizer (Type HELIX)



Fig. 2-19: Cross Section of a “WS” Woltman Totalizer (Type VERTIX)

The combination water totalizer “WPV” (Fig. 2-20) was designed for wide spans. It is a combination of two totalizers, a large (main totalizer) and a small (secondary) one. An automatic pressure controlled spring loaded valve switches to the range that is best suited for the measuring ranges of both totalizers.



Fig. 2-20: Combination Water Totalizer (Type INLINE) with Secondary Totalizer (Type MODUL-METER MO-N)

While the cold water meters have an upper temperature limit of 40 °C (50 °C), the hot water meter can be used up to 120 °C (130 °C). With appropriate material selections the Woltman totalizer can also be used in industrial applications for de-ionized water.

Specifications			
Design	WP	WS	WPV
Nominal diameters	DN 40...DN 500	DN 50...DN 150	DN 50...DN 200
Smallest possible flow rate	350 l/h	200 l/h	20 l/h
Largest possible flow rate	4500 m ³ /h	350 m ³ /h	600 m ³ /h
Viscosity limit	≤ 3 mPa·s		
Approved for official verification			

Turbine Flowmeter

Turbine wheel totalizers “WP”, commonly known as turbine flowmeters, are similar in their design to Woltman totalizers, with one essential difference: the measurement of the rotation is made electrically with almost no feedback on the rotor. The turbine rotors are light in weight producing minimal friction in the bearings.

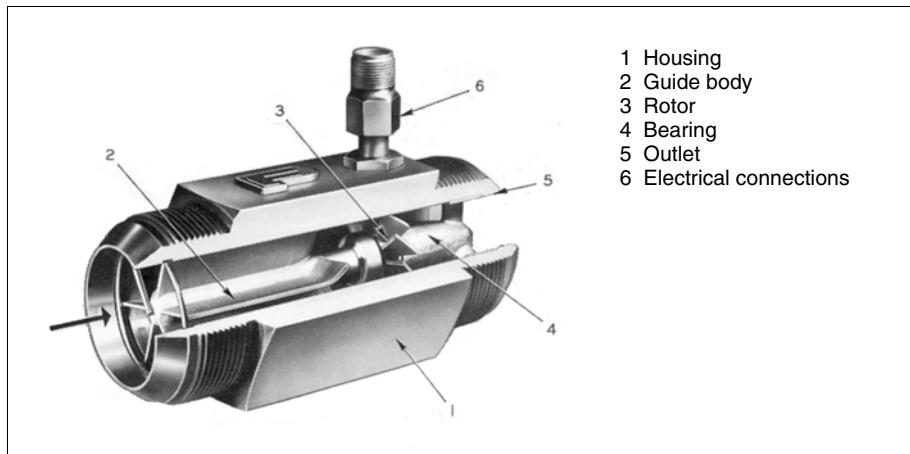


Fig. 2-21: Turbine Flowmeter

As a result, the span can be expanded because the system responds with greater sensitivity. Smaller nominal diameters are possible. The turbine flowmeter measures gases and liquids with increased viscosities.

A coil in the housing opposite the rotor measures the signal using various methods:

- A magnet in one vane induces a voltage pulse in the coil during every revolution.
- The coil encloses a magnet. The vanes are made of a ferromagnetic material. As the vanes pass the magnet, the magnetic field is distorted inducing a voltage pulse.
- A high-frequency AC voltage (10 kHz) is applied to the coil. The ferromagnetic vane varies the amplitude of the supply voltage resulting in a secondary frequency superimposed on the carrier frequency.

In all three cases, a frequency signal is generated which is proportional to the number of revolutions and therefore to the flowrate. The signal is fed to a preamplifier in the connected converter. In this manner the totalizer, each of whose individual pulses represents a defined volume, becomes a flowmeter as a result of the time based frequency which is generated.

Interesting is the fact that this device can measure at higher viscosities, with the restriction, however, that the start of the linear proportional range is shifted (Fig. 2-22).

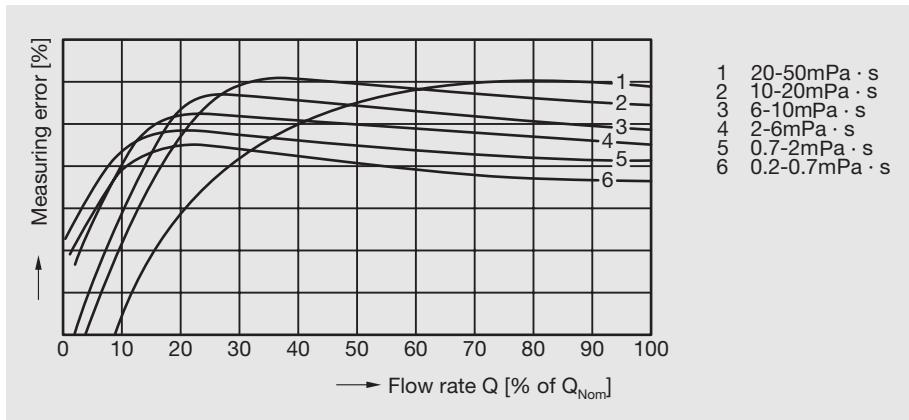


Fig. 2-22: Error Curves as a Function of Viscosity

The span is reduced as the viscosity increases. It is for this reason that for higher viscosities a calibration curve, which is not linear, must be prepared.

Specifications	
Nominal diameters	DN 5...DN 600
Smallest possible flow rate	5 l/h (water)
Largest possible flow rate	10,000 m ³ /h (water)
Max. span	1:100
Viscosity limit	700 mPa·s
Temperatures	-200 °C (cryogenic liquid) up to 250 °C (600 °C)
Pressure rating	up to 100 bar (1000 bar)
Error limits	+ 0.25 %...+1 % of rate

A special turbine flowmeter variation is the turbine gas totalizer for measuring large gas flows. The gas flow velocity is increased by a reducer at the inlet with a ring shaped cross section and guided over the freely turning rotor. The revolutions which are measured are mechanically transmitted to the totalizer using a gear train.

This instrument is often used for the custody transfer of natural gas for which it has received certification approval.

Specifications	
Nominal diameters	DN 50...DN 600
Smallest possible flow rate	2.5 m ³ /h (at operating conditions)
Largest possible flow rate	25,000 m ³ /h
Span	1:20
Calibration error limits	+1 % of rate (span 1:5)
Temperature limits	-10...50 °C

2.1.5 Vortex Flowmeters

Why does the flag flap in the breeze? Why does a taut line (power line) sing in the wind? There are numerous examples of the effects of vortex formation at bodies around which there is flow. What is actually happening?

As already mentioned in Chapter 1.2.4 a flow obstruction causes vortices. On a free standing body vortices are formed on both sides which are alternately shed resulting in the formation of a Karman Vortex Street. The flag mentioned above reacts to the progress of the vortex street, the taut wire vibrates at the vortex shedding frequency.

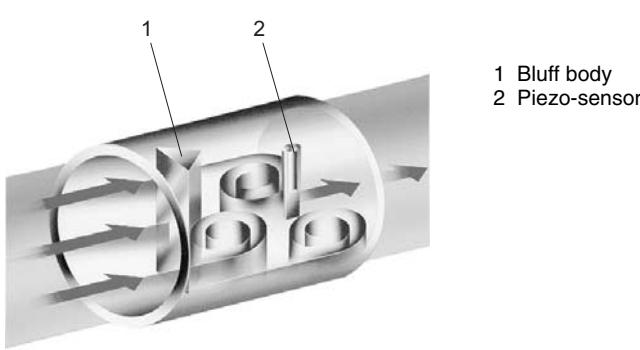


Fig. 2-23: Measuring Principle of a Vortex Flowmeter

If the geometric distance is l between two consecutive vortices and the time interval is t when viewed from a fixed reference point, then the vortex shedding frequency f is:

$$f \sim \frac{l}{t}$$

Strouhal discovered a relationship between geometry and velocity:

$$f \sim \frac{V}{d}$$

In this equation, d is the diameter of the round bluff body. The Strouhal number St , a proportionality constant named after Strouhal, gives:

$$f = St \frac{V}{d}$$

The requirement for the bluff body is that the geometry of vortex formation does not change with the flow rate and that the Strouhal number remains constant over a wide Reynolds number range. The shape and the area ratio in the pipe define the manner of vortex shedding and the constancy of the Strouhal number. Another system requirement is assigned by the flow engineer: that the vortex intensity be strong. Finally, the pressure drop should not be too large.

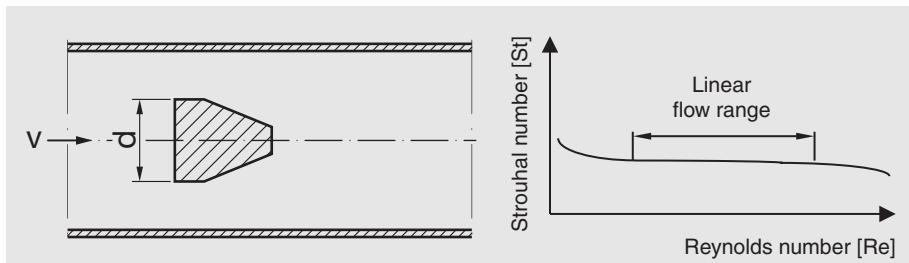


Fig. 2-24: Delta Bluff Bodies and the Dependence of the Strouhal Number on the Reynolds Number

The optimum shape of the bluff body has been determined empirically and through calculations. ABB has selected the delta shape.

The minimum Reynolds number value Re_{min} defines the lower range value, i.e. the span decreases with increasing viscosity. The upper Re limit is so high that it is negligible for the upper range value.

There are various methods of vortex determination. The vortices generate periodic pressure and velocity variations. These provide a corollary means for the measurement. ABB places the sensor either behind the bluff body or in the bluff body in such a manner that it can vibrate freely (the location is determined by the nominal diameter and the type of connection). Its tongue is forced to vibrate at the shedding frequency by the pressure differences.

Piezo-elements inside the sensor convert the resulting pressure forces into electrical measuring pulse signals which can be amplified. An arrangement of four Piezo-sensors has been selected to cancel pipeline vibrations.

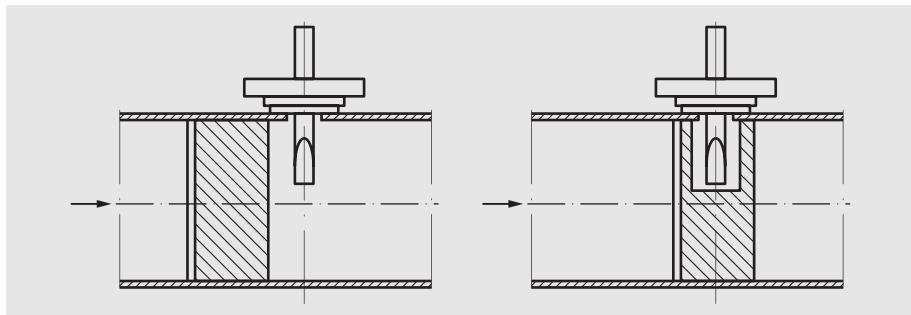


Fig. 2-25: Sensor in the Vortex Flowmeter

If the flow profile of the measuring medium is distorted (vortices, swirl) as it flows into the measuring section, the vortices cannot form properly. For this reason, straight steady sections must be provided upstream of the device, the length of which depends on the type of the distortion.

Vortex flowmeters can be used for measuring the flow of steam, gases and liquids.

The model with integral mount design, FV4000-VT4 (Fig. 2-28), integrates the sensor and transmitter in a single unit with a local indicator for the flow rate and totalized flow value. The transmitter is based on a digital signal processor (DSP) and generates the 4...20 mA analog output signal. As a two-wire device it requires a supply voltage of 14 V...46 V DC which is fed via the analog output two-wire line.

A binary output is available in addition to the analog output. This output can be configured as a pulse output or limit contact (contact output). The measurement display for gases and liquids is made in direct reading engineering units.

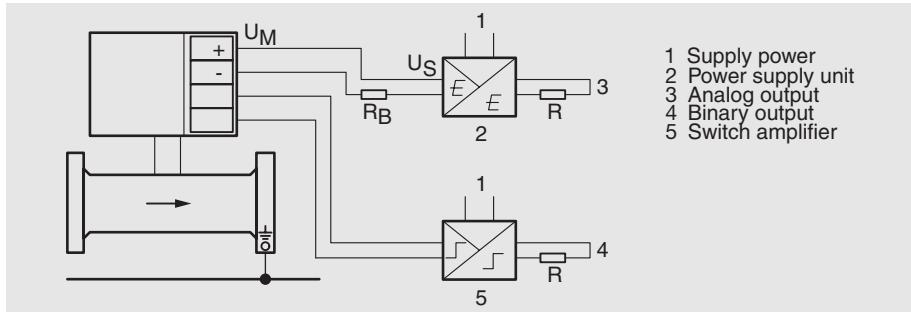


Fig. 2-26: Two-Wire Connection Diagram

Utilizing an integrated Pt 100 in the flow sensor, a saturated steam measurement or temperature monitoring option can be incorporated without any additional costs.

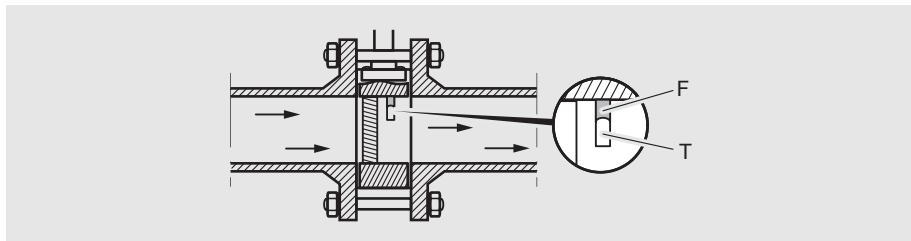


Fig. 2-27: Sensor for Flow Rate (F) and Temperature (T) Measurement



Fig. 2-28: Integral Mount Design: FV4000-VT4 **Fig. 2-29:** Remote Mount Design: FV4000-VR
Flange-Mounted Wafer-Type Design

The transmitter can also be mounted remotely at a distance from the sensor if a special cable (Fig. 2-29) is used. It can be attached to the wall or installed using a pipe mounting toolkit.

Two-Wire Design with Fieldbus Interface

The transmitter is designed in two-wire technology, i.e. the power supply and the digital communication of the fieldbus interface utilize the same cable. In parallel, a switch output is available for limit value or system monitoring. In the event of a power failure all stored data are saved in a nonvolatile memory.

The Asset Vision Basic device management tool can be used for operating and configuring intelligent field instruments, utilizing the FDT/DTM technology. A data exchange with a complete range of field instruments can be accomplished over various communication paths. The main operational purposes are the parameter display, configuration, diagnostics and data management for all intelligent field devices which themselves satisfy the communication requirements.

PROFIBUS PA Communication

The transmitter is suited for connection to a DP/PA segment coupler.

PROFIBUS PA Protocol

Function blocks: **2 x AI, 1 x TOT**

GSD files: -PA139700 (1 x AI)

(device data files) -PA139740 (1 x AI, 1 x TOT)

-ABB_05DC (2 x AI, 1 x TOT + manufacturer-specific data)

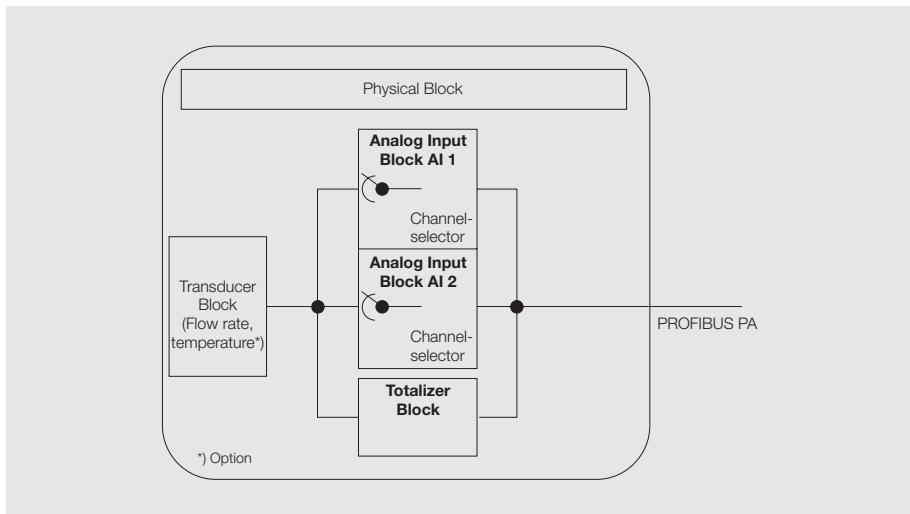


Fig. 2-30: Block Structure of the FV4000 with PROFIBUS PA

The channel selector allows to select the output variable (volume / standard / mass flow or temperature).

FOUNDATION Fieldbus Communication

The transmitter is suited for connection to a special power supply unit or linking device.

FOUNDATION Fieldbus Protocol

Output signal according to the FOUNDATION Fieldbus protocol

Function blocks: 2 x AI

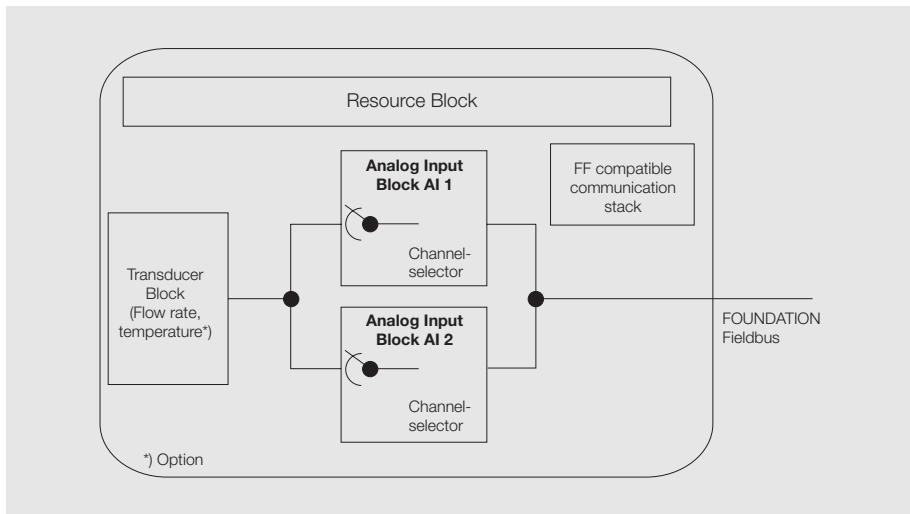


Fig. 2-31: Block Structure of the FV4000 with FOUNDATION Fieldbus

The channel selector allows to select the output variable (volume / standard / mass flow, totalizer or temperature).

Device Selection

Vortex flowmeters are available with the nominal diameters DN 15 to DN 300.

ABB provides at no cost, resource material to help in the selection and sizing of devices suitable for a particular measurement task, as well as order support.

Dimensioning of the Measuring Ranges

Nominal Diameter		Water $\rho = 1000 \text{ kg/m}^3$ $\nu = 1 \cdot 10^6 \text{ m}^2/\text{s}$	Gas $\rho = 1,2 \text{ kg/m}^3$ $\eta = 18,2 \cdot 10^6 \text{ Pa} \cdot \text{s}$
DN	inch	Span [m³/h]	Span [m³/h]
15	½	0.5...6	4...24
25	1	0.8...18	14...150
40	1½	2.4...48	30...390
50	2	3.0...70	40...500
80	3	8.0...170	90...1200
100	4	10.0...270	150...1900
150	6	30.0...630	300...4500
200	8	70.0...1100	250...8000
250	10	60.0...1700	800...14000
300	12	95.0...2400	1400...20000

Tab. 2-1: Vortex Flowmeter FV4000, Measuring Ranges

The values in the table are intended to be used as references. The – seen from the physical point of view – actually achievable lower range values primarily depend on the operating density or viscosity of the measuring medium and the presence/absence of vibrations and/or pulsations. The measuring ranges for which the specified accuracy is reached depend on the minimum required Reynolds number, as below this number no linear relationship can be established between the vortex shedding frequency and the flow velocity.

To avoid cavitation, a positive pressure must be maintained in the measuring section which can be calculated as follows:

$$p_2 \geq 1.3 \cdot p_D + 2.6 \cdot \Delta p$$

p_2 = Static gauge pressure downstream of the device

p_D = Steam pressure of liquid at operating temperature

Δp = Pressure drop (diagram Fig. 2-32)

When selecting devices for gas or steam measurement, it must be taken into account that the values in the table refer to air and that the vortex flowmeter measures in units at operating conditions. For this reason, first the operating density must be calculated:

$$\rho = \rho_N \frac{1.013 + p}{1.013} \cdot \frac{273}{273 + T} \quad (2.2)$$

(ρ_N = Standard density)

Then the flow rate in units at operating conditions is calculated:

$$q_v = \frac{1}{\rho} \cdot q_m \text{ or } q_v = q_n \frac{\rho_N}{\rho} \quad (2.3)$$

q_m = Mass flow rate in kg/h

q_n = Standard flow in m³/h

Based on the fact that a bluff body exists in the inside of a vortex flowmeter, a pressure drop occurs which is a function of the flow rate (Fig. 2-32).

Example: 425 mbar

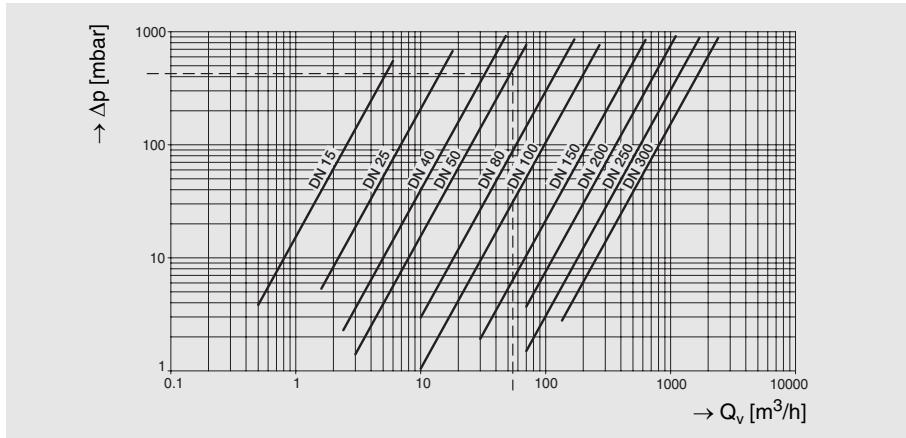


Fig. 2-32: Pressure Drop for Water, DIN-Design

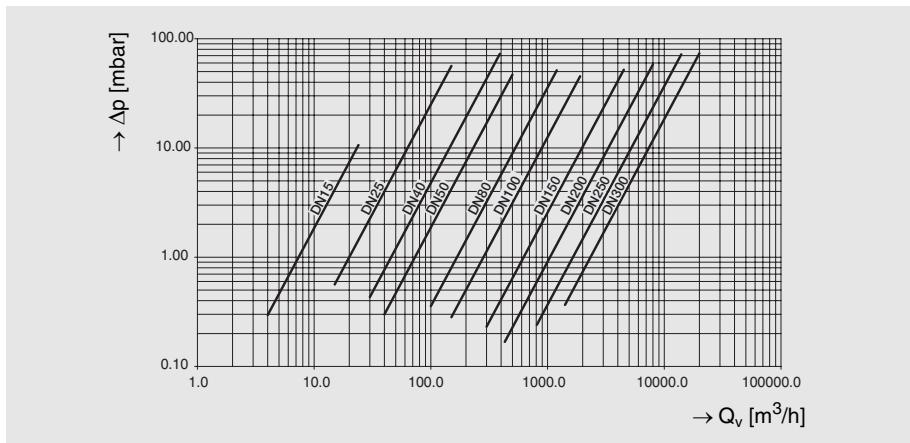


Fig. 2-33: Pressure Drop for Air (20 °C, 1.013 bar), DIN-Design

For saturated steam measurement a special program is integrated in the transmitter which contains the saturated steam tables utilized for correction calculations. With the integrated temperature measurement the measurement can be made with minimum effort. The mass flow rate signal is available directly at the analog output.

Specifications	
Temperature limits	-55...400 °C (meas. medium temperature) -55...70 °C (ambient temperature)
Max. possible pressure	160 bar
Measured error	≤ 1 % of rate for gas, steam ≤ 0.75 of rate for liquids
Medium-wetted material	1.4571, optional Hastelloy-C
Explosion protection	ATEX / IECEx II 2 G Ex ib II C T4 ATEX / IECEx II 2 G Ex d II C T6 ATEX / IECEx II 2D T 85 °C...T _{med} IP 67 FM Class I Div1, Group A, B, C, D

Installation of the Sensor

The following recommendations should be observed when installing the sensor in a piping:

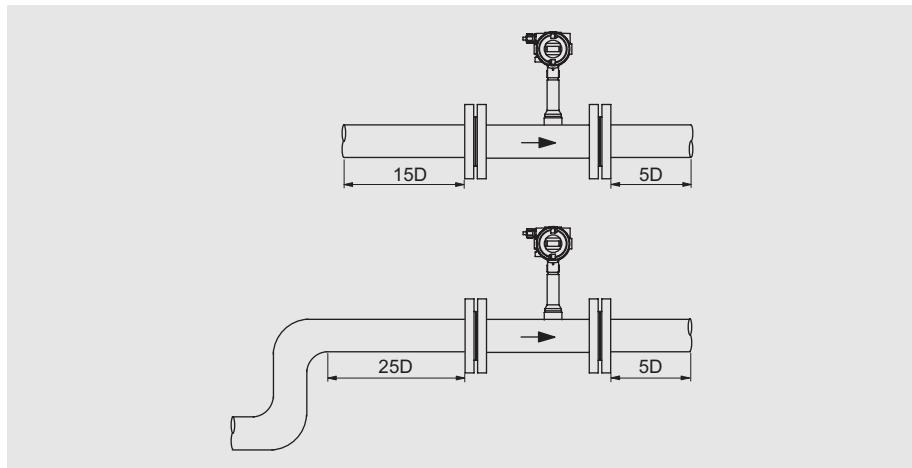


Fig. 2-34: Inlet and Outlet Sections

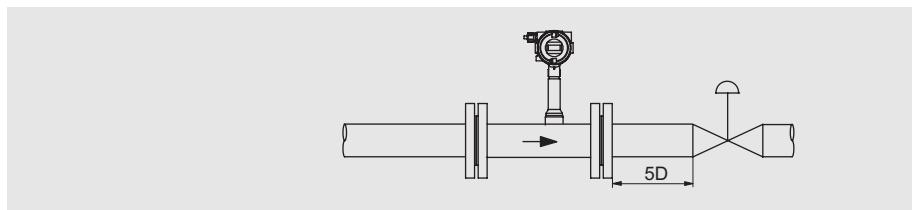


Fig. 2-35: Installation Location of Control Valve

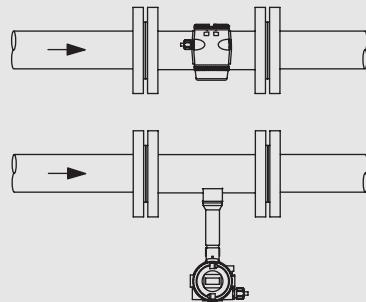


Fig. 2-36: Mounting Position for High Temperatures, Measuring Medium Temperature $> 150 \text{ }^{\circ}\text{C}$

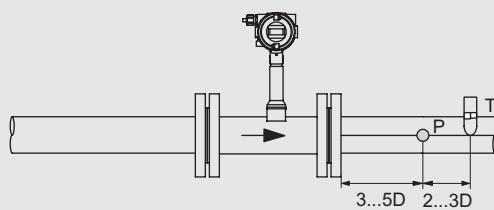


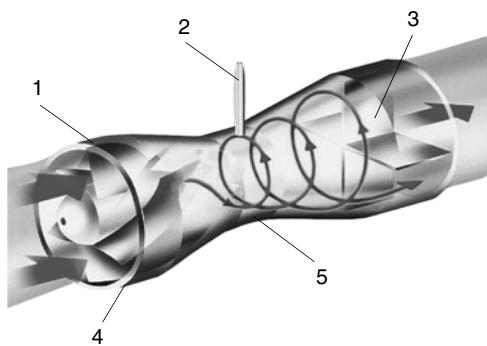
Fig. 2-37: Measuring Points for Pressure (p) and Temperature (T)

2.1.6 Swirl Flowmeters

A guide body whose shape is similar to a stationary turbine rotor is located in the inlet of the measuring device. The measuring medium is forced to rotate and flows through the meter tube of the swirl flowmeter in a thread like rotation.



Fig. 2-38: Cross Section of a Swirl Flowmeter



- 1 Inlet guide body
- 2 Piezo-sensor
- 3 Outlet guide body
- 4 Housing
- 5 Reversal point

Fig. 2-39: Flow in a Swirl Flowmeter

The swirl stabilizes in the cylindrical section of the meter tube. A consideration of the cross sections in this region shows that the rotational velocity at the wall is relatively small and increases toward the tube center until a stable vortex core is formed at the center. During the transition of the flow into the expanding section of the tube the vortex core is displaced because a backflow occurs in the expander section.

The vortex core forms a spiral like secondary rotation whose frequency is linearly proportional to the flow rate over a wide range. This secondary rotation is measured with a Piezo-sensor. The Piezo-sensor utilizes the resultant pressure differences for its pulse measurements.

The same sensors are used in both the swirl and vortex flowmeters. The vortex shedding frequency is between 1 and 2000 Hz; the higher frequencies indicating higher flow rates.

In the transmitter the sensor signals are converted into further processable outputs. The same transmitters as described for the vortex flowmeters are used.



Fig. 2-40: Integral Mount Design:
FS4000-ST4

Fig. 2-41: Remote Mount Design:
FS4000-SR4

Swirl flowmeters can be used for measuring the flow of liquids, gases and steam.

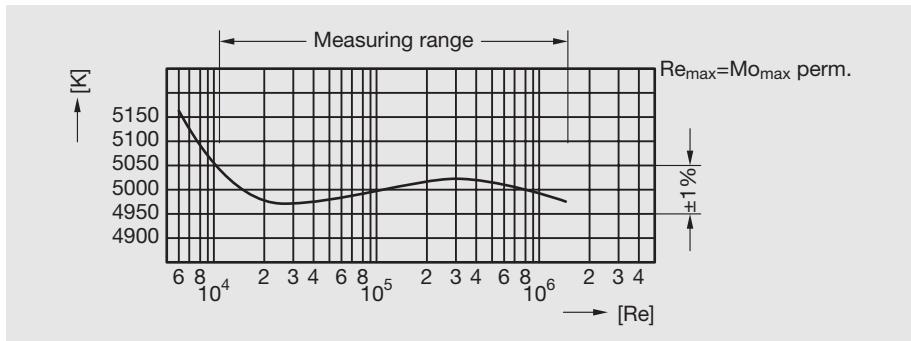


Fig. 2-42: Calibration Curve of a Swirl Flowmeter

Fig. 2-42 shows a typical calibration curve of a swirl flowmeter. On the ordinate is plotted the K-factor in pulses per volumetric unit versus the Reynolds number on the abscissa. A semi-dimensionless presentation is practical because the values related to the measuring medium can be expressed by the Reynolds number. This demonstrates for example, that the lower range value for higher viscosities increases and thereby reduces the linear span. Of course it is also possible to measure values in the nonlinear range. Viscosities of up to 30 m Pas are permissible, depending on the nominal diameter.

Each measuring device has its own calibration curve which is considered as its constant property; it will only change when the shape of the measuring section is mechanically deformed. By using the reduced spans resulting from application conditions a better accuracy can be achieved than for the entire span of $\pm 0.5\%$ of rate.

Using a 5-point linearization for the calibration curve of a DSP-controlled transmitter, an accuracy of 0.5% of rate can be achieved for liquids, gases and steam.

The special advantage of a swirl flowmeter over other systems is the fact that it requires only short inlet and outlet sections. It is recommended to use inlet and outlet sections of 3D/1D to assure that the accuracy specifications can be achieved.

Nominal Diameter		Water $\rho = 1000 \text{ kg/m}^3$ $\nu = 1 \cdot 10^6 \text{ m}^2/\text{s}$	Gas $\rho = 1.2 \text{ kg/m}^3$ $\eta = 18.2 \cdot 10^6 \text{ Pa} \cdot \text{s}$
DN	inch	Span [m^3/h]	Span [m^3/h]
15	$\frac{1}{2}$	0.1...1.6	2.5...16
20	$\frac{3}{4}$	0.2...2	2.5...25
25	1	0.4...6	5...50
32	$1\frac{1}{4}$	0.8...10	7...130
40	$1\frac{1}{4}$	1.6...16	12...200
50	2	2.5...25	18...350
80	3	3.5...100	60...850
100	4	5.0...50	65...1500
150	6	15.0...370	150...3600
200	8	25...500	200...5000
300	12	100...1000	400...10000
400	16	180...1800	1000...20000

Tab. 2-2: Swirl Flowmeters, Measuring Ranges in m^3/h (q_v)

The values in the table are intended to be used as references. The – seen from the physical point of view – actually achievable lower range values primarily depend on the operating density or viscosity of the measuring medium and the presence/absence of vibrations and/or pulsations. The measuring ranges for which the specified accuracy is reached depend on the minimum required Reynolds number, as below this number no linear relationship can be established between the vortex shedding frequency and the flow velocity.

Device Selection

Swirl flowmeters are with the nominal diameters DN 15...DN 400. Tab. 2-2 shows the corresponding measuring ranges. For liquid measurements the maximum flow velocity is 6 m/s, for gases it is 50 m/s.

ABB provides, at no cost, resource material to help in the selection and sizing of devices suitable for a particular measurement task, as well as order support.

It is important to avoid cavitation when measuring liquids. Sufficient static pressure must exist in the measuring section for this reason. To assure satisfactory operation the following check should be made:

$$p_2 \geq 1.3 \cdot p_D + 2.6 \cdot \Delta p$$

p_2 = Static gauge pressure downstream of the device

p_D = Steam pressure of liquid at operating temperature

Δp = Pressure drop (diagram)

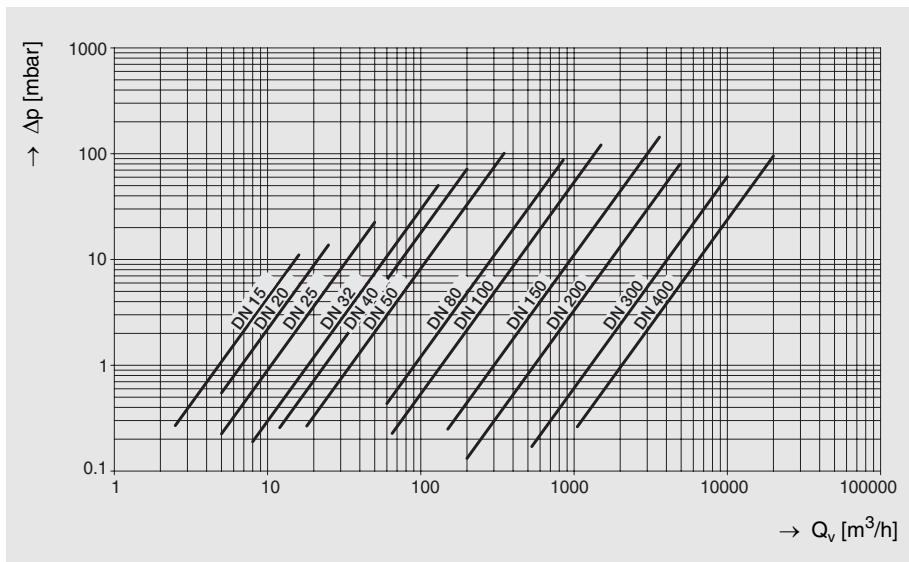


Fig. 2-43: Pressure Drop for Air (22 °C; 1,013 mbar, $\rho = 1.205 \text{ kg/m}^3$)

Example: 300 mbar

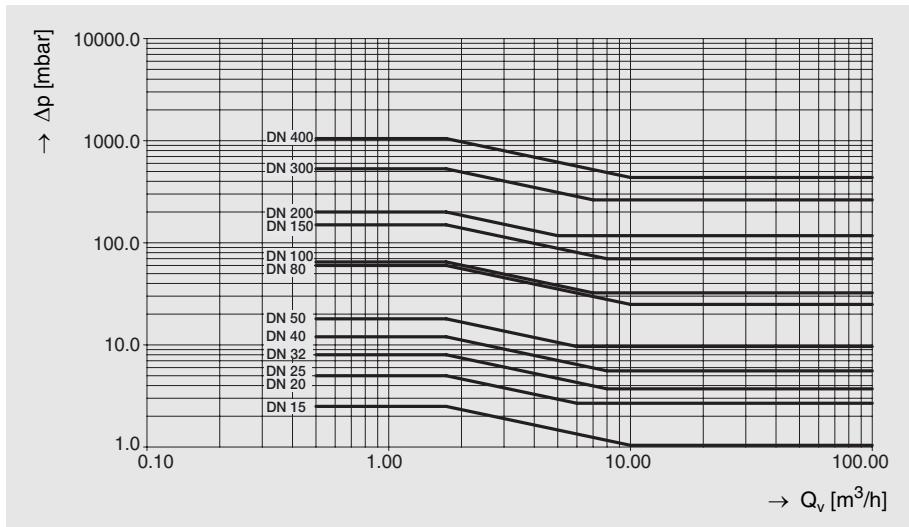


Fig. 2-44: Pressure Drop for Water (20 °C, 1,013 mbar, $\rho = 998 \text{ kg/m}^3$)

When selecting flowmeters for gas measurements, a conversion to the values at operating conditions is required.

$$\rho = \rho_N \frac{1.013 + p}{1.013} \cdot \frac{273}{273 + T} \quad (2.4)$$

ρ = Operating density (kg/m^3)

ρ_N = Standard density (kg/m^3)

p = Operating pressure (bar)

T = Operating temperature (°C)

q_v = Operating flow rate (m^3/h)

q_N = Standard flow (m^3/h)

$$q_v = q_N \frac{\rho_N}{\rho} \quad (2.5)$$

The calculation can be made automatically in the transmitter.

Transmitter

The transmitter used for the swirl flowmeter is the same as the one described for the vortex flowmeter.

Specifications	
Temperature limits	-55...280 °C (meas. medium temperature) -55...70 °C (ambient temperature)
Max. possible pressure	40 bar
Measured error	0.5 % of rate
Medium-wetted materials	1.4571 (Hastelloy C)
Explosion protection	ATEX / IECEx II 2 G Ex ib II C T4 ATEX / IECEx II 2 G Ex d II C T6 ATEX / IECEx II 2D T 85 °C...T _{med} IP 67 FM Class I Div1, Group A, B, C, D

Installation of the Sensor

The following recommendations should be observed when installing the sensor in a piping:

No inlet and outlet sections are required if the radius of curvature for single or double elbows in the inlet or outlet is greater than $1.8 \times D$.

No additional inlet and outlet pipe sections are required for flanged reducers per DIN 28545 ($\alpha/2 = 8^\circ$) installed in the outlet. Fig. 2-45 shows the recommended inlet and outlet sections for different boundary conditions at the installation location.

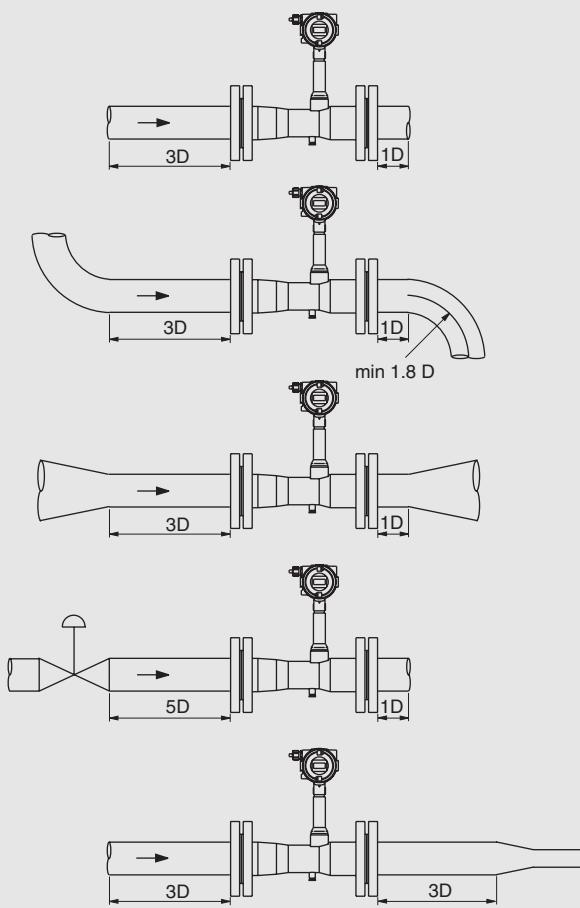


Fig. 2-45: Inlet and Outlet Sections

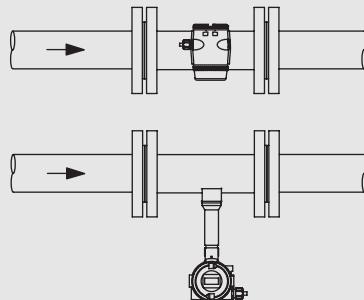


Fig. 2-46: Mounting Position for High Measuring Medium Temperatures > 150 °C

Multivariable Devices

Devices, which measure more than one physical variable are referred to as multivariable measuring devices. They can be provided with an optional Pt 100 for integrated temperature measurement directly in the sensor.

To convert the flow measurements to normal or mass units in many instances an additional temperature measurement is all that is required, e.g. for saturated steam or for gas measurements when the pressure remains constant.

Compensation of Pressure Effects

Integrated Temperature Measurement

Measuring the temperature and the flow rate at the same location provides appreciable advantages:

- High accuracy through optimal positioning of the temperature sensor
- No cabling
- Short response time

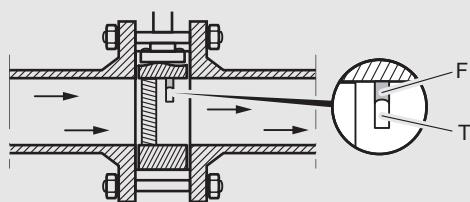
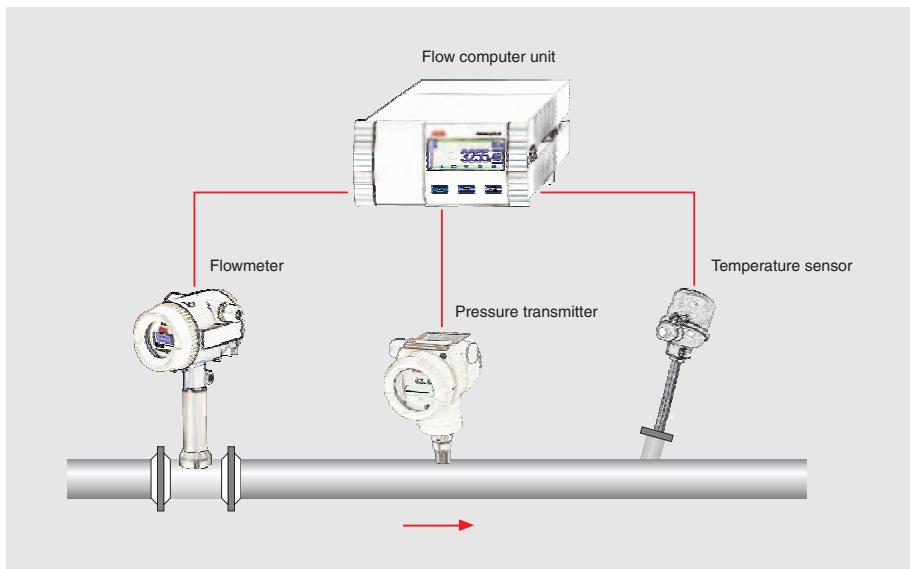


Fig. 2-47: Sensor for Flow Rate (F) and Temperature (T) Measurement

Pressure and Temperature Compensation

If the process conditions are such that pressure variations occur or the measuring medium is superheated steam, then an integrated temperature measurement alone is not sufficient to convert the gas flow volume measurements to mass, standard or steam mass flow values. For these applications swirl and vortex flowmeters in conjunction with flow computer units are the best choice. The power supply is realized via the flow computer unit.

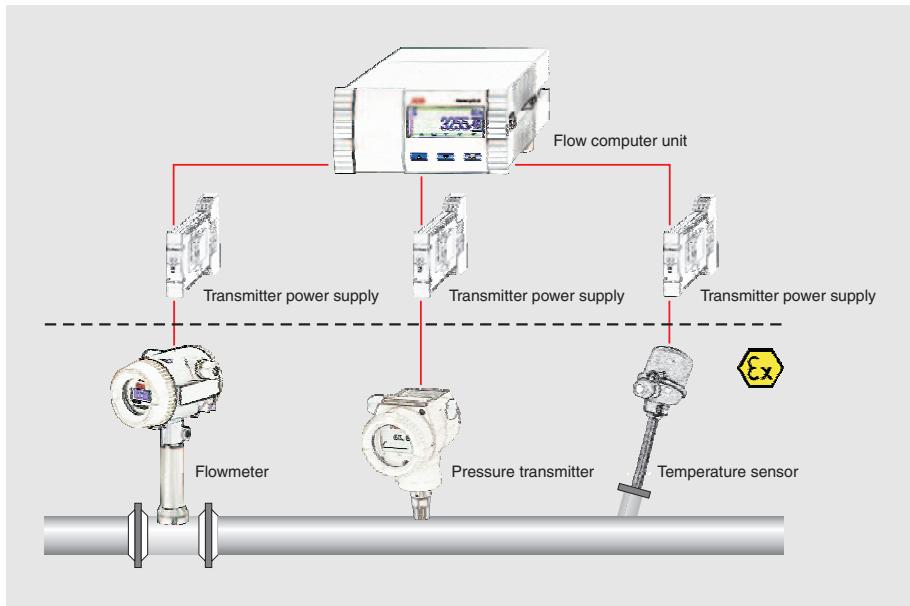


Components Used

- Vortex or swirl flowmeter
- Transmitter for absolute pressure
- Resistance thermometer, optionally with integral transmitter
- Flow computer unit

Measurements in Hazardous Areas

The signals must be fed in intrinsically safe via a transmitter power supply.



2.2 Flowmeters

2.2.1 Flowmeters for Differential Pressure Measurement

In Chapter 1.2.5 the relationship between the pressure drop Δp due to a restricted pipe section and the volume flow rate q_v is described.

This physical phenomenon is the basis for the differential pressure measurements, where a differential pressure flow primary in the piping (which must be running full) causes a pressure difference or differential pressure.

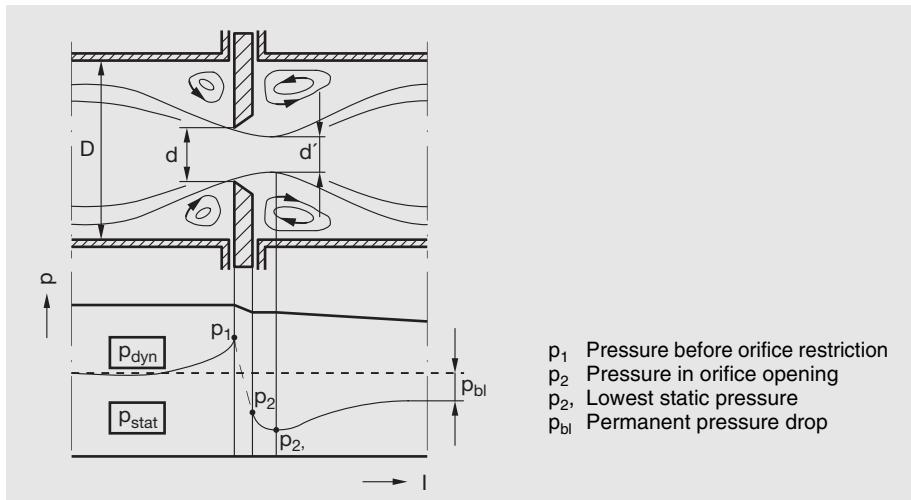


Fig. 2-48: Pressure Curve in a Primary Flow Differential Pressure Product (Orifice Plate)

Fig. 2-48 shows the conversion of the energy forms. In the restricted section the kinetic energy (dynamic pressure p_{dyn}) increases due to the increase in velocity and the pressure energy (static pressure p_{stat}) decreases. The pressure differential results from the difference between the static pressures upstream and the pressure at or directly downstream of the restriction. A partial recovery of the energy occurs downstream of the restriction due to the reduction in the velocity, but there remains some permanent, unrecovered pressure drop p_{bl} .

The differential pressure measurement method is a universally utilized measuring principle for flow measurement. Differential pressure flowmeters can be used for measuring gases and liquids even at extremely high pressures and temperatures. The meters have been optimized by extensive research activities over decades and the results published as standards. The primary standard is DIN EN ISO 5167 with whose assistance exact calculations can be made. The following equations for mass and volume flow rates can be found in these reference documents:

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} d^2 \sqrt{2 \cdot \Delta p \cdot \rho} \quad (2.6)$$

$$q_v = \frac{C}{\sqrt{1 - \beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} d^2 \sqrt{\frac{2 \cdot \Delta p}{\rho}} \quad (2.7)$$

C Flow coefficient

β Diameter ratio

ε Expansion factor (for compressible media, only)

d Inside diameter of the orifice plate

Δp Differential pressure

ρ_1 Density of the meas. medium before the orifice at operating temperature

q_m Mass flow rate

q_v Volume flow rate

The flow coefficient C is a function of the diameter ratio β , the Reynolds number Re , the type of the restriction, the location of the pressure taps and finally the friction due to pipe roughness. The empirically determined values are presented in curves and tables. The expansion factor ε takes into account the changes in the density of gases and steam due to the pressure reduction in the restriction. Tables and curves are also available for ε .

Designs of Primary Flow Differential Pressure Products

Various designs are available which can provide the optimal meter for the operating conditions and requirements of the user. An important consideration is, for example, the pressure drop, which as a rule should be small, or the length of the straight inlet and outlet sections, which may be relatively short for Venturi tubes. Certainly costs are also important considerations.

The following primary flow differential pressure products are included in the standard.

Orifices	Orifice with corner taps Orifice with D and D/2 taps Orifice with flange taps
Nozzles	ISA-1932 nozzle Long radius nozzle
Venturis	Classical Venturi tube Venturi nozzle

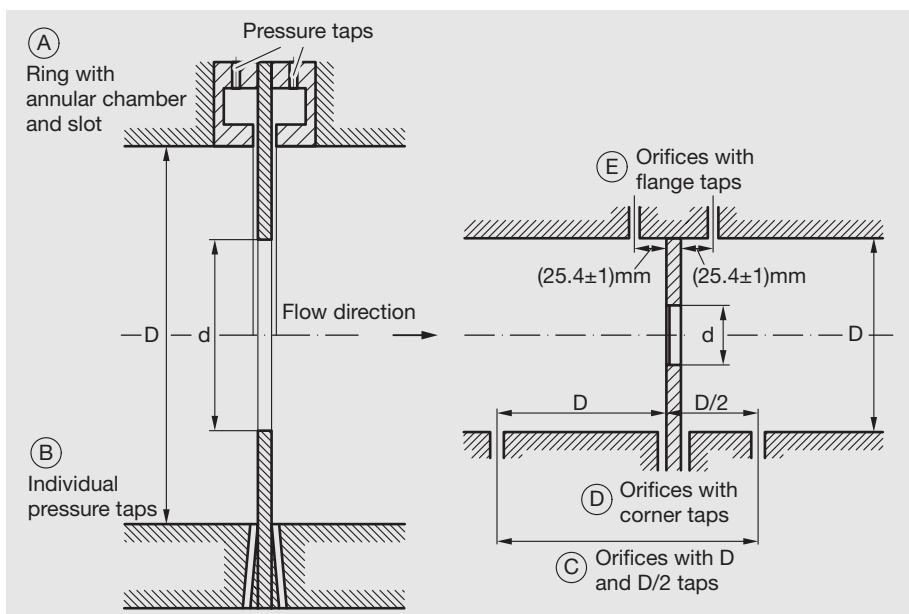


Fig. 2-49: Orifice Designs

The most cost effective design is the orifice plate. Fig. 2-49 shows corner tap arrangements in (B,D) as individual taps and in (A) using angular chambers. The D and D/2 tap arrangement is shown in (C). The pressure connections for the flange tap arrangement (E) with standard 25.4 mm (1") spacing are made by drilling through the flanges. They are often combined with an annular chamber arrangement (A).

Nozzles have lower pressure drops, but require especially precise manufacture. Fig. 2-50 (B) shows an ISA 1932 nozzle and its installation with corner taps (A, lower) and with an annular chamber (upper). Long radius nozzles (C, D) are available for large and small diameters. Their installation is shown in (A).

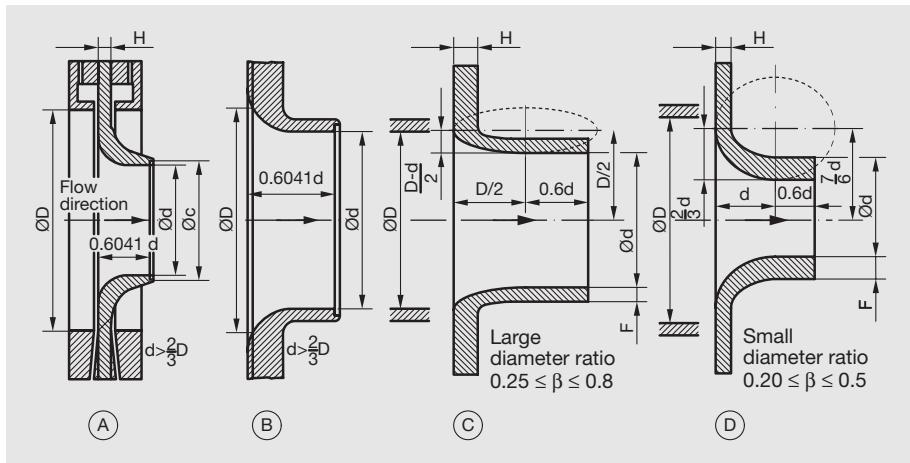


Fig. 2-50: Nozzle Designs

Venturi tubes and Venturi nozzles are characterized by small pressure drops. Both are also available in shortened versions. The fact that the pressure drop is an important factor in evaluating the various designs is shown by the curves (Fig. 2-52).

Pressure drop means energy loss and increased pumping/compression.

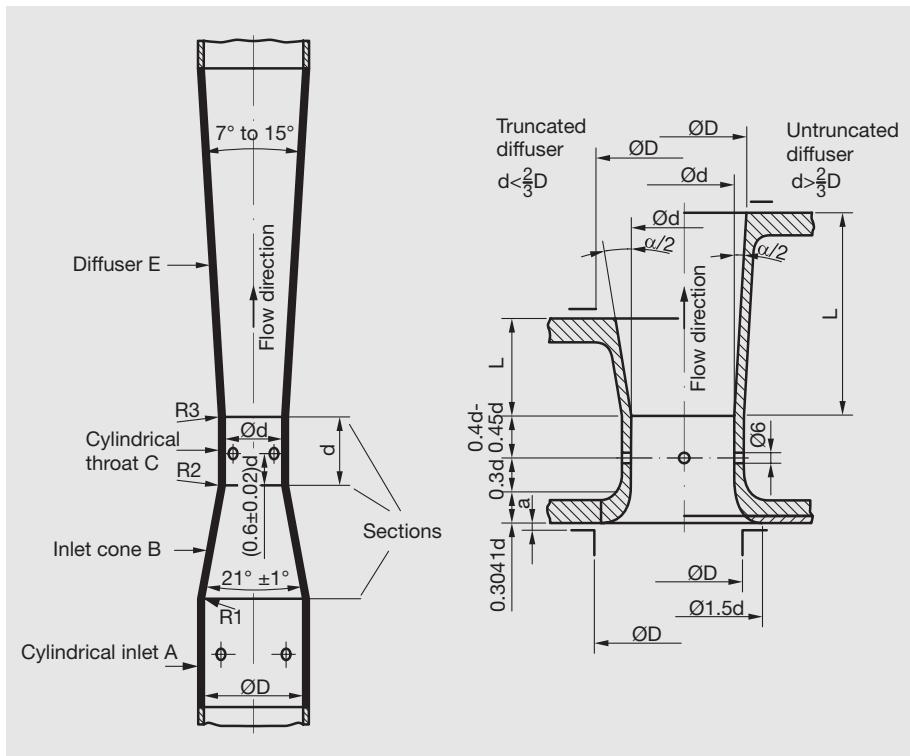


Fig. 2-51: Classical Venturi Tube and Venturi Nozzle

Comparing the range of possible installations shown in Tab. 2-3, it is apparent that orifices are universal, but have the basic disadvantage of high pressure drop. It is important that the edges of the orifice remain sharp. This causes the orifice to be sensitive to contamination and abrasion.

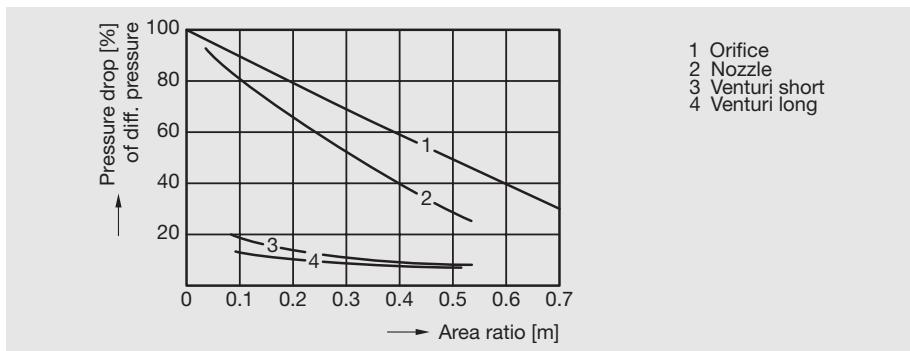


Fig. 2-52: Permanent Pressure Drop for Various Differential Pressure Meters

	Orifices			Nozzles		Venturis	
	Corner Pressure Taps	Flanged Pressure Taps	D and D/2-Pressure Taps	ISA 1932	Long Radius	Venturi Tube	Venturi Nozzle
d _{min} [mm]	12.5	12.5	12.5	15	10	20	50
D _{min} [mm]	50	50	50	50	50	50	65
D _{max} [mm]	1000	760	760	500	630	1200	500
β _{min}	0.23	0.20	0.20	0.3	0.2	0.3	0.32
β _{max}	0.80	0.75	0.75	0.8	0.8	0.75	0.78
Re _{D, min}	5 · 10 ³ ...20 · 10 ³	2.5 · 10 ³ ...540 · 10 ³	2.5 · 10 ³ ...540 · 10 ³	2 · 10 ⁴	10 ⁴	2 · 10 ⁵	1.5 · 10 ⁵
Re _{D, max}	10 ⁸	10 ⁸	10 ⁸	10 ⁷	2 · 10 ⁷	10 ⁶	2 · 10 ⁶

Tab. 2-3: Application Limits for Primary Flow Differential Pressure Products

It is easily understandable that meters as thoroughly researched as differential pressure meters can satisfy many special requirements. Therefore for measuring media containing solids, segmental orifices are utilized in which the measuring zone is restricted only at the top. Also wedge meters are a good solution for such kind of applications. For measuring media with high viscosities the quarter circle nozzle can be used to Reynolds numbers as low as 50. Nozzles with a throat diameter of 0.6 mm can be used to meter liquid flow rates as low as 2 l/h. These nozzles are together with or without the differential pressure transmitter in a single assembly available. The table values can be extrapolated to nominal diameters of 2000 (78") and beyond.

Installation Requirements

Differential pressure meters can be used without problems only under specific flow conditions. Non-uniform velocity profiles after disturbances prevent an axisymmetric velocity profile from forming in the throat and thereby alter the differential pressure values. For this reason the primary flow differential pressure product must be installed between two straight cylindrical pipe sections in which no disturbances or diameter changes may exist. Along these sections the required velocity profile for metering can form. Tab. 2-4 lists the recommendations per DIN EN ISO 5167 for the required straight pipe sections.

	Orifices, Nozzles, Venturi Nozzles				Classical Venturi Tube		
	Diameter Ratio β				Diameter Ratio β		
	0.2	0.4	0.6	0.8	0.3	0.5	0.75
Single 90° elbow or tee	10	14	18	46	0.5	1.5	4.5
Two or more 90° elbows in different planes	(34)	(36)	48	80	0.5	(8.5)	(29.5) ¹⁾
Diffuser from 0.5 D to D with a length of 1...2 D	16	16	22	54			
Diffuser from 0.75 D to D with a length of 1 D					1.5	2.5	6.5
Fully opened gate	12	12	14	30	1.5	3.5	5.5
Outlet side	4	6	7	8	4	4	4

¹⁾ This type of disturbance can still have an affect after $40 \times D$, therefore the values are enclosed in parenthesis.

Tab. 2-4: Required Disturbance Free Straight Sections, Lengths Listed in Multiples of D

A particularly difficult flow condition is swirl, in which the measuring medium rotates around the axis of the piping, often asymmetrically. Some of the longer lengths required in Tab. 2-4 above are required because the combination of fittings induces swirl in the flow, which requires long lengths of piping before it dissipates. The typically-quoted straight sections are not sufficient by any means for conditioning such a flow profile. Therefore a flow straightener must be installed. A flow straightener can also be used to shorten the recommended straight lengths for the other types of disturbances.

Measuring System Setup

The complete flow measurement installation consists of the following elements:

- a) Primary flow differential pressure element (the differential pressure source)
- b) Fittings for the primary flow differential pressure element and protective devices
- c) Pressure piping (impulse line)
- d) Connection fittings and valves and/or isolating & equalising manifold for impulse lines
- e) Differential pressure transmitter
- f) Condensate chamber (sometimes used in steam flow measurement)
- g) Power supply unit for transmitter

The arrangement and design of the installation is a function of the application. The minimum requirements for each measuring point are pressure lines between the primary flow differential pressure product and the differential pressure transmitter. Shut-off valves (b) are installed in both pressure lines after the pressure connections. For protecting the differential pressure transmitter (e) a valve combination (d) consisting of three to five valves (often in a single assembly referred to as a 3-valve or 5-valve manifold) is installed before the transmitter. The valves shut off the transmitter and allow the pressures in each line to be equalised, enabling the transmitter to be zeroed.

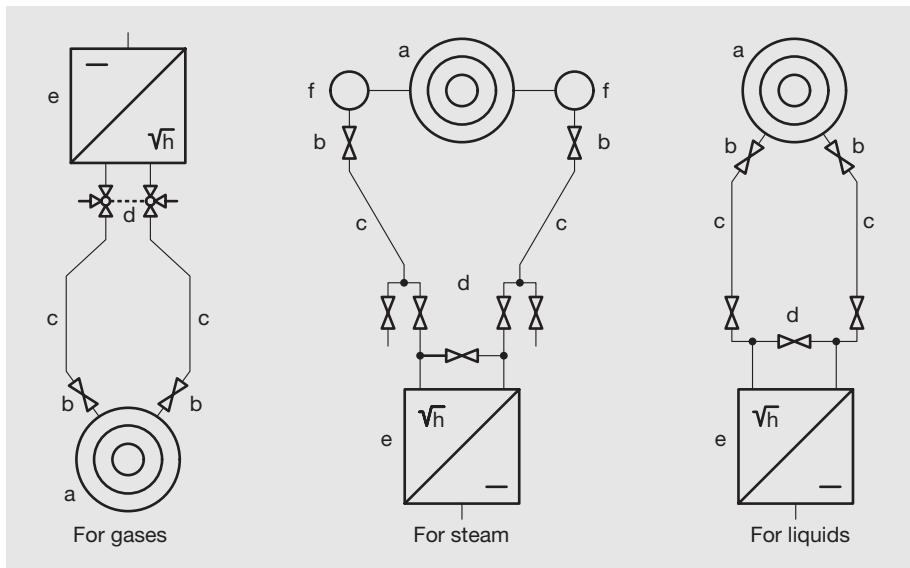


Fig. 2-53: Differential Pressure Measurement Setup

If the differential pressure measurement system is used for gas measurements, the transmitter should be installed above the metering point in order to prevent any condensate from entering the pressure lines. Conversely, gas bubbles must not enter the pressure line when liquids are measured. Therefore, in this case the differential pressure sensor should be installed above the metering point. For steam measurements the condensate chambers (f) are used to maintain the same liquid level in both pressure lines, ensuring that there is no flow reading error caused by a static pressure „offset“ in one pressure line.

There are a number of meter arrangements for extraordinary installation situations. Isolation chambers, for example, protect the transmitter against aggressive measuring media.

Differential Pressure Transmitter

The differential pressure transmitter has the following tasks:

- It should withstand the high static pressure which exists in the piping.
- It should be very sensitive, so that it can operate at low differential pressures, which are often preferred as a high differential pressure usually results in a high pressure loss.
- Its materials should be chemically resistant to aggressive measuring media.
- It should convert the differential pressure into an electrical or analog output signal.
- It should be able to extract the square root in order to achieve a direct linear output proportional to the flow rate.
- It should be easy to operate and include self monitoring functions.
- It should be capable of modern communication including SMART or fieldbus technologies (PROFIBUS PA, FOUNDATION Fieldbus).
- It should be interference resistant (EMC) and explosion proof or intrinsically safe.

With the Series 2600T, ABB provides transmitters which satisfy all of the above requirements.

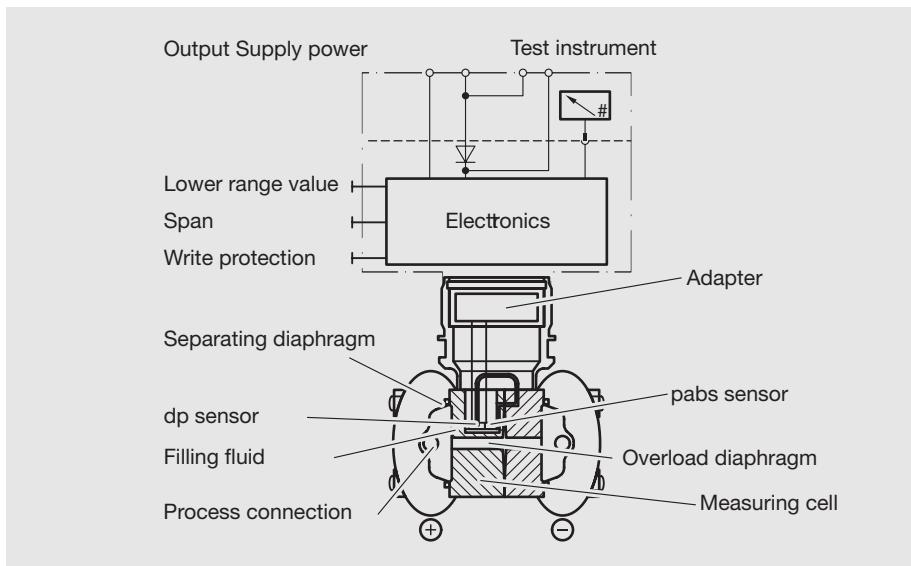


Fig. 2-54: Functional Diagram of a Differential Pressure Transmitter

The 266MST transmitter has a modular design and consists of a measuring element with integral matching electronic and the operator electronics.

This transmitter is a multisensor device for measuring differential and absolute pressures. The completely welded measuring cell is a two chamber system with an internal overload diaphragm and an internal silicone absolute pressure sensor and a silicone differential pressure sensor. The absolute pressure sensor, to which pressure is applied on the plus side, only, measures the process pressure and provides the data for an almost complete compensation of the static pressure effect. The differential pressure sensor is connected to the minus side of the measurement cell by a capillary tube. The existing differential pressure (dp)/absolute pressure (pabs) is transmitted to the measuring diaphragm of the silicone differential pressure sensor via a separating diaphragm and the filling fluid.

A minimal deflection of the silicone diaphragm changes the output voltage of the measuring system. This pressure proportional output voltage is linearized, temperature compensated and then converted by the matching electronic and the electronic unit into an electrical signal 4...20 mA/HART, PROFIBUS PA or FOUNDATION Fieldbus.

To prevent damage to the measurement system due to an overload on one side up to the total nominal pressure, an overload diaphragm is incorporated. For differential pressures within the specified measuring limits the overload diaphragm has no effect on the measurements. When the limits are exceeded, the overload diaphragm shifts from its middle position until it contacts the separating diaphragm. In this way the pressure acting on the sensor is limited.

For local operation an operating option is available that consists of two push-buttons for setting the lower and upper range value and a write protect switch. In conjunction with the integrated LCD display, the transmitter can be completely configured externally using the “local operator option”, independently of the communication protocol selected. The smallest upper range value is 0.5 mbar, the largest 100 bar. The base accuracy is below 0.04 % of the span setting. The process-wetted parts are selected to be suitable for the chemical properties of the measuring medium.



Fig. 2-55: 266MST Differential Pressure Transmitter

When using a differential pressure flow measurement system and the density of the measuring medium changes due to pressure and temperature variations, it is recommended – at least for gas and steam measurements – to additionally measure the process pressure and temperature and then perform a computational compensation. This will assure a reliable measurement of the mass or standard volume flow rates, even under varying conditions.

Even such complex challenges, which in the past had to be satisfied by using individual differential pressure, absolute pressure and temperature transmitters and an additional computation element, can now be solved using the 267CS or 269CS multivariable transmitters which directly measure all the variables and also calculate and apply the corrections required when the state of the measuring medium changes, all in a single device.

The same measuring cell already described for the 266MST transmitter is used for differential pressure and pressure measurement. Only the electronics unit was expanded to include a measurement of the process temperature using an external temperature sensor.

The compensation function does not only calculate the density for the current process conditions. Depending on the differential pressure sensor type, the Reynolds number and the diameter ratio it determines the flow coefficient, compensates the thermal expansion of the piping and differential pressure sensor and, for gases, additionally recalculates the expansion factor and the real gas factors for the prevailing process conditions. This is in fact a dynamic compensation assuring the highest degree of accuracy.



Fig. 2-56: 269CS Multivariable Transmitter

2.2.2 Compact Orifice Flowmeters

To overcome the technical and economic issues involved in correctly creating an orifice-based flow metering installation, the concept of compact orifice flowmeters such as ABB's OriMaster was created.

These comprise all of the following traditional components fabricated into a single flowmeter assembly:

- Orifice carrier
- Pressure taps
- 3-valve manifold
- Differential pressure transmitter (optionally a multivariable transmitter)
- Optional integral temperature assembly for gas/steam flow calculations



Fig. 2-57: OriMaster FPD500 Compact Orifice Flowmeters

As a one-piece, factory-assembled flowmeter, OriMaster has a greatly-reduced number of potential leakage points and takes minimal customer labor to install correctly. It comes in only two Beta ratios, which greatly simplifies configuration and calculation.

Accuracy is enhanced by OriMaster being easily and precisely centered in the piping using the supplied tool. After being assembled in factory, OriMaster is subjected to a pressure test. Due to its integral mount design and the reduced number of potential leakage points this measuring device offers improved long-term stability.

For simple volume measurement OriMaster includes a differential pressure transmitter. The transmitter has an all-stainless-steel body and is, thus, ideal for difficult applications. For applications requiring gas/mass flow / steam calculations, OriMaster is supplied with a multivariable transmitter to measure differential pressure and temperature. With this a single-piece mass flowmeter or flowmeter with volume correction is available. Either an integral temperature element or a conventional, separate pipe-mounted sensor is used for temperature measurements.

2.2.3 Wedge Meters for Critical Applications

The operating principle of a wedge meter is simple and easy to understand. As shown in the illustration below, the wedge meter is equipped with a V-shaped flow restrictor that reduces the area available to flow. Fluid velocity increases as flow is contracted at the flow restrictor. The increase in velocity results in an increase in the kinetic energy of the measuring medium. By the principle of conservation of energy, any increase in kinetic energy must be accompanied by a corresponding decrease in potential energy (static pressure). Thus, the measuring medium directly upstream of the flow restrictor has a greater potential energy (and higher static pressure) than the medium immediately downstream of the flow restrictor. Pressure taps placed on either side of the wedge meter will allow the differential pressure that develops as a result of this imbalance in potential energy to be measured. The volume flow rate can then be directly calculated from the measured differential pressure. Some of the pressure loss created by the flow restriction will be recovered downstream of the wedge meter as kinetic energy is converted back to potential energy.

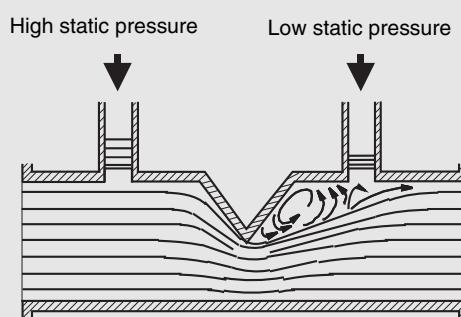


Fig. 2-58: Measuring Principle of a Wedge Meter

A wedge meter is a refinement of a segmental orifice. Whereas the segmental orifice offers a sudden restriction to flow, the wedge meter provides for a gradual restriction. The latter has various advantages over the segmental orifice design, including immunity to erosion and immunity to build-up by any secondary phase. The immunity to erosion is the result of the slanted upstream face of the flow restrictor, which prevents damage due to impingement with any undissolved solids in the measuring medium.

The opening beneath the restriction is large and allows for easy passage of any secondary phase. Eddies and back currents created provide a “self-scouring” action that keeps the internals clean and free from build-up.

Wedge meters are designed to measure flow accurately in all flow regimes: laminar, transition and turbulent. Laminar and transition flow regimes, often encountered with viscous measuring media or low flow rates, may cause other measuring elements to exhibit significant deviation from the square root relationship between flow rate and measured differential pressure. The discharge coefficient of a wedge meter remains highly linear from Reynolds numbers as low as 500 (laminar) to Reynolds numbers in the millions (turbulent). This has been proven by years of testing on water and air at facilities such as Alden Laboratories and CEESI (Colorado Experiment Engineering Station Inc.).

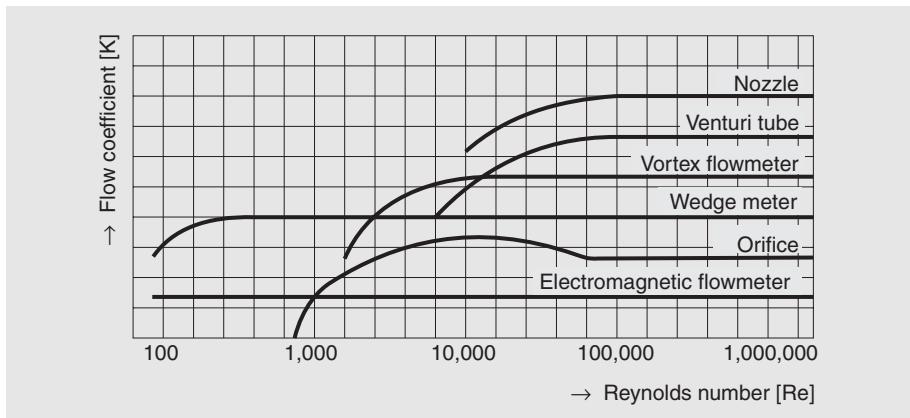


Fig. 2-59: Flow Coefficients of Different Flow Elements

The area restriction in a wedge meter is characterized by the H/D ratio, analogous to the beta ratio of a concentric orifice plate. The H/D ratio is defined as the height of the opening below the restriction divided by the internal diameter of the wedge meter. The H/D ratio can be varied to create a desired differential pressure for any specific flow rate. This gives the user a good degree of flexibility in selecting a suited wedge meter for a given application.

The user can select the wedge meter that presents the optimum compromise between initial cost and pressure loss. As shown in the illustration below, the unrecovered pressure loss for a wedge meter varies with the H/D ratio from 30% of the measured differential pressure to 60%.

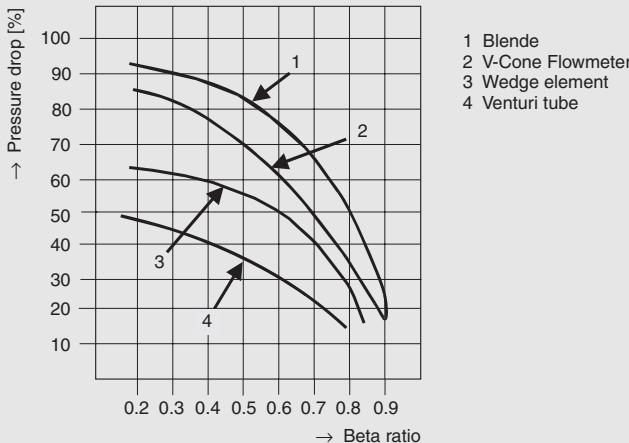


Fig. 2-60: Pressure Loss as a Function of H/D Ratio

Wedge meters are easy to install and do not require any special tools or training. Since wedge meter performance is highly insensitive to piping effects there is no need for especially long straight inlet sections or flow straighteners upstream of the wedge meter. The normal piping recommendation is to use inlet sections of $5 \times D$ to $10 \times D$ and outlet sections of $3 \times D$ to $5 \times D$. Moreover, the wedge meter does not require any strainers or filters in the inlet section, even if the measuring medium is not perfectly clean. Measuring media with undissolved solids and/or unabsorbed gas, gases with solids and/or liquids, and saturated, superheated or wet steam can all be metered without any problems. The choice of a remote seal wedge meter or integral pipe tap wedge meter depends on the amount of secondary phase present.

Typical applications for wedge meters, in addition to those previously mentioned, include:

- Liquids with low electrical conductivity
- Viscous and non-Newtonian liquids
- Processes with high operating pressures and/or high operating temperatures
- Bi-directional flow measurement
- CO_2 or water injection to revitalize existing oil and/or natural gas fields
- Measuring media prone to agglomeration and gum formation

2.2.4 Pitot Flowmeters

Averaging Pitot Tube

An averaging pitot tube is an insertion or fixed probe which spans the process pipe diameter. The outer pitot tube of the probe has a number of pressure sensing ports facing upstream which are positioned at equal annular points in accordance with a log-linear distribution.

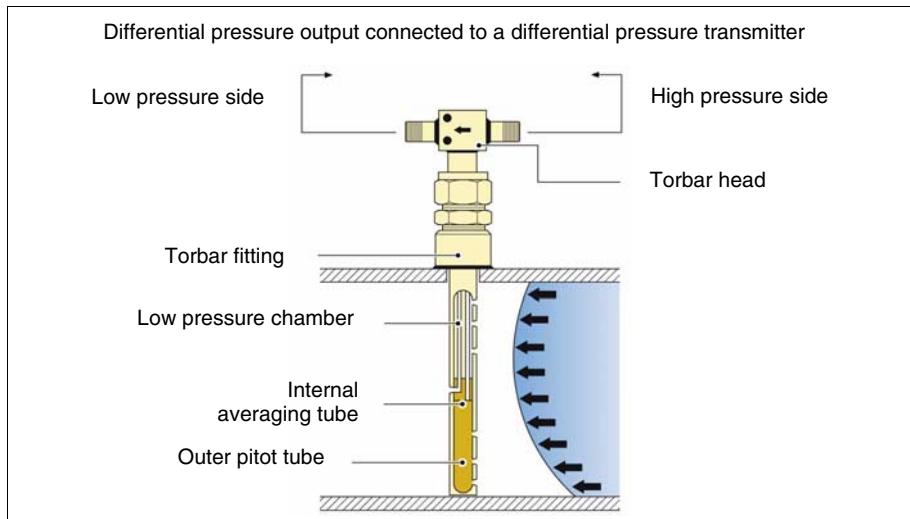


Fig. 2-61: Schema of an Averaging Pitot Tube

The total pressures developed at each upstream port are the sum of two pressures - the static pressure and the pressure caused by the impact of the flowing medium. These pressures are averaged within the probe and the resultant pressure is the high pressure output component of the probe. The spacing of the ports ensures that the resultant average represents the medium velocity of the measuring medium across the pipe diameter.

The low pressure component is generated from a single sensing port located on the downstream side of the probe, measuring the static pressure. The difference between the two pressures is proportional to the flow rate as follows:

$$Q = k \cdot A \cdot \left[\frac{h}{r} \right]^{1/2}$$

Q = Volume flow rate

k = Constant

A = Cross-section of the pipe/duct

h = Generated differential pressure

r = Density of the measuring medium

TORBAR Averaging Pitot Tube

The TORBAR is an improvement on round sensor designs due to the unique profiled flats which are positioned around the downstream hole, in order to define the separation point at which the flow lines separate as the measuring medium passes around the outer pitot tube. This feature creates a stable pressure area at the downstream pressure sensing hole thereby maintaining a more constant flow coefficient at high flow velocities enabling a very wide range of flow measurement (turn down ratio).



Fig. 2-62:

TORBAR is suitable for gases, liquids and steam. Some of the many typical applications include water, natural gas, flue gas, nitrogen, combustion gases, ventilation air, sea water, cooling water, crude oil, saturated and superheated steam. Possible pipe diameters range from 15 mm up to 8 m. TORBAR averaging pitot tubes are available in a variety of designs to suit the application.

Series 100

Inline (full bore) meters with weld-prepared ends or threaded or flanged connections for nominal diameters from DN 15 to DN 50.

Series 300, 400 and 500

Fixed insertion type meters with threaded or flanged connections for nominal diameters from DN 50 to DN 5000.

Series 600, 700 and 800

Withdrawable insertion type meters with threaded or flanged connections for nominal diameters from DN 50 to DN 5000. Retraction of the probe from the piping can optionally utilize an easy-to-operate geared retraction system.

Each series covers a defined range of nominal pipe diameters, static pressures and differential pressures. A special software is available to simplify the calculation, selection and specification of the best suited TORBAR flowmeter for the respective application.

TORBAR flowmeters have been successfully used on a large variety of flow applications throughout the world in many different industries. Among these are:

- Oil production (onshore, offshore)
- Oil refining
- Nuclear power
- Food and beverages
- Chemical
- Pharmaceutical
- Water distribution
- Water treatment
- Effluent treatment
- Power generation
- Building services
- Gas processing
- HVAC
- Gas transmission

Applications where TORBAR flowmeters have been used successfully include the flow measurement of:

- Natural gas
- Flue gas
- Nitrogen gas
- Hydrocarbon gas
- Methane gas
- Combustion gas
- Sour gas
- Exhaust gas
- Coke oven gas
- Carbon dioxide gas
- Petrol vapor
- Ventilation air
- Compressed air
- Hot air
- Solvent laden air
- Saturated air
- Saturated steam
- Superheated steam
- Sea water
- Cooling water
- River water
- Waste water
- Potable water
- Liquid oxygen
- Crude oil
- Nitric acid
- Red wine
- Liquid petroleum gas (LPG)

The versatility of TORBAR flowmeters makes them ideal for flue stack flow rate measurement. The ABB SG 2000 system introduces advanced features. With its secondary averaging feature, two piece design option, and power purge facility, this flowmeter offers a reliable method for determining the flue gas flow rate.

2.2.5 Variable Area Flowmeters

The flowrate of gases and liquids can be determined simply, yet relatively accurately with variable area flowmeters. The measuring medium flows upward through a vertical conical tube whose diameter increases in the upward direction. The upward flowing fluid lifts a float located in the tube to a height so that the annulus has an area which results in an equilibrium of the forces acting on the float.

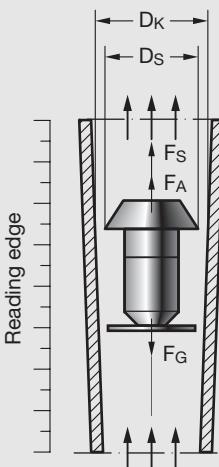


Fig. 2-63: Operating Principle of the Variable Area Flowmeter

Three forces act on the float (Fig. 2-63). Downward the gravitational force F_G acts:

$$F_G = V_s \cdot \rho_s \cdot g \quad (2.8)$$

There are two forces acting in an upward direction.

The buoyancy force F_A and the flow resistance force F_S :

$$F_A = V_s \cdot \rho_m \cdot g \quad (2.9)$$

$$F_S = c_w \cdot A_s \cdot \frac{\rho_m \cdot v^2}{2} \quad (2.10)$$

V_s : Volume of the float

m_s : Mass of the float

ρ_s : Density of the float

ρ_m : Density of the measuring medium

c_w : Resistance coefficient

A_s : Cross-sectional area of the float at the reading edge

v : Flow velocity of the measuring medium

D_K : Inside diameter of the cone at the reading point

D_s : Diameter of the float at the reading edge

At equilibrium or a the float position:

$$F_G = F_A + F_S \quad (2.11)$$

The flow rate is:

$$q_v = v \cdot A = v \frac{\pi}{4} (D_k^2 - D_s^2) \quad (2.12)$$

The resistance coefficient c_w is converted to the flow coefficient:

$$\alpha = \sqrt{\frac{1}{c_w}} \quad (2.13)$$

α is a function of the geometric shape of the meter tube and the float and above all, of the diameter ratio. α also includes the friction effect. This empirically determined value defines device-specific characteristic curves which are incorporated into the basic calculation.

The general variable area flowmeter equation can be formulated taking into account all the aforementioned equations.

Volume flow rate:

$$q_v = \frac{\alpha}{\rho_m} D_s \sqrt{g \cdot m_s \cdot \rho_m \left(1 - \frac{\rho_m}{\rho_s}\right)} \quad (2.14)$$

Mass flow rate:

$$q_m = \alpha \cdot D_s \sqrt{g \cdot m_s \cdot \rho_m \left(1 - \frac{\rho_m}{\rho_s}\right)} \quad (2.15)$$

The annulus available for the flow changes as a result of the conical form of the meter tube with the elevation of the float. Thus, the float height provides information regarding the flow rate. When a glass meter tube is used, the measured value can be read directly from a scale.

In comparison to the differential pressure flow measuring method there is a physical analogy which is evident from the similarity of the basic equations. The essential difference is mechanical, because the flow area remains constant in a differential pressure flowmeter and the pressure difference varies with flow rate while in the variable area flowmeter the flow area varies to suit the flow rate and the pressure difference remains constant.

Float

An important requirement for metering is the exact centering of the float in the meter tube. Three methods have proved themselves:

1. Through slots on the float head the flowing measuring medium forces the float to rotate and center itself. This principle, however, cannot be used with all float shapes. Additionally, there is a considerable dependence on the viscosity of the measuring medium.

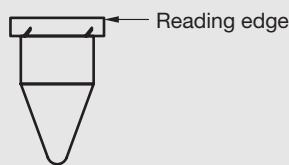


Fig. 2-64: Rotating Float

2. The float is guided by three ribs or three flats (ball floats) which differ from the meter tube cone in that they are parallel to the tube axis. A variety of float shapes are possible. Even for cloudy opaque measuring media the measuring edge remains visible.

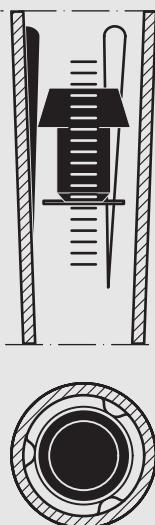


Fig. 2-65: Float Guides with 3 Ribs or 3 Flats

3. A guide rod in the middle of the meter tube is used to guide the float. This method is primarily used for metal tube variable area flowmeters.

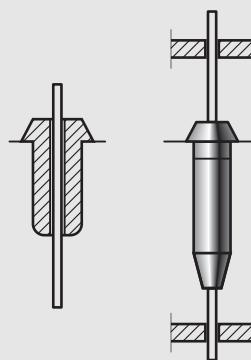


Fig. 2-66: Float with Guide Rod

A wide variety of float shapes are available. The weight, shape and materials are adapted to the individual installations.

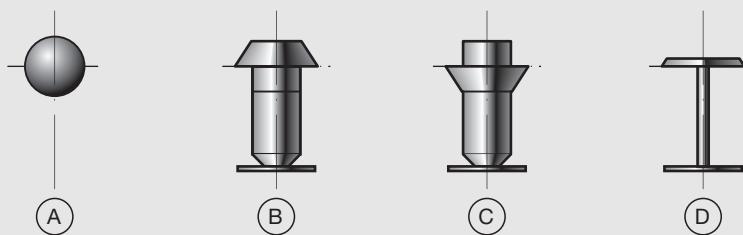


Fig. 2-67: Examples of Float Shapes

- A Ball float
- B Viscosity-immune float
- C Viscosity-dependent float
- D Float for low pressure drop

The ball float is the measuring element preferably used for purgemeters. Its weight can be determined by selecting from a variety of materials. Shape changes are not possible.

Therefore the flow coefficient is defined. The ball shape is responsible for the viscosity effect.

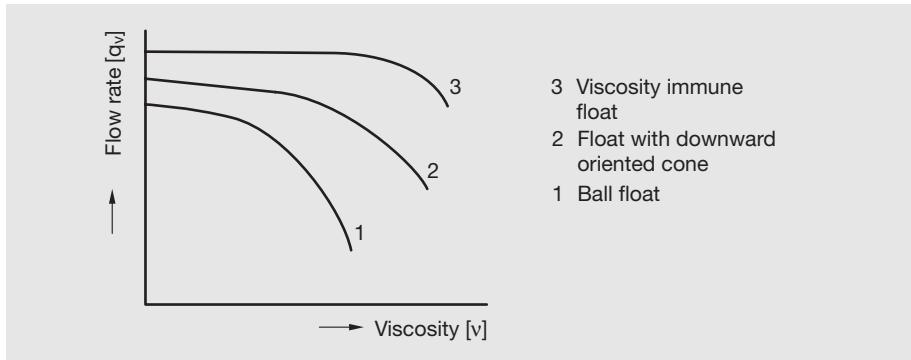


Fig. 2-68: Viscosity Effects for the Various Float Shapes

Fig. 2-68 illustrates the effect of viscosity on the flow rate indication. The curve for the ball float (1) stands out in particular because there is no linear region. That means that every change in viscosity results in indication changes. Remember, that for many fluids small changes in temperature can result in viscosity changes.

The float with the cone directed downward (Fig. 2-64 and Fig. 2-67c) is used rather in larger sized variable area flowmeters than in small ones. The linear region of the curve in Fig. 2-68/2 is relatively small. This confirms the statement made about the rotating floats. Appreciably more insensitive is the float shape shown in Fig. 2-67b. The corresponding curve in Fig. 2-68/3 has a long linear region. Such a device is unaffected by relatively large changes in viscosity, however, for the same size meter, 25% less flow rate can be metered than for the previously described float. The majority of the variable area flowmeters manufactured by ABB include a viscosity-immune float.

Finally there are the very light floats (Fig. 2-67d) with relatively low pressure drops. This design requires minimum upstream pressures and is usually preferred for gas flow measurement.

Pressure Drop

The pressure drop occurs primarily at the float because the energy required to produce the measuring effect is derived from the pressure drop of the flowing measuring medium. On the other hand, the constructional restrictions in the device fitting cause a pressure drop.

The pressure drop at the float is dependent on its largest outside diameter and its weight and therefore is independent of its elevation in the meter tube, i.e. it is constant. The pressure drop through the restrictions in the fittings, however, increases as the square of the increasing flow velocity.

The resultant pressure drop is the reason for the requirement of a minimum upstream pressure.

Sizing Procedures

There are tables for all variable area flowmeters with measuring range values listed for water and air flow in which the empirically determined α values have already been incorporated. Therefore complicated calculations are not necessary. For measuring media other than water or air only a conversion calculation to the equivalent table values is required. The following applies to smooth conical (metal tube) or glass tube variable area flowmeters with three rib guides when measuring liquids:

$$q_{v\text{water}} = q_{v1} \sqrt{\frac{(\rho_s - 1) \cdot \rho_1}{(\rho_{s1} - \rho_1) \cdot 1}} \quad (2.16)$$

q_{v1} = Volume flow rate of the measuring medium

q_{m1} = Mass flow rate of the measuring medium

ρ_s = Float density, usually 8.02 g/cm^3 for stainless steel

ρ_{s1} = Density of the float material actually used

ρ_{s1} = Only for special cases

ρ_n = Density of the measuring medium

ρ_1 = Density of water, here = 1 g/cm^3

$$q_{v\text{water}} = q_{m1} \sqrt{\frac{\rho_s - 1}{\rho_1 \cdot 1 (\rho_{s1} - \rho_1)}} \quad (2.17)$$

Similar sizing procedures are available for glass tube meters with three flats and ball floats.

Example:

Measuring medium	Ammonia, liquid
Mass flow rate q_m	1500 kg/h
Density ρ	0.68 kg/l
Dyn. viscosity η	0.23 mPas
Operating pressure	15 bar
Operating temperature	20 °C

From equation (2.17):

$$q_{vw\text{water}} = 1500 \sqrt{\frac{8.02 - 1}{0.68 \cdot 1(8.02 - 0.68)}}$$

$$q_{vw\text{water}} = 1779 \text{ l/h}$$

This water equivalent value is used in the tables for the selected device to determine the meter size.

It is necessary to calculate the gas density ρ_B relative to air before converting to equivalent table values for air:

$$\rho_{n\text{Air}} = 1.293 \text{ [kg / m}^3]$$

$$\rho_B = \frac{\rho_n}{1.293} \cdot \frac{T_n}{T_n + T} \cdot \frac{p_n + p}{p_n} \quad (2.18)$$

ρ_n = Density of gas at normal conditions

T_n = 273.15 K

T = [°C]

p_n = 1.013 bar

p = [bar]

ρ_1 = Density of gas at operating conditions

Equation 2.16 can be simplified for gases ($\rho_s \ll \rho_w$; $\rho_{s1} \ll \rho_1$) to:

$$(q_v)_n = q_{v1} \sqrt{\frac{\rho_s \cdot \rho_1}{\rho_{s1} \cdot \rho_n}} \quad (2.19)$$

Use this equation and the dimensionless ratio to calculate the ρ_s for the air table values:

$$(q_v)_{nAir} = q_{v1} \sqrt{\frac{\rho_s \cdot \rho_B}{\rho_{s1}}} \quad (2.20)$$

or for the mass flow rate q_m :

$$(q_v)_{nAir} = \frac{q_{m1}}{1.293} \cdot \sqrt{\frac{\rho_s}{\rho_{s1} \cdot \rho_B}} \quad (2.21)$$

Example:

Measuring medium	Ammonia, gaseous
Flow rate q_m	1500 kg/l
Density ρ_n	0.7714 kg/m ³
Pressure p	5 bar
Temperature T	100 °C

from equations (2.18) and (2.19):

$$\rho_B = \frac{0.7714}{1.293} \cdot \frac{273}{373} \cdot \frac{6.013}{1.013} = 2.592$$

$$(q_v)_{nAir} = \frac{1500}{1.293} \cdot \sqrt{\frac{8.02}{8.02 \cdot 2.592}} = 720.6 \text{ m}^3/\text{h}$$

Viscosity Effects

After selection of the flow meter size the viscosity effects should be checked using the viscosity influence value, VUZ:

$$VUZ = \eta \sqrt{\frac{\rho_s - \rho_w}{(\rho_{s1} - \rho_1) \rho_1 \cdot \rho_w}} = \eta \sqrt{\frac{\rho_1 - 1}{(\rho_{s1} - \rho_1) \rho_1}} \quad (2.22)$$

η = Current viscosity value of the measuring medium.

The calculated viscosity influence value must be smaller than the value listed in the flow rate tables. The flow rates are unaffected by viscosities less than the calculated value even when the viscosity changes. If the calculated viscosity influence value exceeds the listed values, then the device must be calibrated using the current viscosity.

Example:

Measuring medium	Ammonia
Dyn. viscosity η	0.23 m · Pas
Density ρ	0.68 kg/l
Float density $\rho_s = \rho_{s1}$	8.02 (stainless steel)

$$VUZ = 0.23 \sqrt{\frac{8.02 - 1}{(8.02 - 0.68) \cdot 0.68}} = 0.27$$

In the table a viscosity influence value of 28 is specified; the calculated value is much smaller.

There is no viscosity effect.

Variable area flowmeters can be selected and exactly calculated in a much simpler way using the ABB calculation software “flow calc”.

Device Selection

A typical range of variable area flowmeter products includes a metal tube and a glass tube line that are used for the most different applications:

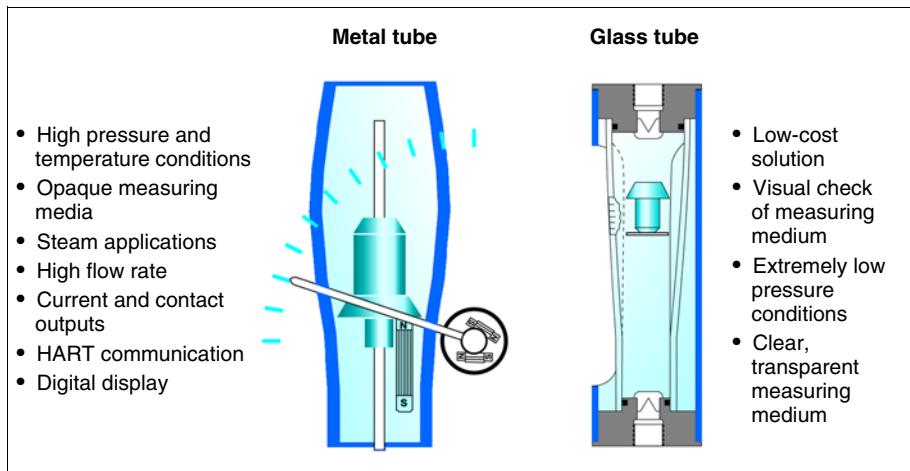


Fig. 2-69: Comparison of Metal Tube and Glass Tube VA Flowmeters

Device Description of Purgemeters

Purgemeters are built small and designed for small flow rates with local indication. All are designed so that the meter tubes can be exchanged and include a needle valve to set the flow rate. The span is 1:10 or 1:12.5 for scale lengths between 38 and 250 mm. A ball float is used. The accuracy is a function of the meter tube material and the scale length.

For water, or equivalently calculated other liquids, the upper range value is between 0.03 l/h and 140 l/h, for air and gases it is between 2.88 and 4330 l/h.

“SNAP-IN” Purgemaster Series FAG6100

“SNAP-IN” is an elegant method for exchanging meter tubes. The meter tube holder and seals in the upper fitting are spring loaded so that the meter tube can be pushed up and pulled out towards the bottom. A polycarbonate protection cap locks the meter tube in place. An integrated non-return valve prevents reverse flow. A DVGW certificate has been granted.



Fig. 2-70: FAG6100 Series

Materials	
Housing	Stainless steel
Meter tube holder	1.4401 brass
Meter tube	Borosilicate glass, Trogamid
Float	Glass, sapphire, tantalum, 1.4401, Carboloy
O-rings	Buna N, Viton A, ethylene-propylene
Protection cap	Polycarbonate

Specifications

Type	Scale Length (mm)	Housing Length (mm)	Meas. Range for Water
10A6134/44	38	120	3...48 cm ³ /h to 3...132 l/h
10A6131/41	70	151	24...264 cm ³ /h to 10...105 l/h
10A6132/42	130	264	2.6...32 cm ³ /h to 11.2...140 l/h

The flow rate value set with a needle valve varies when the pressure changes. A differential pressure regulator is an available accessory which maintains a constant flow rate independent of pressure changes.

Ring initiators are used as alarm signalling units.

Principle of Operation

The ring initiator has a bistable operation which engages the relay in the switch amplifier when the ball float reaches the limit value. The relay remains engaged even if the float continues its travel beyond the limit value. The relay is released as soon as the float passes back through the limit value in the opposite direction into the acceptable range. The instantaneous position, either above or below the limit value, is unambiguously indicated. The use in the hazardous area is possible because the ring initiators used are intrinsically safe sensors with intrinsically safe circuits. Because of the relatively short meter tube length the model 10A6131/41 is only recommended for either a minimum or a maximum limit value. For both minimum and maximum limit values the model 10A6132/42 is more suited.

Glass Tube VA Flowmeter Series FAG1190

This rugged and simply designed process meter is the most used model. Flanges, female pipe threads or for the food industry, the preferred round threads (DIN 11851) provide connections to the process. Glass tube VA flowmeters are suitable for flow rate measurements in many industries, e.g. oven manufacture. The standard housing material is stainless steel.

The meter tube is sealed and positioned with O-rings to eliminate mechanical stresses.

A supplementary protection shield is provided for gas measurements which protects the meter tube from contact or mechanical damage. This ensures personnel safety. A DVGW certificate has been granted.

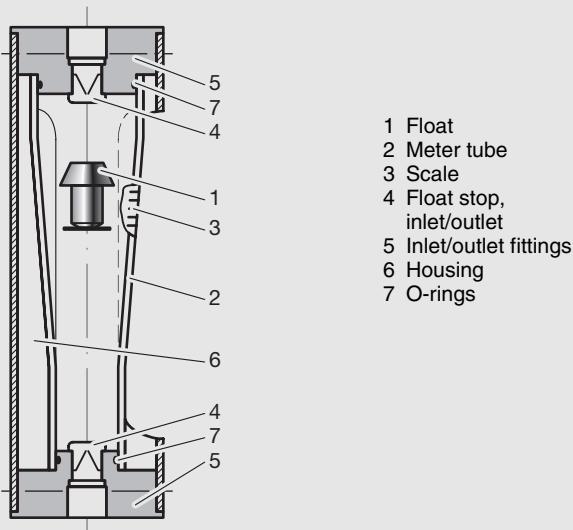


Fig. 2-71: Basic Design

Materials	
Meter tube	Borosilicate glass
Float	Glass, sapphire, tantalum, 1.4301, 1.4571, PVDF and others
Fittings	PVC, PVDF and others
O-rings	Buna N, Viton A, ethylene-propylene
Housing	Stainl. steel 1.4301
Connections	FAG1190-97: Female thread FAG1190-98: Flanged connections FAG1190-87: Threaded pipe connection



Fig. 2-72: FAG1190 Series

Specifications:

Housing Size	Meter Tube Size	Scale Length	Upper Range Value (Water) [l/h]	(Air) [m ³ /h]	Max. Permeable Pressure [bar]	Accuracy Class
1/4	1/16	100	0.03...1.1	0.003...0.04	38	6
1/4	1/18	130	0.37...10	0.022...0.33	33	1.6
1/4	1/4	130	4.7...132	0.223...4.03	30	1.6
1/2	1/2	250	43...418	1.3...12.3	21	1.6
3/4	3/4	250	144...1300	4.3...38.7	17	1.6
1	1	250	310...2800	9.2...83.0	14	1.6
1 1/2	1 1/2	250	560...4800	17.3...142.5	9	1.6
1	1	250	1420...17000	42.6...510	7	1.6



Proximity switches switch the contacts of the alarm signalling unit, e.g. for minimum and maximum values. The adjustable inert gas switches have a bistable operation, i.e., once activated, the self holding contact will only be released by the float moving in the opposite direction.

Fig. 2-73: 55AX1000 Alarm Signalling Unit

Metal Tube VA Flowmeter

The all metal armored variable area flowmeter can be used more universally than the glass tube meter. The operating pressure can be as high as 250 bar and the maximum allowable measuring medium temperature (dependent on the ambient temperature) is 400 °C.

The transmission of the float position to the indicator is accomplished by a magnetic coupling system consisting of a permanent magnet located in or on the float and a permanent magnet follower on the indicator axis. The follower system does not lose its coupling even when the float takes a sudden jump due to a flow rate change. The guide rod of the float remains within the meter pipe even for extreme float excursions.

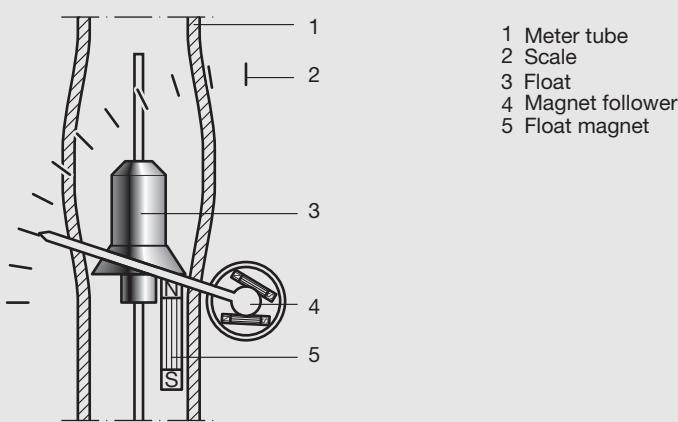


Fig. 2-74: Basic Design of a Metal Tube VA Flowmeter

Metal Tube VA Flowmeter Series FAM540

Besides the standard local flow indicators, this metal pipe flowmeter can also be equipped with plug-in units for one or two alarm signalling units, electrical transmitters with 4...20 mA output and an additional digital display for local indication of the current flow rate and totalized flow values. These units can be retrofitted without interrupting the process. After correct selection of the suited material for the process-wetted parts, even chemically aggressive (and cloudy) liquids, gases or vapors can be measured. In combination with the application proven multi-function float this flowmeter opens new application horizons for this traditional flow measurement technology.

An appropriate damping system prevents compression oscillations in gas and steam measurements. A double jacket is available to heat the meter tube with steam or hot water when heat is required for difficult applications.

Materials	
Meter tube	1.4404 or PTFE liner
Float	1.4571, Hastelloy C, PTFE
Flanges	1.4404
Indicator housing	Aluminium

Measuring Ranges

Nominal Diameter DN	inch	Length [mm]	Upper Range Value	
			Water [m ³ /h]	Air [m ³ /h]
15	1/2	250	0.03...0.85	0.1...25
25	1	250	0.28...6.1	8.4...180
50	2	250	4.2...24	125...720
80	3	250	7...54	210...1550
100	4	250	25...120	760...3600

Specifications	
Scale length	100 mm
Max. possible pressure	450 bar
Max. possible temperature	400 °C (for ambient temperature 50 °C)
Accuracy class	1.6
Contact output	1 or 2 limit contacts using proximity switches
Analog output	4...20 mA; supply voltage 14...28 V DC
Communication	intrinsically safe supply ATEX/IECEx II 1/2G Ex ia IIC T4 non-intrinsically safe supply ATEX/IECEx II 1/2G Ex d IIC T6 HART protocol

Electrical Transmitter

All metal tube flowmeters with transmitters are designed so that the mechanical indicator will continue to operate even if the transmitter should fail. This means that the measured value can always be read at the meter location even if the transmission of the electrical signals has been interrupted.

The transmitter is a two-wire device. It allows to access and change all measuring parameters if required.

The transmitter monitors itself and includes automatic error diagnostics. Three programming switches are accessible when the cover is removed. It is also possible to configure the transmitter through magnetic pen operation without opening the cover. A high-contrast two-line LCD display is provided for viewing the measured values and parameters.

FAM541 Standard design	FAM544 Hygienic design	FAM545 PTFE-lined	FAM546 Heat jacket design
			
For universal application	For food and beverage/pharmaceutical applications	For aggressive media	For temperature-sensitive processes

Fig. 2-75: Metal Tube VA Flowmeter Series FAM540

Armored Purgemeter Series FAM3200

This small variable area flowmeter in an all-metal design allows to readily measure the flow rate of gases and liquids under extreme conditions. Cloudy liquids, which are common in the chemical, petrochemical and pharmaceutical industries, present no problems to this flowmeter.

Even in the laboratory, for gas analyzers and wherever the prevailing conditions exclude the use of a glass tube meter, the advantages of the small armored purgemeter come to the fore.

Materials	
Medium-wetted parts	1.4571, PVDF
O-rings	Viton A, Buna N
Indicator housing	Aluminium, stainless steel
Cap	Polycarbonate, Trogamid, stainless steel with glass window

Specifications	
Min. meas. range	0.1...1.0 l/h water 0.008...0.048 m ³ /h air
Max. meas. range	300...3000 l/h water 8...90 m ³ /h air
Scale length	60 mm
Max. perm. pressure	100 bar
Max. perm. temperature	150 °C
Accuracy class	6
Analog output	4...20 mA
Contact output	1 or 2 limit values using proximity switches



Fig. 2-76:

Design Types

Section View

2.2.6 Electromagnetic Flowmeters

If an electrical conductor is moved in a magnetic field which is perpendicular to the direction of motion and to the conductor, an electrical voltage is induced in the conductor whose magnitude is proportional to the magnetic field strength and the velocity of the movement. This characterization of the laws of induction also applies to the movement of a conductive liquid in a pipe through a magnetic field.

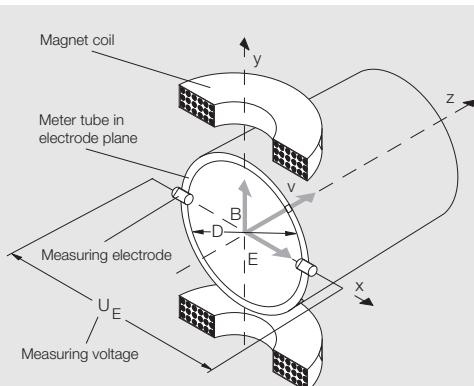


Fig. 2-77: Operating Principle of an Electromagnetic Flowmeter

For the resulting electromagnetic flowmeter the following equation applies:

$$U_0 \sim B \cdot v \cdot D \quad (2.23)$$

with the induction B , the flow velocity v and the conductor length (pipe diameter) D .

The flow rate q_v through the cross section A under consideration is

$$q_v = A \cdot v = \frac{D^2 \pi}{4} \cdot v \quad (2.24)$$

Combining the two equations results in the defining relationship for the measuring system:

$$U_0 \sim q_v$$

To utilize the principle shown in Fig. 2-77 requires that a magnetic field exist within the pipe and that the induced voltages can be measured without any interference. Two coils generate the magnetic field that extends through the pipe only if it is not shunted by permeable pipe materials. Austenitic steel does not hinder the magnetic field; therefore it is the most commonly used material for the meter pipe in the electromagnetic flowmeter. To prevent shorting out of the measuring signal U_E the meter tube must be provided with an insulating internal lining. The measuring voltage U_E is measured by means of two metallic electrodes that are in electrical contact with the measuring medium.

An additional requirement for the operation has already been mentioned, namely the fact that the measuring medium must be an electrical conductor. Therefore a minimum conductivity between 20 and 0.05 $\mu\text{S}/\text{cm}$ is required, depending on the device type.

Structure of the Magnetic Field

The measuring voltage U_E measured at the electrodes is the sum of all the elemental voltages induced in the entire area of the magnetic field within the meter tube. The following consideration ignores the three dimensional nature of the field and is limited to the cross sectional area in the plane of the electrodes. It turns out that the magnitude of the elemental voltages at the electrodes, i.e. the ratio of the partial voltage due to each element to the total measuring voltage U_E at the electrodes is a function of the geometric location of that element.

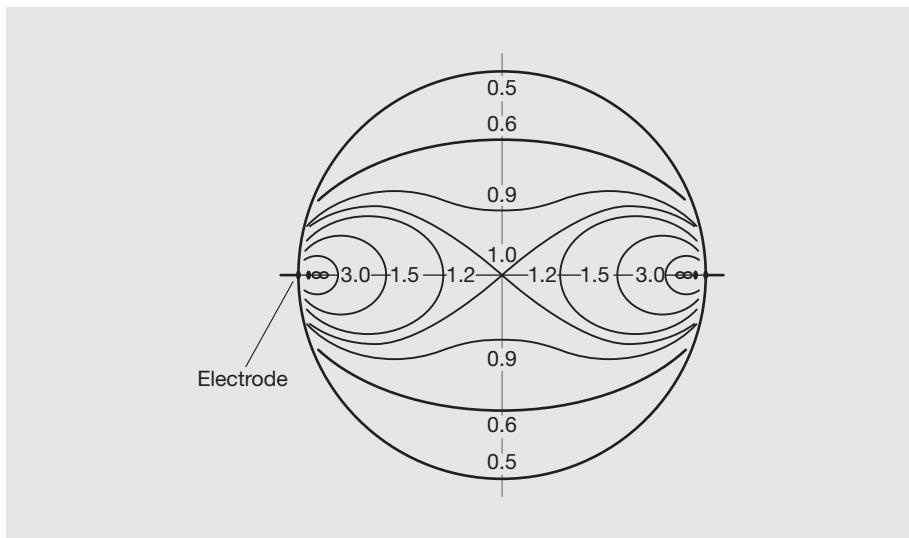


Fig. 2-78: Weighting Factor Distribution in the Electrode Plane

Fig. 2-78 shows the distribution of the weighting factor of the elemental voltages based on an assumed value of "1" at the center. It is obvious that the elemental voltages induced in the vicinity of the electrodes have a greater effect than those induced in the regions near the poles. The weighting factor W concept is used to define the location related magnitude. In a homogeneous magnetic field, in which the field strength B is the same throughout, the elemental voltages measured at their sources are all the same when the flow velocity of the measuring medium is constant throughout.

For a nonsymmetrical flow profile, for example after an elbow (Fig. 1-7a), the various regions in the metering pipe cross section have differing velocity values. Some areas are overevaluated and others are underevaluated; as a result, the total measuring voltage U_E is no longer the average of all the elemental voltages and no longer represents the flow rate.

With a magnetic field design in which the field strength is inversely proportional to the weighting factor a method of compensation was discovered. The magnetic field strength is increased in the low weighting factor areas and conversely decreased in the high weighting factor areas, so that the product of the weighting factor W and the field strength B is constant over the entire cross section under consideration:

$$W \cdot B = \text{constant} \quad (2.25)$$

Now the magnitude of all the elemental voltages is the same and a nonsymmetrical flow profile causes no error.

The practical implementation of a weighting factor inverse magnetic field can only be approached in practical designs. This fact is the basis for the recommendation that short inlet sections, 3 to 5 times the pipe diameter in length, be installed upstream of the electromagnetic flowmeter. This length is sufficient to effectively eliminate the effects of upstream flow disturbances.

Noise Voltages

The measuring voltage U_E is smaller than 0.5 mV per 1 m/s of flow velocity. The magnitude of the noise voltages superimposed on the signal voltage may sometimes be appreciably larger. The connected transmitter has the function to reject the influences of the noise signals and to convert and amplify the measurement signal so that other connected evaluation units such as indicators, recorders, or controllers can be operated.

What noise voltages exist?

First there is an electrochemical direct voltage. It occurs in a galvanic system at the interface between the electron conductive metal electrodes and the ion conductive liquid. These "polarization voltages" are a function of a variety of ambient conditions such as temperature, pressure and composition of the measuring medium. Their values are not reproducible and are different at each electrode so that their effects can not be predicted.

The magnetic coils are capacitively coupled to the signal lines and to the electrodes inside the flowmeter sensor. This coupled “capacitive noise” voltage is a function of the excitation voltage and of the internal impedance of the measuring section and is therefore also a function of the conductivity of the measuring medium. Careful shielding measures, especially when the conductivity is low, can prevent stray capacitance influences.

The signal lines in the device are the connection elements coming from the electrodes and are brought together at the top of the metering pipe and together with the measuring medium form a single turn loop in which the excitation circuit induces a “transformer voltage”.

Precise mechanical assembly and orderly placement of the lines minimize this voltage. Liquid filled flowmeters, particularly in the larger sizes, are good conductors of ground currents from a nonsymmetrical electrical distribution system.

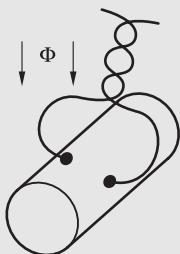


Fig. 2-79: Conductive Loop in a Transformer

The voltage differential existing between the electrodes due to these currents induces an additional “external” noise voltage, which can be prevented by shunting the ground current around the meter. This can be achieved through a parallel connected low resistance grounded conductor (large copper wire).

To reduce the noise voltages various means are employed which are a function of the different types of magnetic field excitation to prevent either their generation or their effects. Direct current voltages, e.g. polarization voltages, can be blocked by capacitively coupling to the transmitter.

Methods of Magnetic Field Excitation

The geometric design of the magnetic field has already been described. How do the time relationships affect the noise voltages?

Simplest would be to use permanent magnets for the field generation. All alternating current induced noise voltages would be eliminated. Unfortunately the polarization voltages, whose magnitude cannot be predicted, would be so large that they would swamp the measuring signal. Is a 50 Hz alternating current excitation the answer? This system must cope with the noise voltages generated by the alternating current field, but there are still reasons for its existence.

A magnetic field excitation means which combines the advantages of both of the aforementioned systems and reduces their disadvantages is the pulsed DC field.

Pulsed DC Field

At time t_0 a DC voltage is applied to the magnetic coils. Because of the inductance of the coils the excitation current I increases slowly to its final value.

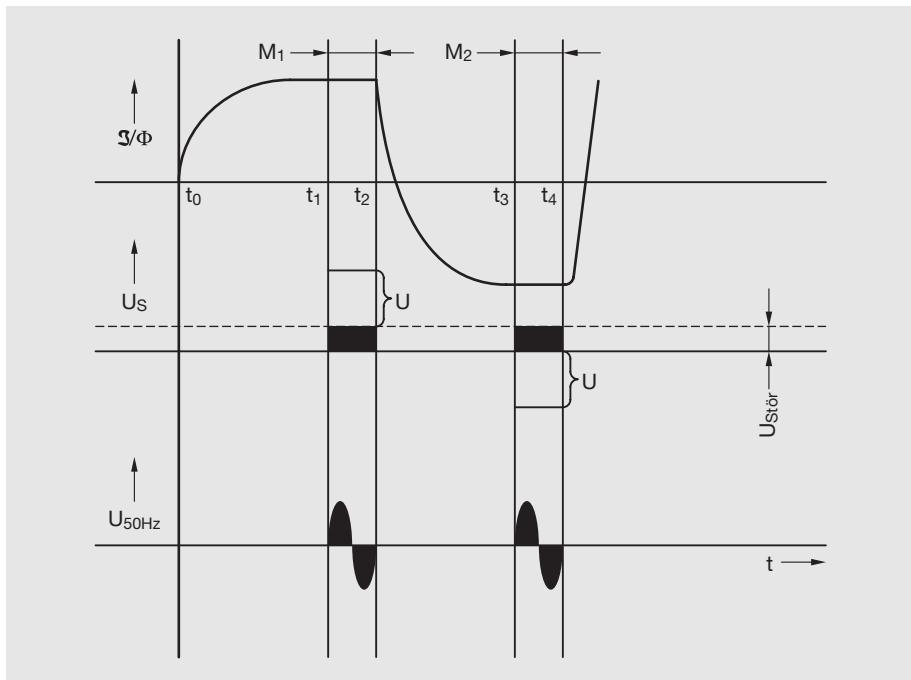


Fig. 2-80: Magnetic Field with Pulsed DC Excitation

After the decay of the transients which occur as a result of the excitation reversal the excitation current I and the magnetic flux remain constant so that the time differential of the flux is zero:

$$\frac{d\Phi}{dt} = 0$$

The transformer noise disappears and to a great extent the capacitive noise also.

Only when this condition has been reached after 60 ms, is the transmitter turned on at time t_1 and during the next 20 ms time interval measures the electrode signal U_s . 20 ms is one period of a 50 Hz system (for other frequencies there are corresponding time intervals). The 50 Hz noise signals, which are primarily due to external influences, are automatically eliminated.

The electrode signal U_s includes the desired measuring voltage U and the remaining uncompensated noise U_{noise} . During the measurement interval M_1 , the following applies:

$$U_{s1} = U + U_{noise} \quad (2.26a)$$

This value is stored.

At t_2 the polarity of the DC voltage is reversed and therefore also the measuring voltage U . The polarity of U_{noise} does not reverse so that during the measurement interval M_2 the following applies:

$$U_{s2} = -U + U_{noise} \quad (2.26b)$$

The transmitter subtracts this value from the value of the previous measurement interval:

$$U + U_{noise} - (-U + U_{noise}) = 2U \quad (2.26c)$$

The result is a measuring voltage U proportional to the volume flow rate; it is free of noise signals. This is called a system with automatic zero adjustment since at 6 1/4 Hz its value is calculated six and one quarter times a second.

A higher accuracy can be achieved because of the stable zero even at measuring medium conductivities at the lower limit of 5 $\mu\text{S}/\text{cm}$.

AC Magnetic Field

The pulsed DC field has some limitations when a fast measurement is required and the 160 ms measurement cycle is too long.

An example is the filling technology in which extremely short measurement intervals are coupled with exact valve closure characteristics. Another application is the measurement of two-phase media, i.e. the hydraulic transport of solids like, for example, paper pulp or dredged material. With direct current excitation these measuring media generate a noise voltage that is superimposed on the measuring signal and results in errors. These noise voltages do not occur with alternating current excitation.

The field excitation is provided directly from the mains voltage (e.g. 50 or 60 Hz) or from a driver circuit in the transmitter. Due to the high inductance of the magnetic coils, the magnetic flux Φ lags to the excitation current I by almost 90°.

The measuring voltage U is in phase with Φ , i.e. it is a sinusoidal voltage at mains frequency whose amplitude is proportional to the flow rate. The various noise voltages are fed together with the signal voltages to the connected transmitter which must sort them out accordingly.

The DC noise voltages (polarization voltages) are capacitively decoupled. The AC noise voltages (transformer and capacitive voltages) are not in phase with the measuring voltage U . Their effects are automatically compensated using phase selective circuits.

Unfortunately, the amplitude or phase of the external AC noise voltages cannot be predicted. All components that are not in phase with the measuring voltage U are automatically compensated. Only the in-phase component affects the measuring signal, resulting in an unstable zero. This noise component is eliminated by static compensation of the measured values that exist at zero flow.

The zero adjustment can be automated when a defined zero flow occurs during the measurement. This is, for example, the case in filling processes. When the closed shut-off valve signals a "stand-still", the transmitter receives the command for zero correction. AC field excitation allows for a minimum conductivity of the measuring medium down to 20 $\mu\text{S}/\text{cm}$. This conductivity limit can be reduced to 0.5 $\mu\text{S}/\text{cm}$ with an impedance converter. Continued development of this technology has resulted in a driver circuit which will provide an excitation current at a frequency considerably higher than the normal line frequency of 50 or 60 Hz. Using this technology, mains frequency induced noise components can be automatically compensated and the zero stability is almost as accurate as when a pulsed DC excitation is used.

Signal Measurement

The discussions up to this point all assumed that the electrodes were galvanically connected to the measuring medium. This is the normal case. There are, however, special installation conditions where this is unsatisfactory, for example, extremely low conductivities or measuring media where deposits form an insulating coating in the flowmeter. This coating interrupts the signal circuit.

A smooth flow passage is formed by the outer surface of the standard electrode together with the inner surface of the liner. A degree of self cleaning for readily removable deposits can be achieved with pointed electrodes which extend into the higher velocity regions of the flow. For difficult applications, e.g. for thick grease layers, a mechanical cleaning through a clean out flange or a removal of the meter from the line is necessary.

This relatively large effort seldom assures satisfactory long term operation. It can only be achieved by using capacitive signal measurement.

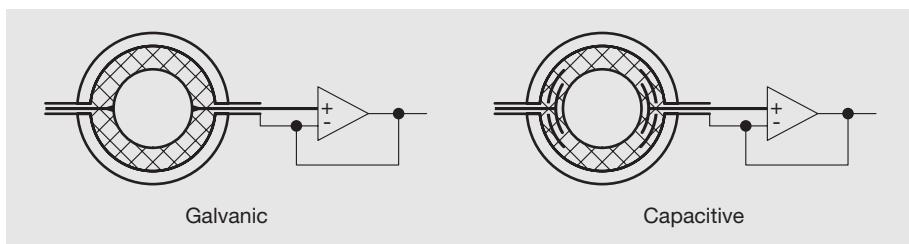


Fig. 2-81: Signal Measurement

Two metallic area electrodes are located behind the meter liner. They form two capacitors together with the process-wetted inner wall whose dielectric is the liner.

The signal generation occurs as previously described with a pulsed DC or an AC magnetic field. The generated voltage charges the capacitors so that on the outer side a proportional flow signal can be measured. Since the capacitance must be at least 20 pF, minimum area dimension limits exist which cannot be met by electromagnetic flowmeters with a nominal diameter below DN 25.

Shielding electrodes between the measuring electrode and the meter tube prevent a capacitive loss to the outside. The Driven-Shield technique eliminates the capacitance between the signal line and the shield. The signal voltage amplitude is coupled back to the shield so that the voltage differential between the conductor and the shield is zero.

The minimum conductivity which can be measured with capacitive electrodes is 0.05 $\mu\text{S}/\text{cm}$.

Flowmeter Sensor

The electromagnetic flowmeter consists of a sensor and a transmitter. Determining factors for the selection of the appropriate sensor are its material and the type of process connection. Inside the meter tube, the tube liner and the electrodes are in contact with the measuring medium. As a result, they must be made of materials that are chemically resistant to the measuring medium which, in some cases, may be extremely aggressive. The most commonly used liner materials are hard rubber, soft rubber, PTFE, PFA and ceramics; common electrode materials are stainless steel 1.4571, 1.4539, Hastelloy, tantalum and platinum.

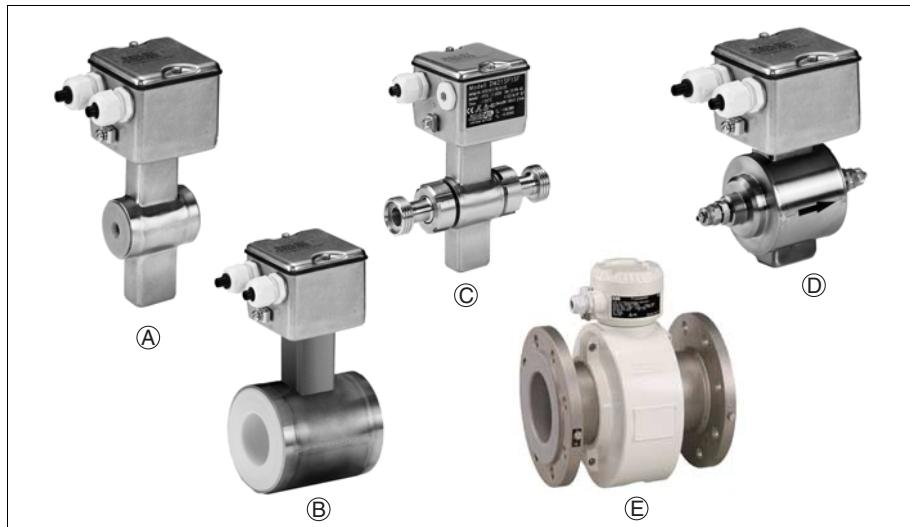


Fig. 2-82: Sensor Types for Electromagnetic Flowmeters

A + B Wafer type design

C Threaded pipe connection conforming to DIN 11851

D Sanitary design

E Flange design

A housing, meter tube and pipe connections form the exterior of the sensor. Here also the specific installation conditions, i.e. the ambient conditions, determine the material selection. For technical reasons and to ensure the appropriate physical properties the meter tube must be made of austenitic, i.e. stainless, steel. The pipe connections are generally steel or stainless steel while the housing is usually either painted cast aluminum or stainless steel.

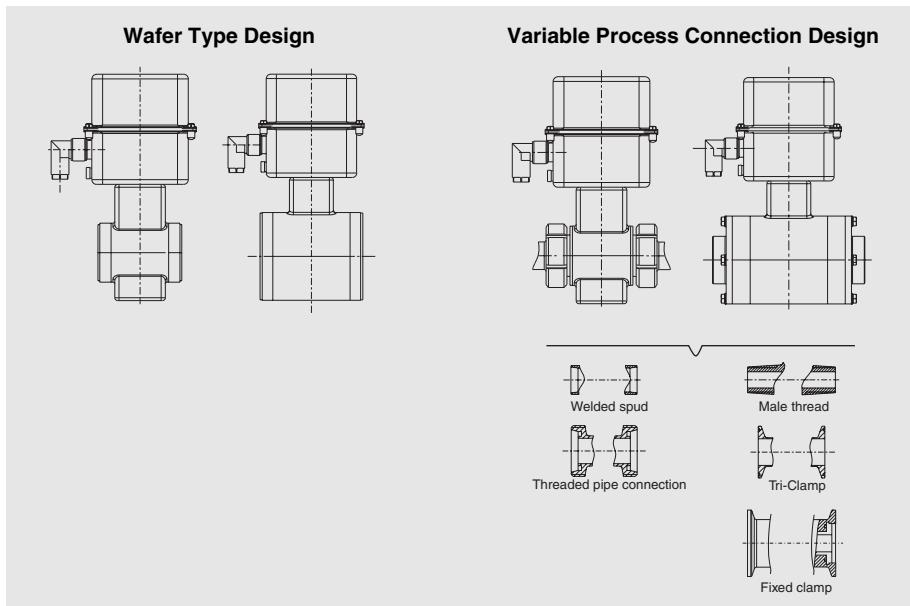


Fig. 2-83: Stainless Steel Sensor with Vacuum-Tight PFA Liner and Variable Process Connection

Magnetic Field Stabilization

According to equation (2.23) the signal voltage U_0 is proportional to three variables: the magnetic induction B , the diameter D and the flow velocity v . A direct proportionality to only one of the variables requires that the other two be constant. This means, if the voltage U_0 is to be proportional only to the flow velocity v , then the magnetic induction B and the diameter D must remain constant. While D , as a mechanical value, is constant, the magnetic induction B changes as a function of the excitation current I . The latter is maintained constant by monitoring a voltage U_{Ref} generated in the sensor/transmitter.

As a rule, electromagnetic flowmeters are flow calibrated, usually at an ambient temperature of approximately 20 °C. If the device is later used at other temperatures, the ohmic resistance of the coils changes and with it the excitation current I and the magnetic induction B , resulting in a changed signal voltage U_0 .

The excitation voltage, which influences the current, is line related and can also vary.

These effects can be prevented through utilization of constant current devices, a costly solution. A more elegant procedure is the compensation circuit.

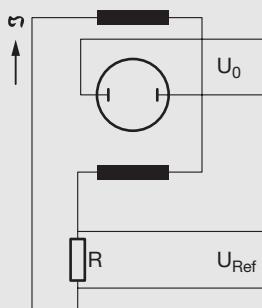


Fig. 2-84: Generation of a Compensation Voltage

Across a resistor R in the excitation circuit, a voltage drop U_{Ref} occurs which is proportional to the excitation current I and therefore the magnetic induction B. The voltage U_0 is also proportional to the induction B. When the ratio of these two variables U_0/U_{Ref} is calculated, the influence of the magnetic induction B is canceled. From the basic equations (2.23) and (2.24):

$$q_v = \frac{A}{D} \cdot \frac{U_0}{B} \quad (2.27)$$

and replacing B by U_{Ref} :

$$q_v = K \cdot \frac{U_0}{U_{\text{Ref}}} \quad (2.28)$$

This equation with K as the calibration factor forms the basis for the calibration of the electromagnetic flowmeters from ABB. For devices with pulsed DC excitation, the calibration factor K is replaced by the calibration factors C_z/S_z (zero) and C_s/S_s (span) for each excitation frequency. These values are stored in a memory module (EEPROM/FRAM) together with additional parameters, e.g. the nominal diameter, measuring range, pulse value and selected inputs and outputs.

The transmitter used continuously operates with these values and thereby controls the excitation current and the reference voltage. Thus the continuous monitoring of these values assures that the excitation current remains under control. Since the calibration values and parameter settings are stored digitally in an EEPROM/FRAM or SensorMemory, it is possible to exchange a transmitter for each an every sensor. The same transmitter electronics can be used universally for all nominal diameter ranges.

Transmitter

The task of the transmitter is to amplify the relatively small measuring voltages, free them from noise voltages and convert them to usable signals and indicate their values or provide them for further processing.



Fig. 2-85: Platform Concept, Universal Transmitters and Sensors

Different transmitter designs in conjunction with the sensor satisfy the specific requirements for a particular electromagnetic flow measurement system.

Transmitter FSM4000

This transmitter belongs to the AC field excited flowmeters with increased excitation frequency. Therefore after start-up a zero adjustment is rarely required. The measuring system has a system accuracy of $\pm 0.5\%$ of rate, similar to a pulsed DC device. The sensors incorporate expanded diagnostic functions with which the user can obtain additional information for a possible upcoming measurement system verification requirement. Communication using HART, PROFIBUS PA and FOUNDATION Fieldbus is possible.

Mounting the Transmitter

Based on the requirements of the user the arrangement of the electromagnetic flow measurement systems may vary. The different designs of the flowmeter sensor have already been described earlier in this publication. The transmitter variants are defined by the appropriate housing arrangements. There are two distinctly different mounting options: the remote mount design and the integral mount design.



Fig. 2-86: Remote-Mount Designs with Transmitter in a Wall Mount Housing

Transmitter ProcessMaster / HygienicMaster

The transmitter is provided with a local flow indicator and totalizer. The device is operated using the TTG (Through The Glass) technology with non-contact capacitive buttons. The local LCD display can be easily rotated as required to ensure readability in all mounting positions. The parameters related to the measuring point are automatically monitored and possible errors reported. In its basic version the transmitter provides a configurable current output (4...20 mA) and a pulse output (optoelectronic coupler, passive or active), switch inputs and outputs and an empty pipe detection function. The measured error is $\pm 0.4\%$ of rate. The communication is either via HART, PROFIBUS PA or FOUNDATION Fieldbus.

The integral mount design of the ProcessMaster or HygienicMaster unites the transmitter and sensor in a single housing in which local operating or display possibilities are available. The big advantage of this variant is the elimination of the interconnection cabling.



Fig. 2-87: ProcessMaster
Integral Mount Design



Fig. 2-88: HygienicMaster
Integral Mount Design

Online Diagnostic Functions Improve the Availability

In order to better support plant operators in error analysis, ProcessMaster and HygienicMaster are provided with a diagnostics package that indicates both process-related and device-related faults. The classification of the diagnostic notices is in accordance with Namur Recommendation NE107 (VDI/VDE Directive 2650). The four specified symbols represent the following status signals:

Symbol	Status Signal	Examples for Detail Information
	Failure	Device-related failure cause Process-related failure cause
	Function check	Configuration change Local operation Specify substitute value
	Out of specification	Device is operated out of specified range. Unsecure through ambient or process effects
	Maintenance required	Maintenance now required Maintenance soon required

Plain text messages provide detailed information about possible errors. Process errors like gas bubbles, empty pipes, partially filled pipes, electrode corrosion or electrode deposits are recognized. Moreover, the diagnostic tool delivers direct suggestions (instructions of action) to remedy the malfunction. All information can be read directly on site from the device's LCD display.

This data can also be uploaded into process control systems via HART or fieldbus communication and then processed using a Plant Access Management or Maintenance Software.

Verification of Built-In Devices

ScanMaster is a DTM-based verification tool for checking the functionality and integrity of the transmitters and sensors of built-in ProcessMaster or HygienicMaster flowmeters. Gradual changes like electrode deposits are logged by ProcessMaster or HygienicMaster 500 as trend data and can be read out and represented graphically by ScanMaster. The tool provides any easy method for cyclic verification of all measured values and of the functional reliability of the installed devices. The determined test and verification results are stored in a database and can be retrieved and printed as required.



Fig. 2-89: SanMaster FZC500 Diagnostic and Verification Software

FXL5000 (Miniflow) – For Simple Flow Measurements

The electromagnetic flowmeter FXL5000 (Miniflow) is an alternative to the flowmeters described so far. It has been designed specifically for simple flow measurements which have no special requirements.

The nominal diameter range extends from DN 10 ($\frac{1}{2}$ " threaded connections) up to DN 50 (2" threaded connections). The transmitter is mounted directly on the flowmeter sensor. The complete unit is very compact, has low weight and can be quickly installed in the piping using the threaded connections. The electrical connection is realized by using connector plugs. In addition to the two-line LCD display, which indicates the current flow rate and the total flow value, the device incorporates a flow rate proportional 20 mA output and a pulse output. The flowmeter can be configured using the clear text display in conjunction with the foil keypad.



Fig. 2-90: FXL5000 (Miniflow)

FES7000 (Fill-MAG) – For Filling and Dosing Applications

Exact filling and dosing with high reproducibility often presents difficulties in conjunction with small but also with very large containers. These problems have been addressed and solved by ABB with an electromagnetic flowmeter based solution: FES7000 (Fill-MAG) and FXF2000 (COPA-XF).

Depending on the individual application requirements (measuring medium, fill and dosing time, boundary conditions, etc.) it is also possible to use mass, vortex and swirl flowmeters for batch processes. The control technology for mass flowmeters offers the same comfort as an FES7000 system (for more detailed information about these devices see the corresponding device descriptions).

The FES7000 provides a very compact and intelligent electromagnetic flowmeter system whose major features are a fast response time and specialized software adapted to batch and fill processes coupled with an ability to CIP/SIP clean the abrasion resistant sensor. This specialized software allows for filling and dosing processes with measurement periods ≥ 500 ms and assures a reproducibility of $\leq 0.2\%$ of rate. In a fill system the automatic measurement and correction of the second stage flow, which is a function of the valve characteristics, is of great importance. Good and reproducible measurement results can only be achieved with systems such as the FES7000, which can compensate for these effects and is suitable for a variety of diverse boundary conditions.

Flowmeter Technology

The FES7000 is a system with remote mount design. The transmitter is available as a 19" plug-in unit and in a field housing. The process connection options for the stainless steel flowmeter sensor include all the usual commercially available connections. Customer-specific design variants are also possible.

The FES7000 system operates with defined input and output contacts (Fig. 2-91). Four different fill and preset volumes can be set directly at the transmitter or selected by an external fill volume selector switch or from a PC, PLC or distributed control system.

The fill cycle is initiated by a start signal which opens the valve. After the anticipatory or end contact volumes have been reached the transmitter directly controls the fill valve. Up to 32 transmitters can be connected using the RS 485 interface and configured via an operator station, PLC or transmitter dialog unit. The connection of additional components such as control loops, control elements (weigh scale) as well as printers is possible.

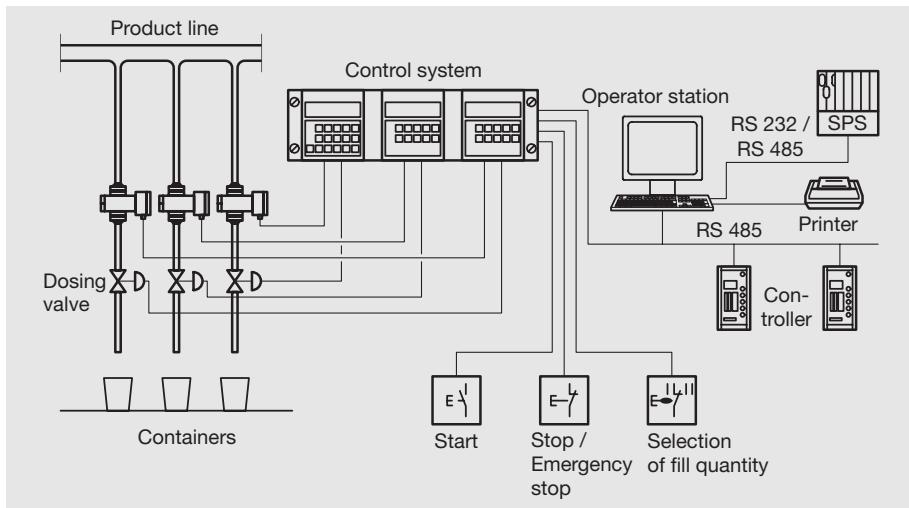


Fig. 2-91: Schematic of a Fill System with Supervisory Recipe Control
And Integration in a Distributed Control System

Special features of the FES7000 system include:

- Suitable for fast as well as continuous fill and batch processes from the smallest amounts to large containers.
- Nominal diameters from DN 1 to DN 100.
- Accurate, reproducible fill cycles reducing the amount of safety overfill quantities.
- Monitoring the adherence to the user programmable overfill and underfill limits after each fill operation.
- Automatic emergency shutoff if the maximum fill time is exceeded or an error is detected by the system monitor in the transmitter.

Single and Two Stage Fill Cycles

To achieve a high degree of reproducibility of the fill or dosing cycles, in addition to the flowmeter, components such as valves, good level and pressure control as well as the system concept are of critical importance.

One of the most important factors is the quality of the fill valve (fast response time, reproducible closing characteristics). The second stage flow occurs during the closing cycle of the valve based on the valve closing time. This flow quantity is measured by the flowmeter and a correction made by a specially developed algorithm in the transmitter to assure that the desired fill quantity has been reached when the valve, whose closing cycle is initiated by an end contact signal from the transmitter, is finally closed.

The second stage flow measurement is used to adjust the end contact activation for the following fill cycle. In this manner continuously changing second stage quantities are recognized and automatically corrected in comparison to fill systems which use a pre-set totalizer value to correct for the second stage flow. The control of the second stage flow is ultimately decisive for the reproducibility of the fills. Use of an anticipatory contact (two stage fill cycle, Fig. 2-92) which reduces the flowrate prior to the valve closure decreases the second stage quantity and thereby increases the reproducibility. A prerequisite is a very similar fill curve, which is a function of the valve, the upstream pressure, the system concept and lastly of the product itself.

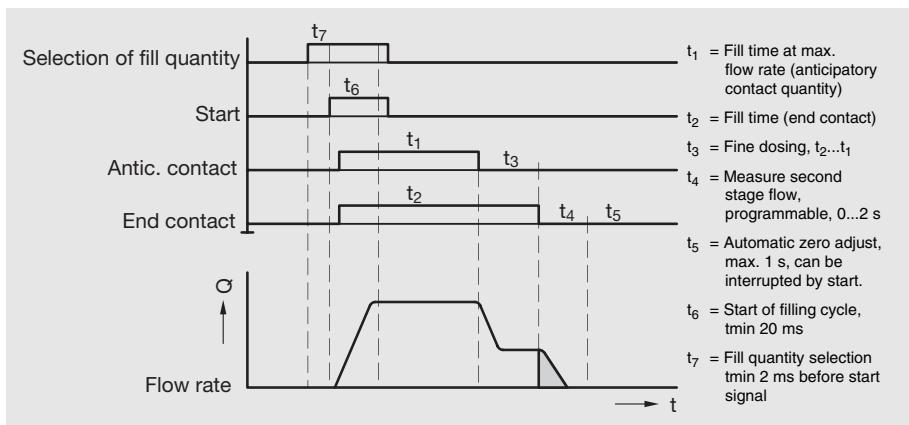


Fig. 2-92: Two Stage Fill Cycle

For very short fill and dosing times (approx. 3. seconds) it is recommended that the valve be controlled directly by the end contact (single stage fill cycle, Fig. 2-93). Anticipatory and end contacts are user programmable.

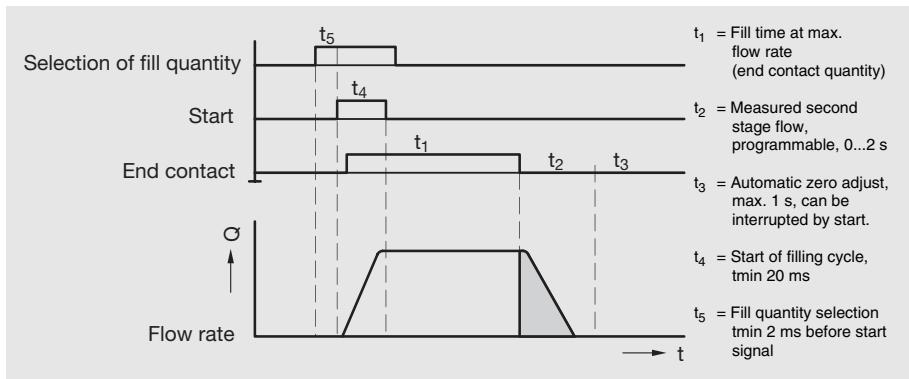


Fig. 2-93: Single Stage Fill Cycle

Official Calibration

The measuring system has been approved by the PTB (Physikalisch-Technische Bundesanstalt, the German National Institute of Technology) for official calibration. Approvals for a variety of measuring media have been granted. Specialized application areas for this electromagnetic flowmeter type are KEG-filling (of reusable barrels), as well as the measurement of chemical products. Regular recording of the process fill cycles, centralized data acquisition and recording parameter settings for a certification report are possible. Depending on the printer protocol selected, various data sets can be printed and used for statistical analysis.

The above-described FES7000 system offers a number of possibilities for automating a wide variety of processes. Fast amortization of the investments by reducing the actual fill quantity due to a reduction of the safety overfills and thereby the product cost, improvement of the product quality, increase in productivity and profit optimization plus reduction of the operating, maintenance and service costs.

Electromagnetic flowmeters additionally provide convincing advantages over the existing mechanical fill and dosing systems using fill pistons or pumps, intermediate or prefill containers, rotary vane or turbine flowmeters and weighing systems.

Advantages include:

- Wear-free system requiring low maintenance.
- CIP/SIP capability of the flowmeter reducing the cleaning and sterilization time.
- Shortest fill times for a variety of fill quantities possible because of the wide range span.
- Higher product output through optimal utilization of the system, because suction phase and tare determination required by mechanical systems are eliminated.
- Communication possible with the measurement system including integrated statistical functions.

FXF2000 (COPA-XF) – For Simple Filling and Dosing Applications

This flowmeter with integral mount design is an all stainless steel device. Due its small dimensions it is ideal for cluster mounting in round and series filling machines. It is also suitable for continuous flow measurement, when only a pulse or current output is required and display is not required for indication. The reproducibility of the device is 0.2 % of rate for fill cycles longer than 2...4 seconds.

The flowmeter is available with nominal diameters from DN 3 to DN 100. All the usual commercial process connections are available. Customer-specific connection variants are also possible. For harsh operating conditions the FXF2000 includes an instrument air connection for creating a protective air stream. The device is also available in a tropicalized design with coated circuit boards.

The FXF2000 incorporates three different operating modes. In addition to the “Batch” operating mode for fill and dosing processes with a function as flow rate proportional sensor and a pulse output, the “Conti” operating mode for continuous measurement with an additional 0/4...20 mA current output is available. The “Filler” operating mode includes the function as a stand-alone fill system and is mainly based on the FES7000 technology described above.

As the FXF2000 basic functions just include a pure flowmeter functionality with frequency or current output and a standardized pulse output, additional hardware and software are required for realizing fill and dosing processes. Value-loaded pulses must be totalized and processed using a presetting counter, PC, PLC or DCS.

Fill quantity preselection, utilization of single or two stage fill system, start/stop function, second stage flow measurement and correction, control and/or monitoring functions as well as valve actuation are all functions which must be carried out by other evaluation electronics connected to the flow rate sensor. These electronics or software have a tremendous effect on the quality of a fill and dosing system and the reproducibility of the fill processes. Fig. 2-96 shows a schematic of such a filling system.



Fig. 2-94: Flowmeter FXF2000 (COPA-XF)



Fig. 2-95: Flowmeter FXF2000 (COPA-XF) with Integral Mount Design and Communication Capabilities

Decisive for the development of such a device were the market demands for an economical, small and effective compact electromagnetic flowmeter in an integral mount stainless steel design for multivalve fillers with up to 168 fill valves.

Due to the impressive number of fill valves per system and the possibility to develop and configure the required software in-house, this system concept became interesting from technical and economic viewpoints.

One time developed software together with know-how can be transferred to many other systems. Each system type can utilize the economical standard flowmeters, but is provided with individually adapted software with different user interfaces and system-specific components.

Since central computers already exist for other control tasks of the fill machine, they can also be used for the signal processing, fill quantity presetting and required corrections as well as the valve control functions.

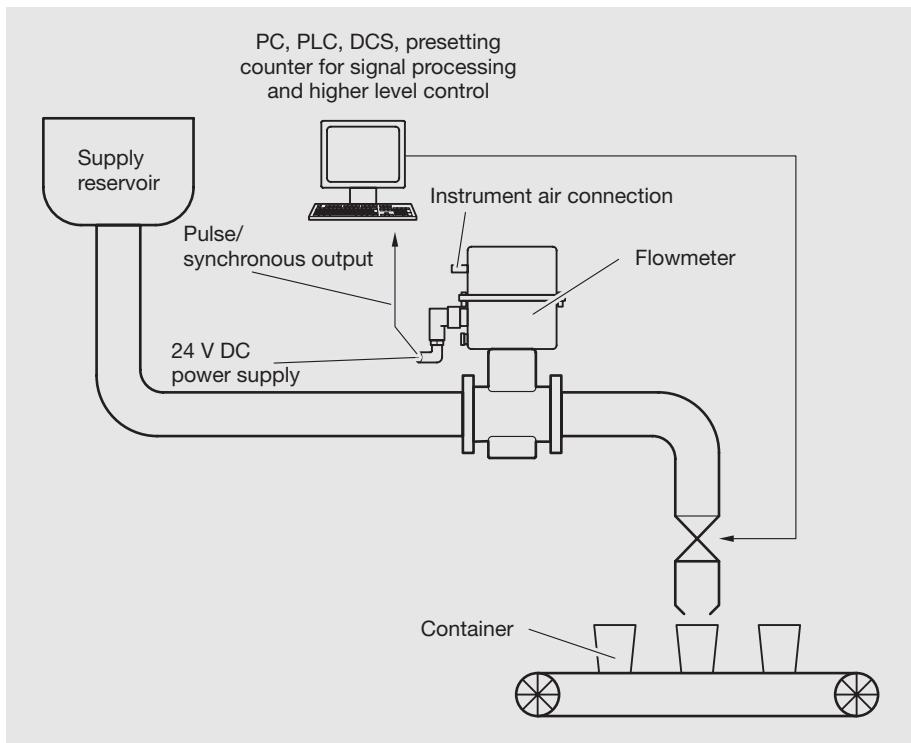


Fig. 2-96: Schematic of a Fill System with the Electromagnetic Flowmeter FXF2000 (COPA-XF)

Communication Capabilities

For the configuration and control of the device two possibilities are available. If the device requires service, a transmitter control unit with display can be plugged on.

If parameter changes for the process or information about the present status of the process is required the RS 485 interface can be used.

The ASCII Protocol allows for communication with a distributed control system, a programmable logic controller or a PC with the required individual software. The connection is made using a separate communication plug.

A complete solution including the monitoring of the flowmeter and parameter setting without the need to open the housing is provided by a dialog unit with integral display.

This new generation of volumetric operating fill machines with electromagnetic flow measurements instead of fill systems with intermediate or preset fill containers (limitations for fluid varieties and fill time) or weigh systems, takes advantage of the many benefits which an electromagnetic flow measurement system offers. The CIP/SIP-cleanability, wear free and low maintenance technology, viscosity insensitivity coupled with the wide span of the electromagnetic flowmeter with a simple and fast change over to other fill quantities results in quality improvements, product savings by reducing overfills, productivity improvement and cost reductions.

Sizing of Electromagnetic Flowmeters

The user provides the nominal diameter of the flowmeter sensor and the existing piping. A check calculation using the current flow rate should however be made which should indicate the same size. Otherwise, the piping size must be adjusted.

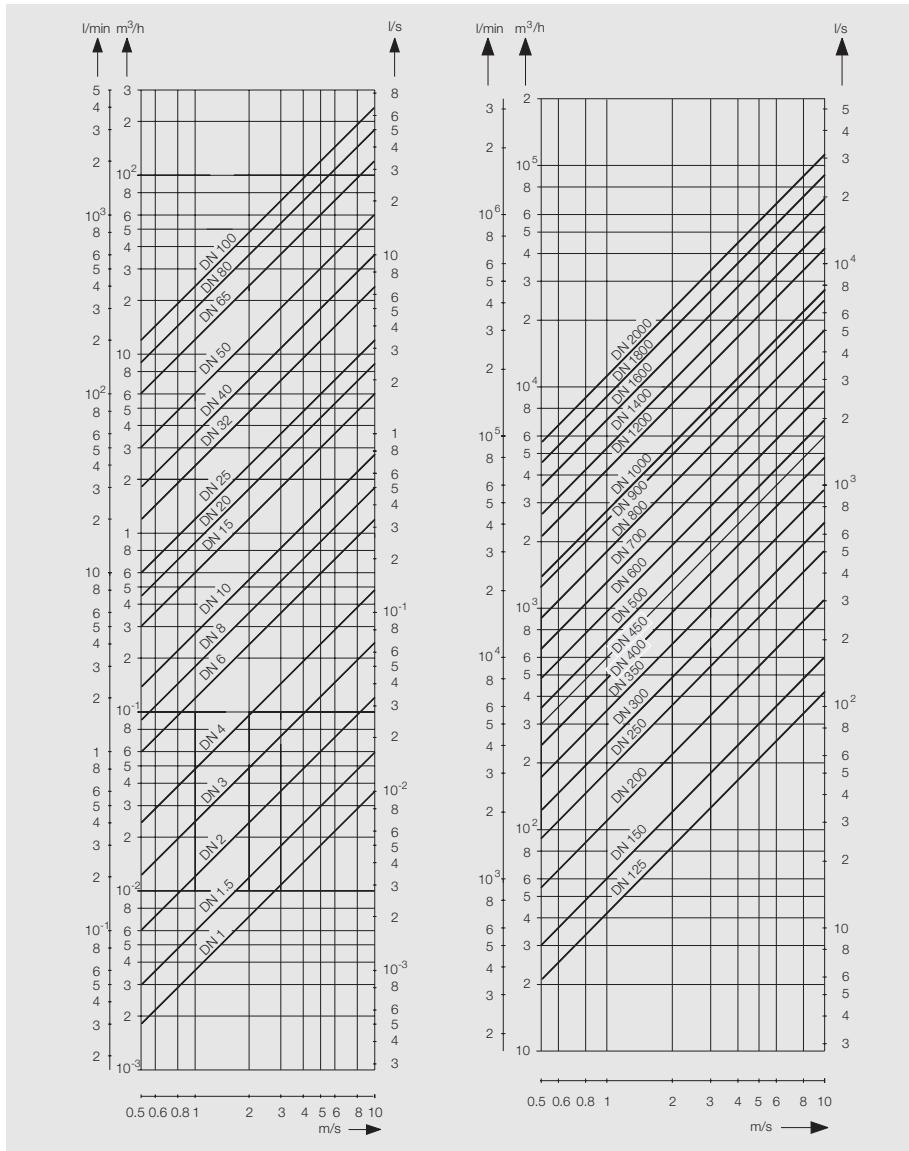


Fig. 2-97: Flow Rates as a Function of the Nominal Diameter

The basis for the calculation is the flow velocity as a standard size independent of the nominal diameter.

A few examples from actual situations (the values refer to upper range value):

Slurries, pulps, pastes	0.5...1 m/s
Liquid food stuff	1...2 m/s
Liquids in chemical processes	1...3 m/s
Potable water	3...6 m/s
Water to transport solids up to	15 m/s

Using the nomograph Fig. 2-97 the desired flowmeter size can be determined. When the values in the nomograph are used to determine the pipe size, differences between the calculated value and the actual pipe diameter may exist. This is due to the differing liner thicknesses and is compensated for during the calibration.

Occasionally, differences exist between the calculated pipe size and the nominal diameter of the flowmeter, with the size of the electromagnetic flowmeter usually the smaller. A transition using conical sections is possible when cone angles are less than 8° .

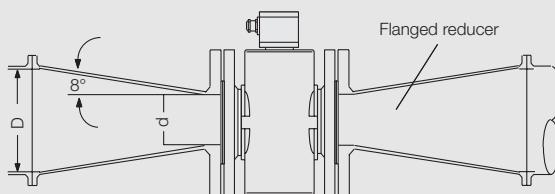


Fig. 2-98: Reduction at the Measuring Point

The pressure drop resulting from the 8° reduction can be calculated using the nomograph Fig. 2-99. For this the diameter ratio d/D must be calculated and the curve for the current flow velocity v selected from the family of curves. The pressure drop Δp can be read at the intersection between these two values.

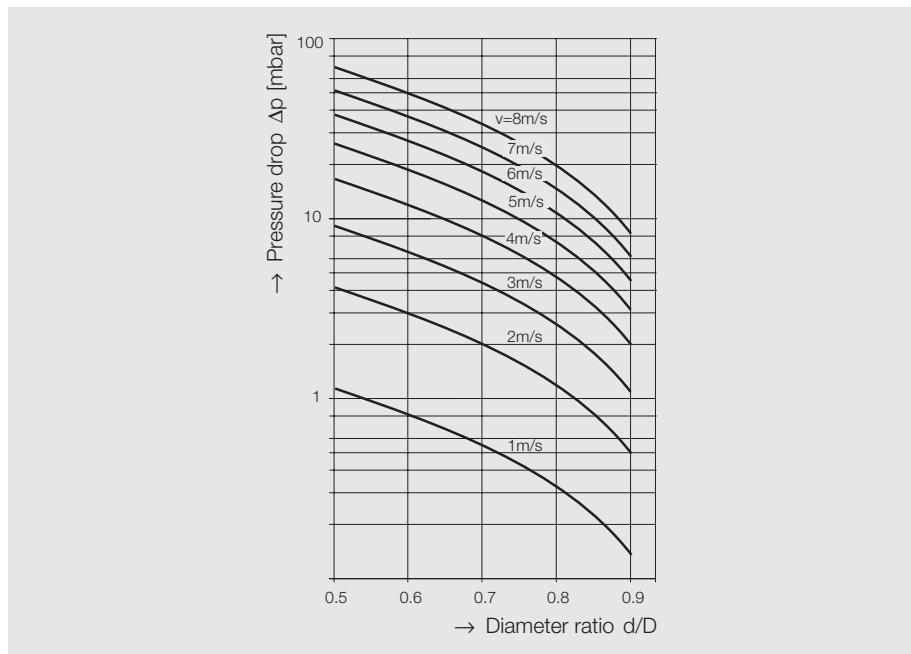


Fig. 2-99: Pressure Drop with Pipe Restriction

Specifications

Signal Measurement	Galvanic					
Magn. Field Excit.	With Pulsed DC Excitation					
Model	ProcessMaster FEP300/500 HygienicMaster FEH300/500				FXF2000 (COPA-XF)	
Liner material	DN	PN			DN	PN
Hard rubber	15...2000	10...100	Cl150...Cl600			
Soft rubber	50...2000	10...40	CL150/CL300			
Ceramic carbide	25...1000	10...40	CL150/CL300			
PTFE	10...600	10...40	CL150/CL300			
ETFE	25...1000	10...40	CL150/CL300			
PFA	3...200	10...40	CL150/CL300		3...100	10...40
Peek	1...2	10				
Electrode material	Stainl. steel 1.4571 or 1.4539, Hastelloy C4 or B2, titanium, tantalum, platinum-iridium					
Excitation frequency	6 1/4 Hz, 12 1/2 Hz or 25 Hz			12.5/25 Hz		
Min. conductivity	5 µS/cm					
Max. poss. pressure rating	PN 100/Cl600 and higher			PN 40/Cl300		
Max. poss. temperature	180 °C			130 °C (150 °C)		
Electrode design	Standard electrode, pointed electrode					
Process connection	Flange	DN 3...2000		Wafer Des.	DN 3...100	
	Wafer design	DN 3...100		Weld st.	DN 3...100	
	Welded spud	DN 3...100		Thr. pipe conn.	DN 3...100	
	Threaded pipe conn.	DN 3...100		Tri-Clamp	DN 3...100	
	Tri-Clamp	DN 3...100		Fixed clamp	DN 10...40	
	Male thread	DN 3...25		Male thread	DN 3...25	
	1/8" sanitary conn.	DN 1...2				
Upper range value	0.5...20 m/s			0.5...10 m/s		
Max. meas. error	FEP300/FEH300: 0.4 % of rate opt. 0.2 % of rate FEP500/FEH500: 0.3 % of rate opt. 0.2 % of rate			0.5...10 m/s 0.5 % of rate Reproducibility ≤ 0.2 % of rate		
Current output	4...20 mA, 4...12...20 mA selectable			0...5 mA, 0/2...10 mA, 0/4...20 mA, 0...10...20 mA, 4...12...20 mA selectable		
Load	0...600 Ω			0...600 Ω		
Pulse output	Passive, active			Passive, active		
Pulse width	Selectable from 0.1 ms...2000 ms			Selectable from 0.1 ms...2000 ms		
Supply power	Switch-mode power supply 85...253 V AC 16.8...26.4 V AC 16.8...31.2 V DC			16.8...31.2 V DC		

Tab. 2-5: Overview of Flowmeter Sensor and Transmitter Designs

Signal Measurement	Galvanic	
Magn. Field Excit.	With Pulsed DC Excitation	
Model	ProcessMaster FEP300/500 HygienicMaster FEH300/500	FXF2000 (COPA-XF)
Autom. empty pipe detection	yes \geq DN 10 (TFE \geq DN 25)	yes \geq DN 10
Max./min. alarm	yes	Operating modes <ul style="list-style-type: none"> • Continuous • Batch • Filler
2 meas. ranges	yes (FEP500/FEH500)	
Presetting totalizer	yes (FEP500/FEH500)	
Expanded diagnostic functions	yes (FEP500/FEH500) <ul style="list-style-type: none"> • Electrode deposit detection • Gas bubble detection • Conductivity monitoring • Sensor temperature monitoring • Trend analysis 	–

Tab. 2-6: Continued: Overview of Flowmeter Sensor and Transmitter Designs

Specifications

Signal Measurement	Galvanic				
Magn. Field Excit.	With AC Field Excitation				
Model	FES7000 (Fill-MAG)			FSM4000	
Liner material	DN	PN	DN	PN	
Hard rubber			15...2000	10...100	Cl150...Cl600
Soft rubber			50...2000	10...40	Cl150/Cl300
Ceramic carbide			25...1000	10...40	CL150/CL300
ETFE			10...600	10...40	Cl150/Cl300
PTFE			25...1000	10...40	CL150/CL300
PFA	3...100	10...40	Cl150/Cl300	3...200	10...40
Peek	1...2	10		1...2	10
Torlon	1...2	10		1...2	10
Electrode material	Stainl. steel 1.4571 or 1.4539, Hastelloy C4 or B2, titanium, tantalum, platinum-iridium				
Excitation frequency	50/60 Hz AC		50/60/70 Hz AC		
Min. conductivity	20 $\mu\text{S}/\text{cm}$, optional: 5 $\mu\text{S}/\text{cm}$ or 0.5 $\mu\text{S}/\text{cm}$				
Max. poss. pressure rating	PN 40		PN 100/Cl600 and higher		
Max. poss. temperature	130 °C (150 °C)		180 °C		
Electrode design	Standard electrode, pointed electrode			Standard electrode, pointed electrode Swedish design	
Process connection	Wafer design	DN 3...100	Flange	DN 3...1000	
	Welded spud	DN 3...100	Wafer design	DN 3...100	
	Thr. pipe conn.	DN 3...100	Welded spud	DN 3...100	
	Tri-Clamp	DN 3...100	Threaded pipe conn.	DN 3...100	
	Fixed clamp	DN 10...40	Tri-Clamp	DN 3...100	
	Male thread	DN 3...25	Male thread	DN 3...25	
			1/8" sanitary conn.	DN 1...2	
Upper range value	0.5...10 m/s		0.5...10 m/s		
Max. meas. error	1 % of rate Reproducibility \leq 0.2 % of rate		0.5 % of rate Reproducibility \leq 0.2 % of rate		
Current output	–		0/4...20 mA; 0/2...10 mA		
Load	–		0...600 Ω		
Pulse output	Passive (10 kHz)		Active, passive		
Supply power	24, 115, 230 V AC 50/60 Hz		Switch-mode power supply 85...253 V AC 16.8...26.4 V AC 16.8...31.2 V DC		
Autom. empty pipe detection	yes \geq DN 10 (except for impedance converter)				
Max./min. alarm	no		yes		

Tab. 2-7: Overview of Flowmeter Sensor and Transmitter Designs

WaterMaster – For Water Applications

WaterMaster provides the flexibility to solve your most demanding water applications, enabling previously unattainable operational and financial benefits. WaterMaster is the ultimate solution for flow measurement and management in sectors as diverse as water, wastewater, sewage and effluent. Innovative and versatile attributes allow to achieve interoperability within a wide range of asset management systems. WaterMaster delivers speed, simplicity and ease of use.

Advanced Sensor Design

The WaterMaster range is available in sizes DN 10 to DN 2400 (3/8 to 94 inch). An innovative octagonal sensor design improves the flow profile and reduces upstream and downstream piping requirements for the most commonly installed sizes DN 40 to DN 200. Flowmeters with traditional sensor designs are used for sizes over DN 2000. Using a higher excitation frequency combined with advanced filtering, WaterMaster improves measurement accuracy by reducing liquid and electrode noise.

Submersible and Buriable Installation Options

All WaterMaster sensors have a rugged, robust construction to ensure a long, maintenance-free life under the most difficult conditions experienced in the water and waste water industries. The sensors are, as standard, inherently submersible (IP68, NEMA 6P), thus ensuring suitability for installation in chambers and metering pits which are liable to flooding. A unique feature of the WaterMaster sensors (DN 500 to DN 2400) is that they are buriable. Installation merely involves excavating to the underground pipe, fitting the sensor, cabling to the transmitter and then backfilling the hole.



Fig. 2-100: Electromagnetic Flowmeter WaterMaster

Custody Transfer

WaterMaster has an MID/OIML R49 Approval for Accuracy Classes 1 and 2 for pipings with any mounting position and bidirectional flow. A water meter with MID approval is suitable for billing applications. It provides a high measuring accuracy and reliable measured values.

Self-Calibration

A unique self-calibration concept developed by ABB (patent pending) has been implemented in WaterMaster. Compliance with OIML R49 Type P (Permanent) checking requirements requires that electromagnetic flowmeters have 'Checking Facilities', where a simulated signal is fed into the input of the flow transmitter and the output is compared and checked within predetermined limits. ABB's WaterMaster has taken this to the next level. It uses this signal to not only check the accuracy, but also to perform automatic calibration. This not only meets and exceeds the OIML R49 requirements, it also means the device has the following features:

- Self-calibrating device.
- No factory calibration necessary.
- Calibration adjustment is continuous during normal running.
- Exceptional long-term stability.
- Very low temperature coefficient.
- Measurement accuracy depends on one precision resistor only.
- Adjustment % displayed to user for diagnostic use.
- Alarm limits to trap hardware failures and out-of-range adjustments

VeriMaster Insitu Verification Software

WaterMaster can be expanded with the VeriMaster software for insitu verification. VeriMaster is a PC application. When the PC is coupled to the WaterMaster through the infrared service port, it generates a report on the accuracy of the complete flowmeter, both sensor and transmitter. This technology builds on over 10 years of ABB's experience in the field of insitu verification, through its leading CalMaster range. VeriMaster is a quick and easy to use utility, that uses the advanced self-calibration and diagnostic capability of WaterMaster, coupled with fingerprinting technology. This allows to determine the accuracy status of the WaterMaster flowmeter to within +/- 1 % of its original factory calibration. VeriMaster also supports printing of calibration verification records for regulatory compliance.

VeriMaster integrates with WaterMaster seamlessly, meaning:

- No interruption to any of the wiring.
- No cover removal, with operation through the front glass using the infrared service port.
- No interruption to the measurement.

If desired, an operator can additionally check and record the accuracy of the current and pulse outputs.

Improved Results through Digital Signal Processing

Digital Signal Processing (DSP) gives improved performance and enables real time measurements for maximum reliability. DSP allows the transmitter to separate the real signal from the noise, thereby providing high quality outputs especially in harsh environments involving vibration, hydraulic noise and temperature fluctuation.

Speed, Ease and Security in the Field

Data storage in the WaterMaster using the “SensorMemory” principle eliminates the need to match sensor and transmitter in the field. On initial installation, the self-configuration sequence automatically replicates into the transmitter all calibration factors, nominal diameter and serial numbers as well as customer site specific settings. This eliminates the opportunity for errors and leads to increased speed of start-up. Redundant storage of data in both the sensor and transmitter memory is continually updated during all operations to ensure total integrity of the measurement. The on-board “SensorMemory” eliminates the possible problems associated with pluggable data memory modules. Easy access to wiring also minimizes the time for problem solving in the field.

Detailed Diagnostics for Rapid Decision Making

WaterMaster is proven to be robust and reliable, with unmatched diagnostic capabilities providing the right information to keep the process up and running. In accordance with NAMUR NE107, alarms and warnings are classified as “maintenance required”, “function check”, “failure” and “outside of specification”.

AquaProbe – The Insertion Flowmeter

AquaProbe insertion flowmeters are used for clean water flow measurement. Compatible with ABB's AquaMaster 3 and WaterMaster transmitters, the latest generation AquaProbe opens up new possibilities for both temporary and permanent installations. Supply options like battery, solar or wind power also makes AquaProbe ideal for use in challenging locations.

AquaProbe can be fitted without interruption to the flow, even when the piping is under pressure. Contrary to full-bore electromagnetic flowmeters, the AquaProbe's magnetic field does not reside in the entire pipe cross-section. The flow velocity is only measured at a representative point of the pipe section and then the flow rate is calculated from this in the transmitter. The accuracy of 2 % of rate is also assured for low flows. With this, AquaProbe is also suited for leakage monitoring in drinking water networks.

The $\frac{1}{2}$ " connector on the sensor permits to connect a pressure transmitter to the AquaProbe, to provide pressure measurement capabilities in addition to flow measurement. In drinking water networks these two measured values (pressure and flow rate) allow to draw conclusions regarding the degree of incrustations/deposits in the piping. This is especially important for fire extinguishing pipe systems where incrustations or deposits may affect the water throughput and, thus, cause danger in the event of a fire.



Fig. 2-101: AquaProbe system for permanent or temporary installations

2.2.7 Ultrasonic Flowmeters

The **sound velocity** c which is a material property value is the propagation velocity of a sound wave in a medium. It changes with the density of the measuring medium. Therefore it is temperature dependent in liquids and pressure and temperature dependent in gases. When a sound impulse is transmitted from location A it arrives at a second location B with the velocity of sound at time:

$$t = \frac{l}{c}$$

The time changes when the sound carrier is also in motion, in fact, it is the sum of the sound velocity in the measuring medium and the measuring medium velocity. This effect is utilized in an ultrasonic flowmeter.

There are two basic methods for ultrasonic flow measurements:

1. Transit time method
2. Doppler method

Transit Time Method

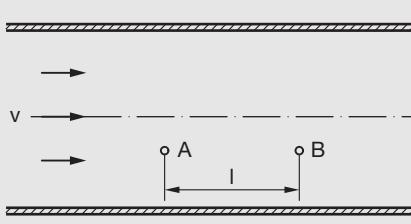


Fig. 2-102: Sound Path in a Liquid Flow

A sound impulse transmitted from a fixed point A travels with a velocity $c + v$ and arrives at point B after a time interval t_1 :

$$t_1 = \frac{l}{c + v} \quad (2.29a)$$

The time required for an impulse to travel from B to A is t_2 :

$$t_2 = \frac{l}{c - v} \quad (2.29b)$$

Since the measurement of t_2 is made immediately after t_1 it is assumed that during this time interval the sound velocity c in the fluid is constant. Then from

$$c = \frac{l}{t_1} - v \quad c = \frac{l}{t_2} + v$$

the flow velocity in the measuring medium can be extracted using

$$v = \frac{1}{2} \left(\frac{1}{t_1} - \frac{1}{t_2} \right) \quad (2.30)$$

This measurement value is independent of the sound velocity, the pressure, the temperature and the density of the measuring medium.

In a practical meter design a sound impulse is sent diagonally across the meter tube. Then the flow velocity of the measuring medium becomes

$$v = \frac{l}{2 \cdot \cos \alpha} \left(\frac{1}{t_1} - \frac{1}{t_2} \right)$$

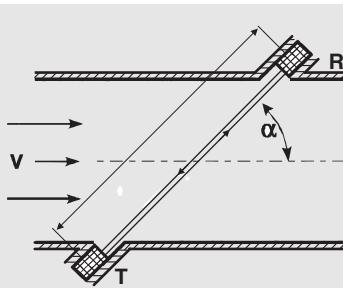


Fig. 2-103: Schematic of Transit Time: R = Receiver, T = Transmitter

An essential requirement for the transit time measurement is the acoustic transparency of the measuring medium. There should be few solid particles or gas bubbles in the measuring medium.

Doppler Method

For ultrasonic flow rate measurements using the Doppler effect there must be inhomogeneities or impurities (dispersers) in the measuring medium so that a portion of the sound energy can be reflected.

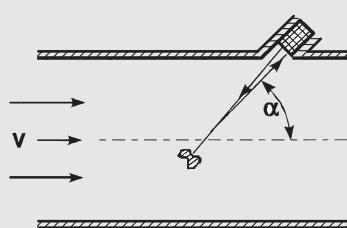


Fig. 2-104: Schematic of the Doppler Principle

The sound wave with a transmitter frequency f_1 impinges on a particle in the measuring medium (solid particle or gas bubble) and is reflected. Therefore every particle acts as a moving transmitter with the transmitter frequency f_1 . The frequency shift Δf of the reflected signal received is a function of the flow and sound velocities:

$$\Delta f = 2 \cdot f_0 \cos(\alpha) \cdot \frac{v}{c}$$

Since the sound velocity is a function of the temperature, pressure and composition of the measuring medium, even small changes in these variables affect the Doppler shift and an appropriate compensation must be provided. The solution is to include a defined inlet section for the ultrasound, e.g. a sound path made of resin, in which a Piezo transmitter is cast.

Applying the refractive equation of Snellius

$$\frac{\cos(\alpha)}{c} = \frac{\cos(\beta)}{c_v}$$

from which

$$\Delta f = 2 \cdot f_0 \cos(\beta) \cdot \frac{v}{c}$$

and therefore

$$v = \frac{c_v}{2 \cdot f_0 \cdot \cos(\beta)} \cdot \Delta f = \text{constant} \cdot \Delta f$$

The factor $c_v/\cos(\beta)$ can be determined. The Doppler shift is therefore essentially independent of the sound velocity in the measuring medium. Only sound velocity changes in the acoustic inlet section change the Doppler frequency. This change can be determined beforehand and compensated.

Limitations of Ultrasonic Flow Measurement

For the ultrasonic flow measurement the flow velocity is measured within the narrow band of the sound beam. The calculated flow rate through the entire pipe cross-section is only valid for axisymmetric flow profiles. In order to assure that these conditions exist, inlet sections with a length of up to $15 \times D$ and outlet sections of up to $10 \times D$ are required. It is possible to reduce the effects of nonsymmetrical flow by using two or more sound beams for additional profile samples.

Installation

Ultrasonic flowmeters are available in two variants. There are inline systems and clamp-on systems. In the inline design the ultrasonic transducers are mounted rigidly in the pipe wall and are directly or indirectly in contact with the measuring medium. These measuring systems can be calibrated and achieve a measuring accuracy of $\pm 0.5\%$ of rate and better.

Different is the clamp-on technology. The ultrasonic transducers are mounted on the outside of the piping. The sound pulse must traverse the pipe wall and any coatings which may be present with differing sound velocities twice. During installation the laws of refraction and reflection must be considered. Although the determination of the flow velocity is straightforward, the exact pipe geometry must be known if conversion to a volume flow information is desired.

These measuring systems can only be dry calibrated and achieve an accuracy better than $\pm 2.0\%$ of rate. If an on-site calibration can be conducted then accuracies up to $\pm 0.5\%$ of rate are possible.

Specifications	
Nominal diameter	DN 25...DN 3000 above DN 600 clamp-on systems are preferred.
Flow velocity	1...10 m/s
Measuring accuracy	+ 0.5 % of rate for inline systems + 2.0 % of rate for clamp-on systems
Max. measuring medium temperature	-40 °C...260 °C with special designs up to 500 °C and higher

2.2.8 Coriolis Mass Flowmeters

Measuring Principle

For cost and material balance calculations mass flow information is preferred in technical processes because it is independent of physical influences when compared to volume flow information. Pressure, density, temperature and viscosity do not change the mass. Therefore, the mass flow rate is the favored measuring variable. Mass can only be measured indirectly, e.g. with the help of Newton's second law which states that force times acceleration equals mass. When weighing the acceleration is due to gravity and this law is applicable.

How can the mass of a liquid be determined using this relationship? One must accelerate the liquid in a rotating system and measure the inertia effects. A physical effect named after the French mathematician Coriolis is utilized.

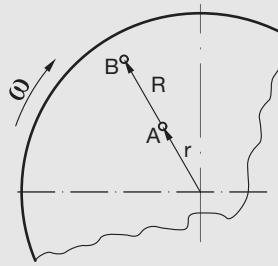


Fig. 2-105: Rotating Disk

A mass m is located at point A at an average distance r from the center on a rotating disk with an angular velocity ω which is to be moved radially towards B at a radius R , that is to a location with a higher torque and a higher energy content.

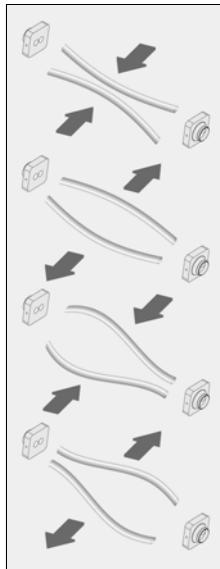
If no energy is added to the system the mass will not arrive at point B or a different variable is changed, namely ω . The inertia force which opposes the change is the Coriolis force F_c :

$$\vec{F}_c = -2 m (\vec{\omega} \times \vec{v}) \quad (2.35)$$

v is the velocity of the mass on the way from A to B. These principles are transferred to a liquid filled pipe.

Measuring principle: When a mass flows through a vibrating pipe Coriolis forces exist which bend or twist the pipe. These very small meter tube distortions are measured by optimally located sensors and evaluated electronically. Since the measured phase shift between the sensor signals is proportional to the mass flow rate, the mass flow rate through the Coriolis mass flowmeter can be determined directly.

This measuring principle is independent of density, temperature, viscosity, pressure and conductivity. The meter tubes always vibrate at resonance. The resonant frequency which exists is a function of the meter tube geometry, the material properties and the mass of the measuring medium vibrating in the meter tube. It provides exact information about the density of the medium to be measured. In summary, it can be stated that the Coriolis mass flowmeter can be used to simultaneously measure the mass flow rate, density and temperature of a measuring medium.



Movement of the pipes inward
no flow

Movement of the pipes outward
no flow

Direction of the Coriolis force **with flow** and movement of the pipes inward

Direction of the Coriolis force **with flow** and movement of the pipes outward

Fig. 2-106: Simplified Presentation of the Coriolis Force

Advantages of this Measurement Method:

- Universal measuring system for flow rate, density and temperature, independent of
 - conductivity
 - inlet and outlet sections
 - flow profile
 - density and, thus, pressure and temperature of the measuring medium
- Direct mass flow measurement
- Very high measuring accuracy (typically $\pm 0.15\%$ of rate)
- Multi-variable measuring principle, simultaneous measurement of
 - mass flow rate
 - volume flow rate
 - density
 - temperature
- No moving parts, therefore wear free

Disadvantages of this Measurement Method:

- Relatively high initial cost (for an accuracy of 0.15 % of rate)
- Installation limitations for multi-phase measuring media or high gas content
- Deposits or abrasion can lead to errors, especially in the density measurement
- Limited material selections for process wetted parts, corrosion resistance must be checked

Twin Tube Measuring System

The overwhelming majority of Coriolis instruments today are based on the twin tube principle with a flow splitter and two bent meter tubes. The advantage of this design, e.g. the CoriolisMaster-MC2 from ABB, is temperature stability and in particular, the de-coupling of the meter pipe vibrations from external vibrations. The amplitudes of the vibrations which are required for determining the phase shift, are measured between the two meter tubes and not relative to the housing. Possible vibrations of the housing therefore have no effect on the measurements.

Based on the appreciably more stable and defined signals this system provides the most accurate measurements coupled with insensitivity to outside influences. A well-designed twin tube meter requires minimum energy to start and keep the system resonating and generates measurement signals even for the smallest flow rates. The twin tube design is used in approximately 80 to 90 % of present applications.



Fig. 2-107: Bent Single Tube Design

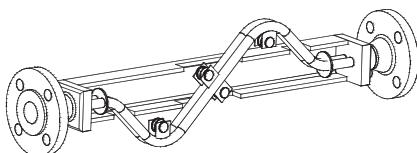


Fig. 2-108: Twin Tube Design

Single Tube Measuring System

Besides the twin tube design there is also the single tube design, e.g. the ABB flowmeter CoriolisMaster-MS2. In order to maintain the insensitivity to external vibrations, the meter tubes in this design are bent into loops. The amplitudes of the vibrations, and thereby the phase shift, are measured between the tube loops and not relative to the housing. This principle offers distinct advantages for the smaller size meters because a flow splitter is not required.

The straight single pipe design has advantages in that it can be more easily cleaned, has a reduced pressure drop and is less harsh on the measuring medium. However, these advantages come with a lower accuracy and a higher sensitivity to external vibrations. Because of the straight meter tube, the amplitude differences must be measured relative to the housing. If the housing is also vibrating, the effects are difficult to compensate. Moreover, the measured signals are appreciable smaller which also contributes to the reduced accuracy mentioned earlier, especially for the density measurement.

It is difficult to start and keep a single straight tube resonating. The elasticity of a pipe is directly related to its wall thickness. Therefore vibrating straight tubes must be constructed thin and are available only for limited nominal diameters. For abrasive or corrosive measuring media, however, the thin wall sections of the meter tube can add additional safety concerns.

Application Areas

Based on the advantages mentioned above it is not difficult to understand that this Coriolis measurement principle is being preferred by more and more industries over other measuring principles. Of particular interest is the direct mass measurement, because many recipes or processes are based on the mass of the used materials. Previous dependence on density variations and therefore temperature or pressure changes are concerns of the past. If in the past a volume measurement had to be converted to mass, the Coriolis technology allows to skip this step.

Since this principle is independent of the properties of the measuring medium, such as conductivity, flow profile, density, viscosity, etc., almost all materials can be measured: e.g. oils and fuels, cleaning agents and solvents, fats, silicone oil, alcohol, methane, fruit mixtures, starch, dyes, biozide, vinegar, catsup, mayonnaise, beer, milk, sugar solution, gases, liquefied gases, etc.

As a result of the simultaneous measurement of the density and temperature of the measuring medium, a real time quality analysis of the medium can be made. If the density of the measuring medium changes from the set point value, quality problems in the process are identified. Also the presence of air inclusions or similar effects can be monitored from the density signal.

In the food and beverage industry a decisive factor is the good cleanability of the instruments, even of a twin tube system, as the EHEDG-certified flowmeter sensor design from ABB has demonstrated. Furthermore the highly accurate mass and density measurements of the materials are a great advantage. Compositions can thus be monitored online. The concentrations of two phase measuring media can be determined from the density measurement using special software. Thus for the sugar concentration in a liquid the °BRIX is readily available. Up to 3 different density-concentration curves can be entered in the transmitter of the CoriolisMaster, so that every type of concentration can be measured.

In the chemical industry, the high-accuracy mass flow measurement is particularly important. The variable explosion protection concept (Ex "e" and "i" exclusively defined by the customer's connections) including isolation and, not least, the additional security of a flameproof enclosure around the meter tubes are also important advantages. ATEX Approvals up to Group 1 (Zone 0) have been granted. The high reproducibility (typically 0.1 % of rate) is a great advantage for control or fill processes.

In the petrochemical field the additional material compatibility per NACE and the rugged design are of importance, especially where extreme ambient conditions exist. The meters are used in oil fields at -50 °C or in offshore applications where a highly corrosive salt water environment is present. For this last application, ABB offers a special protective coating for the demanding North Sea applications.

In the paper industry the Coriolis mass flowmeters are predestined for use in the coating and color kitchens. Problems always occurred due to the varying density of viscosity values; there e.g., the CoriolisMaster measures the mass directly, providing excellent stability and high accuracy. Also, the conversion from volume to mass flow units has become unnecessary.

Due to the multivariability, flexibility, high accuracy, wear resistance and ruggedness, the Coriolis mass flow measurement continues to conquer new markets and application fields. Although at first it may appear that the initial acquisition costs are higher they often become negligible when compared to the later savings due to more accurate and simpler dosing. In contrast to the traditional measuring devices the measuring accuracy remains constant for a long time period at a minimum maintenance cost.

Density and Concentration Measurements

The meter tubes of a Coriolis mass flowmeter vibrate at the corresponding resonant frequency which is a function of the current meter tube weight. When the meter tube weight changes, the resonant frequency changes as well. As the meter tubes themselves usually remain unchanged, it is the weight of the measuring medium in the meter tube that changes. The meter tube weight and the internal volume are known. As a result, the density of the measuring medium in the meter tube can be calculated from this. This means that the current resonant frequency gives the current density of the measuring medium.

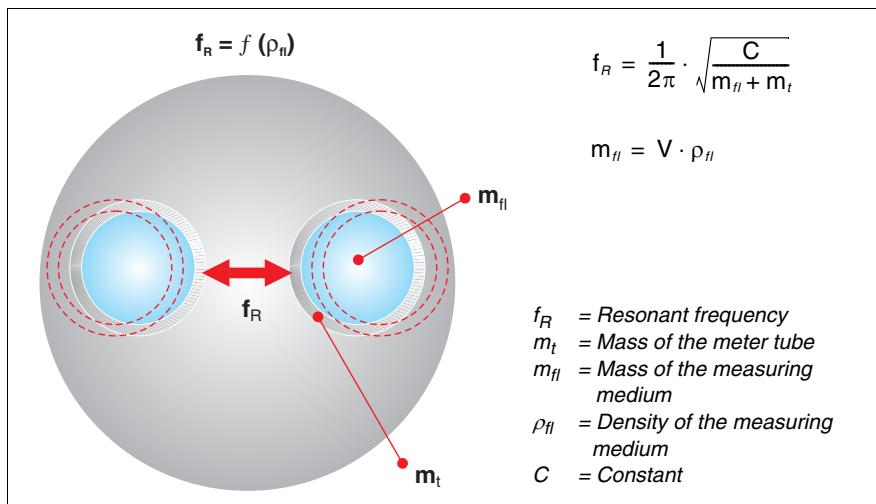


Fig. 2-109: Basic Principle of Density Measurement

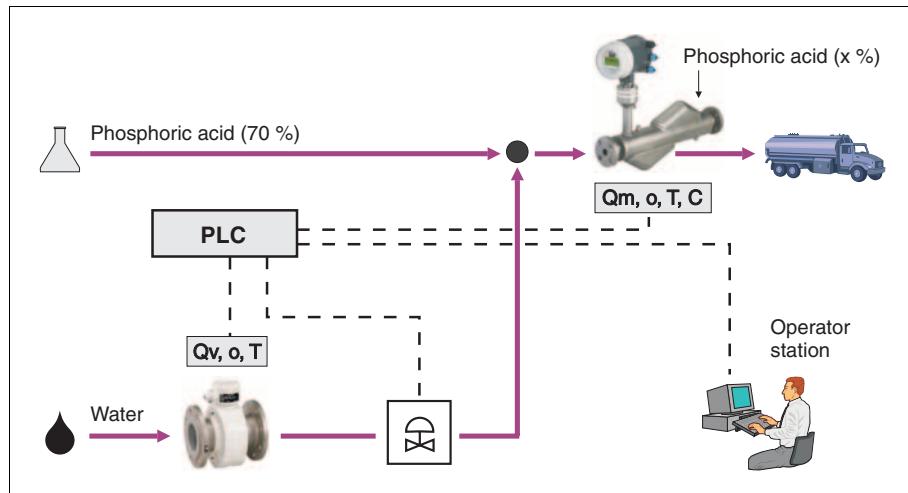
This principle opens up a variety of possible applications. On one hand, the meter can be used not only for flow measurement, but also for controlling the quality of the measuring medium. With this, the user can open another window to his process. If, on the other hand, the measuring medium should remain constant, the density measurement provides information about the meter reliability, because the frequency characteristics will change immediately when the meter tube is changed by deposits or abrasion.

But density measurement can do a lot more than this: For compounds of two substances with different densities the density and temperature measurements of the measuring medium allow to draw conclusions about the concentration of each substance.

This can be realized by using either complex polynomials or, as ABB does, simple matrices as described below:

	Temp. Concentration	Temp1	Temp2	Temp3	...	Temp 10
% 1	C1	Density	Density	Density	Density	Density
% 2	C2	Density	Density	Density	Density	Density
% 3	C3	Density	Density	Density	Density	Density
...	...:	Density	Density	Density	Density	Density
% 10	C10	Density	Density	Density	Density	Density

Usually, matrices for standard applications like alcohol in water or sugar in water are preset.



In practice, this allows to achieve considerable savings of time and, thus, resources in mixing processes or fill processes with simultaneous setting of the mixing ratio. Depending on the application, the average fill time can be reduced by approx. 60 %.

Frequently Asked Questions and Answers

What must be considered during the installation?

These devices in comparison to the other flowmeters are relatively easy to install. They can be installed horizontally or vertically. Specific distances from elbows or valves, etc. are negligible because the measurements are unaffected by flow profile effects. The devices should be installed right before or after the flanges, but should not be attached directly to the housing.

What effect do gas or air bubbles in the measuring medium have on the measurement?

First gas bubbles tend to dampen the vibration of the pipes, which is compensated by a higher excitation current. If the gas content is not too large and has an essentially homogeneous distribution, the mass flow measurement is hardly affected. The density measurement however can be impaired. This can be explained by the measurement method. The resonant frequency of the vibrations is proportional the instantaneously vibrating mass, consisting of the measuring medium and the meter tubes. Assuming that the tubes are completely filled, the density can be calculated from the equation:

$$m = \rho \cdot V$$

If the pipes are not completely filled or contain a gas or air components then an error will occur.

How do solids affect the measurement?

As long as the solids vibrate exactly the same as the meter tube and thereby add a contribution to the flow rate signal, there are no problems with the measurement. Decisive is the relationship between the particle size (inertia) and the viscous forces (acceleration forces). The lower the viscosity the smaller the particle size should be. Generally, a self draining design is preferred, to prevent particles being deposited in the pipe bends, especially when there is no flow.

What is affected if the back pressure is too low?

When the back pressure is low the fullness of the meter tubes cannot be guaranteed, and also the danger that cavitation may occur exists when the vapor pressure is less than the system pressure.

What happens if the meter pipes are not completely filled?

In this case the meter tubes cannot reach a stable vibrating condition and a measurement is no longer possible. This condition can be recognized by an unstable, too low density signal and also by a large increase in the driver current.

Coriolis Mass Flowmeter CoriolisMaster

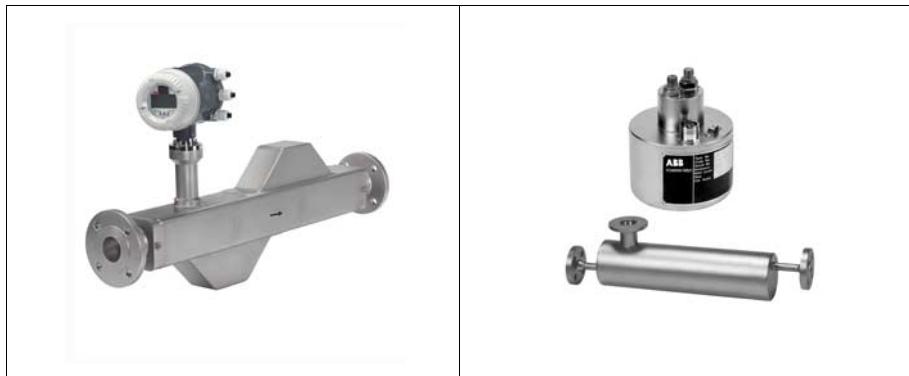


Fig. 2-110: Twin Tube Measuring System
CoriolisMaster MC2

Fig. 2-111: Single Tube Measuring System
CoriolisMaster MS2

The flowmeter sensor of the CoriolisMaster MC2 is characterized by two bent one-piece meter tubes through which the measuring medium flows in parallel. A twist-proof and bend-proof structure which joins the inlet and outlet is especially suited for absorbing the external forces and torques. The meter tubes are welded into flow splitters at the inlet and outlet ends. Thus, there is no direct coupling to the process connections. This design to a large extent minimizes the effects of external vibrations.

The elimination of welds at the highest stressed locations as well as hard soldering in a vacuum the pipe, driver and sensors brackets assure long term durability. An exceptional long term stability is achieved by thermal treatment of the meter tubes.



Fig. 2-112: CoriolisMaster Certified for the Food and Beverage Industries

The optimized design of the flowmeter sensor in conjunction with the meter tube material 1.4435/316L allows unrestricted use in hygienic applications. The entire construction consisting of meter tube, flow splitter and process connection has been tested and certified per EHEDG. The CIP and SIP processes can be carried out at temperatures up to 180 °C.

The CoriolisMaster transmitter is available in integral or remote mount design and incorporates a digital signal processor (DSP) which allows for mass flow rate and density measurements at the highest precision. An exceptional long term stability and reliability are the results. Self-diagnosis of the flowmeter sensor and transmitter and absolute zero stability are additional advantages.

2.2.9 Thermal Mass Flowmeters for Gases

The most commonly used flowmeters for gases measure the operating volume flow. This requires additional measurements of pressure and temperature to calculate the mass flow rate. These corrective measures add cost and increase the complexity of the measurements; in addition they decrease the measuring system accuracy. The thermal mass flow measurement for gases, on the contrary, provides mass flow rate in kg/h directly without any additional measurements or calculations. Using the normal density of the gas the normal volume flow rate can be calculated, e.g. in Nm³/h.

There are two industrial methods used for thermal gas mass flow rate measurement, hot film anemometers and calorimetric or capillary meters.

Functionality of a Hot Film Anemometer

This method uses the flow rate dependent heat transfer from a heated body to the measuring medium. In the fields that are relevant for process engineering, this flow rate dependent cooling is not a function of the pressure and temperature, but of the type and number of particles that get into contact with the hot surface. This means the method determines the mass flow rate of the measuring medium directly.

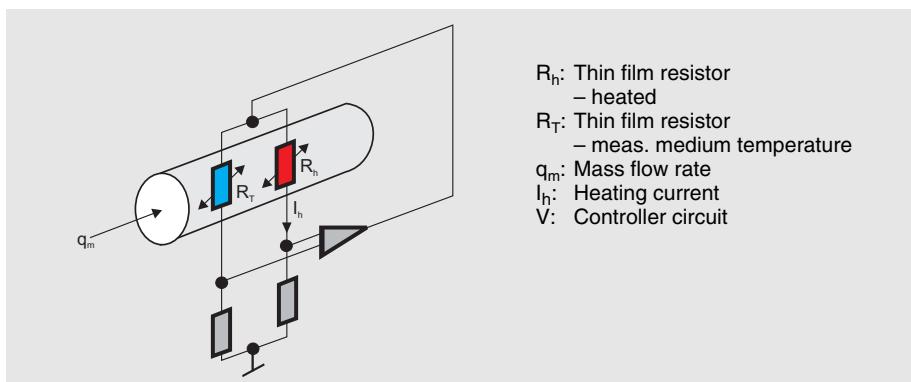


Fig. 2-113: Hot Film Anemometer, Operating Principle

The sensor unit consists of two measurement resistors that are part of an electrical bridge circuit. One of these resistors assumes the temperature of the flowing gas, whereas the other resistor is electrically heated and, at the same time, cooled by the gas mass flow. A control circuit applies heat to the resistor so that a constant temperature difference exists between the resistors. The power P is, thus, a measure of the gas mass flow rate. With the instrument and gas dependent constants $K_{1\dots 3}$ this relationship can be represented by King's equation:

$$P = \Delta T \cdot K_1 + K_2 \cdot (q_m)K^3 \quad (2.36a)$$

This provides the measured value directly in the units kg/h or standard m³/h. The density correction of the measured value otherwise required is no longer necessary. The compact design of the sensor unit assures a minimum pressure drop of typically 1 mbar. For thin film sensors the response time is in the ms range. Vibration insensitivity and an extremely wide span at accuracies up to 1 % of rate are the rule for all thermal mass flowmeters.

Thermal Mass Flowmeter in Digital Technology

For digital devices the measuring principle described above was further developed to include a gas temperature measurement and appreciably extended diagnostic functions. The measuring range could be expanded to 1:150 due to the improved signal quality. The separate measurement of the gas temperature can be used to compensate for the temperature dependence of the gas constants. The diagnostic functions can be used as a preventative maintenance tool to evaluate the operating time, temperature spikes and system loads.

Technical Designs

Different device concepts were developed for pneumatic, test bench, machine construction, hygienic and chemical process applications. Their primary difference is the design of the sensor units, dependent on whether quick response, flexibility or chemical resistance is required.

Devices for the Process Technology

With the Sensyflow FMT400-VTS and FMT500-IG flowmeters rugged, universal device models are available for process applications. All models are connected to the process via special pipe components which ensure a defined, reproducible installation condition.

- Sensyflow FMT400-VTS is a flowmeter with integral mount design which directly provides a flow rate proportional 0/4...20 mA signal.
- The digital Sensyflow FMT500-IG is available with PROFIBUS DPV1 or analog/HART communication. It can be delivered with up to 4 characteristic curves for different gases or pipe diameters.

For hygienic applications the Sensyflow FMT400-VTCS series flowmeters can be used. Special materials and an adapted sensor design make the devices capable of CIP and SIP.

Typical Applications

- Gas flow measurements in the chemical and process industries
- Compressed air balancing
- Gas burner control
- Digester gas and aeration measurements in sewage treatment plants
- Gas measurements in air separation systems
- Hydrogen measurements in processes
- Carbonization in breweries and soft drink production



Fig. 2-114: Models for the Different Industries

Specifications of the Sensyflow FMT400-VTS and FMT500-IG Series

Diameter	From DN 25, also for non-round cross sections
Span	
Oper. temp. of the meas. medium	-25...300 °C
Pressure range	0.5...40 bar absolute
Measuring uncertainty	≤ 1 % of rate
Typical pressure drop	1 mbar
Response time	0.5 s
Output signal	0/4...20 mA; pulse; frequency; binary
Communication	HART, PROFIBUS DPV1
Supply power	230; 110; 24 V AC; 24 V DC
Materials	Stainl. steel; Hastelloy; Ceramic
Explosion protection	Zone 0

Devices for Flow Rate Test Benches

Test bench applications, e.g. intake air measurements of combustion engines, include a high accuracy requirement over a wide measuring range. Additionally, a quick response is essential. Only then can the dynamic processes be depicted correctly with sufficient resolution. Sensyflow FMT700-P has been designed specifically for such applications.



Fig. 2-115: Thermal Mass Flowmeter for Test Benches – Sensyflow FMT700-P

Specifications for Sensyflow FMT700-P	
Diameter	DN 25...DN 200
Span	1:40
Oper. temp. of the meas. medium	-25...80 °C
Pressure range	2.5 bar absolute
Measuring uncertainty	≤ 1% of rate
Typical pressure drop	10 mbar
Response time	T ₆₃ ~ 12 ms
Output signal	0/4...20 mA; 0...10 V; RS 232, ASAM-GDI
Supply power	230/115 V AC

Devices for Compressed Air Regulation

In paint robots the ratio of paint to atomization air for color application control must be controlled with a very fast response time. The Sensyflow FMT200-ECO2 specifically designed for this application is a compact unit incorporating the complete electronics. It is also suitable for all compressed air applications to DN 25 as a result of its universal connection concept.



Fig. 2-116: Thermal Mass Flowmeter for Compressed Air – Sensyflow FMT200-ECO2

Specifications of Sensyflow FMT200-ECO2	
Diameter	to DN 25
Connections	Small flange, G 3/8"…1", Legris, Transair
Span	1:100
Oper. temp. of the meas. medium	0...50 °C
Pressure range	10 (16) bar absolute
Measuring uncertainty	≤ 3 % of rate
Typical pressure drop	10 mbar
Response time	T ₆₃ ~ 25 ms
Output signal	0/4...20 mA; 0...5/10 V; pulse, digital, frequency, RS 232
Supply power	24 V DC

Heating Method

For very small pipe diameters or extremely small flow rates, which primarily exist in the gas analyses sector and in laboratories, the heating method can be used. The gas flows through a capillary which is heated with a constant power P.

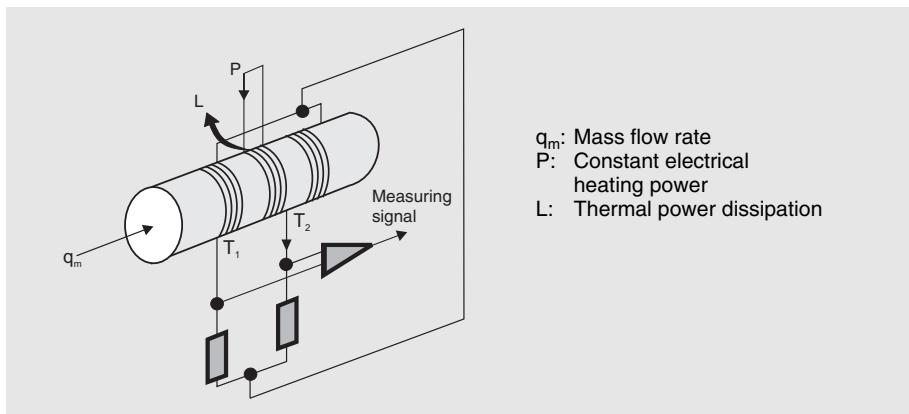


Fig. 2-117: Heating Method, Operating Principle

$$q_m = \frac{(P - L) \cdot C}{C_p \cdot (T_2 - T_1)}$$

The mass flow rate can be calculated from the resultant temperature difference, the heat loss of the system and a device constant C.

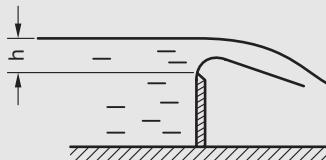
Specifications	
Diameter	to DN 25
Span	1...50
Max. operating temperature of meas. medium	70 °C
Max. permissible pressure	100 bar
Measured error	< 1 % of rate
Response time	1...5 s
Output signal	0/4...20; 0...10 V; digital
Supply power	24 V DC
Materials	Aluminium, stainless steel, plastic

2.3 Flow in Open Channels and Free Surface Pipelines

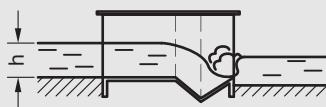
2.3.1 Flow Measurement in Open Channels

Open channels are found extensively in the water and waste water industries. They are characterized by one surface bounded by the atmosphere. The same is valid for free surface pipelines which are additionally found in the process industry.

Indirect method using height measurement



With measuring weirs

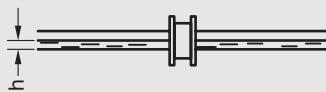


With Venturi flumes

Velocity measurement in a free surface pipeline using an electro-magnetic flowmeter



Flowmeter in a fully filled culvert



Flowmeter for partially filled pipes

Fig. 2-118: Flow Rate Measurement Methods

Measurement Methods

Measuring Weirs

For large water flows and small slopes where the water can be dammed and the flow stream is completely ventilated measuring overflows are the appropriate measuring equipment. Ventilation means that air has free access under the overflow so that the stream will separate and fall freely. Measuring weirs consist of thin wall plates with sharp metering edges placed perpendicular to the flow direction. Various shapes are used as a function of the application conditions. For smaller flow rates a V-notch weir is used.

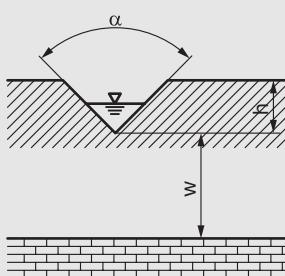


Fig. 2-119: Thomson V-Notch Weir

Based on Equation (1.27) the flow through the V-notch weir is:

$$q_v = \frac{8}{15} \cdot \mu \cdot \tan \frac{\alpha}{2} \sqrt{g \cdot h} \cdot h^{5/2} \quad (2.37)$$

The discharge coefficient μ is a function of the ratio of the overflow height h to the weir height w . The value can be determined using a complicated calculation procedure. Fig. 2-120 shows the μ values in curve form.

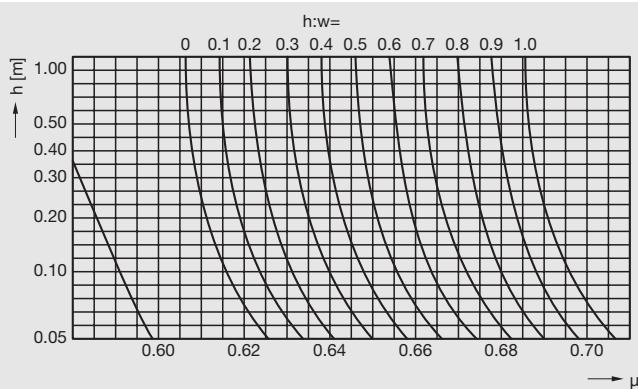


Fig. 2-120: Discharge Coefficient μ for a V-Notch Weir per Rehbock and Thomson

V-notch weirs are suitable for flow rates between 2 and 100 l/s. By paralleling a number of V-notch weirs a reasonable arrangement can be designed for higher flow rates.

For good edge conditions the span is 1:100.

For very large flow rates rectangular weirs are used, with the disadvantage of a limited measuring accuracy in the lower part of the measuring range.

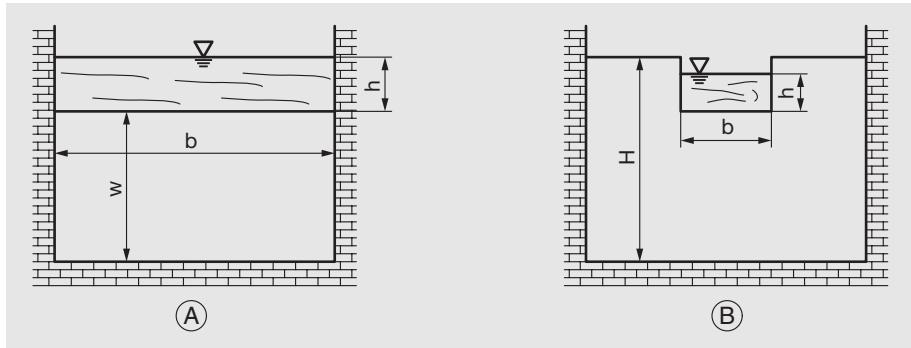


Fig. 2-121: Rectangular Weir without (A) and with (B) Side Contraction

The basis for the calculations is Equation (1.27). For rectangular weirs without side contractions (Fig. 2-121a) applies:

$$q_v = \frac{2}{3} \mu \cdot b \cdot \sqrt{2g} \cdot h^{3/2} \quad (2.38)$$

where the discharge coefficient is μ and $h_e = h + 0.0011$ (m):

$$\mu = 0.602 + 0.083 \cdot \frac{h}{w}$$

for:

$$w \geq 0.3 \text{ m}; \quad \frac{h}{w} \leq 1; \quad 0.025 \leq h \leq 0.8 \text{ m}$$

Because of the side containment of the overflow stream in a rectangular weir without contractions the air supply can become restricted. Therefore ventilation must be assured.

For side contractions the basic equation is applied.

$$q_v = \frac{2}{3} \mu \cdot b \cdot \sqrt{2g} \cdot h^{3/2}$$

for a coefficient: $\mu = 0.6161 - \left(0.1 \cdot \frac{h}{b}\right)$

for: $0.075 \leq h \leq 0.6 \text{ m}$ $b \leq 2 \cdot h_{\max} \leq 0.3 \text{ m}$

The span of the rectangular weir is 1:20. The measurement of the height h is made approximately $4 \times h$ upstream of the weir. The water velocity should not exceed 6 cm/s upstream of the weir. And naturally the water level after the weir must be low enough to permit an overflow; therefore the height between the lower edge of the opening must be at least 5 cm above the lower water level.

Venturi Flume Flowmeter

For flow measurement using measuring weirs the water must be dammed which may cause changes in the inflow area under certain conditions. These restrictions do not apply to a Venturi flume.

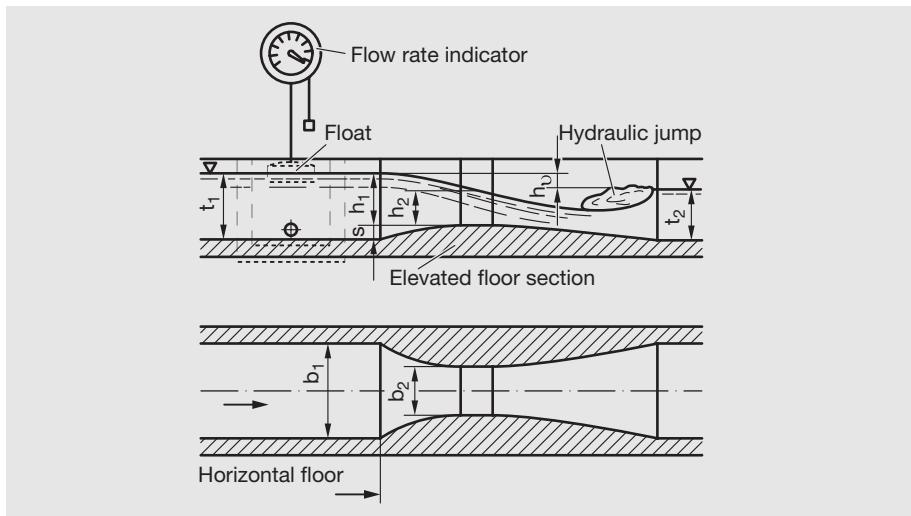


Fig. 2-122: Venturi Flume

Therefore it can react to the smallest flow rates. As with the Venturi nozzle the constriction of the flow cross sectional area results in an energy conversion, which accelerates the measuring medium in the region of the constriction. The constrictions are usually at the sides; there are some however with elevated floor sections.

Calculations for the rectangular Venturi flume using Equation (1.27):

$$q_v = \frac{2}{3} \mu \cdot b_2 \cdot \sqrt{2g} \cdot h^{3/2}$$

The water level upstream of the flume inlet (headwater) is quiet, the water is in the subcritical regime. This occurs automatically because the water is dammed causing the flow velocity v to decrease resulting in subcritical flow conditions.

The acceleration of the water in the constricted region must bring the water to a supercritical state, so that the tailwater conditions do not have an effect on the flow level ahead of the constriction. Only when this condition is assured will a unique relationship exist between the level of the headwater and the flow rate. Subsequently, a subcritical flow state may be reached again after the channel expansion characterized by a hydraulic jump and a standing wave. A backflow must be avoided, because it influences the operation of the measuring system.

Channel Flowmeter Sensor

Once the measuring weirs or Venturi flumes have been installed, which provide defined relations between the measurable values and the flow rate, a device is still needed with which the liquid level can be measured and converted to flow rate proportional values. The headwater level h can be measured directly or indirectly.

- Direct measurement method
 - Float measurement
- Indirect measurement method
 - Hydrostatic pressure measurement
 - Non-contact water level measurement using an echo-sounder
 - Hydrostatic pressure measurement using a bubbler

Float Measurement

The water level is sampled by a float whose elevation is mechanically transmitted to a nonlinear scale or is electrically linearized and converted to a standardized output signal. Contamination, fouling, mechanical abrasion, and frost can affect the float and transmitting element, and since these affect the flow profile they are responsible for errors. Possibly the float will have to be installed in a separate float chamber. Additionally, increased maintenance expenditures must be expected.

These are the reasons that a float measurement is seldom used in these applications.

Hydrostatic Pressure Measurement

The hydrostatic pressure is the force exerted by a column of water above a reference point. The measured pressure is proportional to the height.

$$p = h \cdot \rho \cdot g + p_0 \quad (2.40)$$

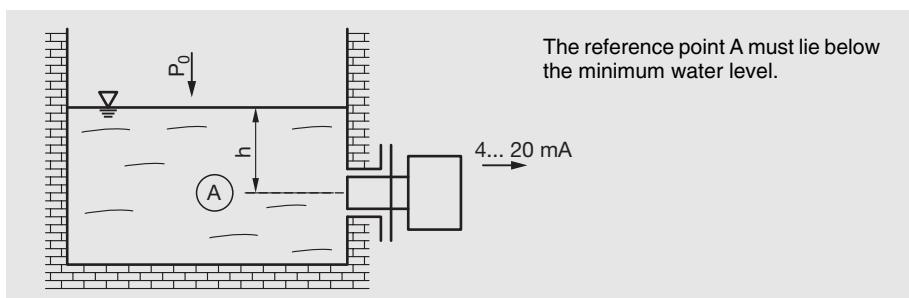


Fig. 2-123: Hydrostatic Pressure Measurement

In a Venturi flume it is possible to integrate the measurement location in the floor of the flume. Fig. 2-123 shows a specially designed transmitter for installation in a side wall.

The transmitter (Fig. 2-124) includes an extended diaphragm flush-mounted to the flume wall. An oil fill transmits the diaphragm pressure to a capacitive measuring cell that generates the 0/4...20 mA output signal.



Fig. 2-124: Pressure Transmitter Type 266MDT for Level Measurement

The measuring cell operates as a differential pressure meter in the sense that the minus side is open to the atmospheric pressure p_0 . This pre-pressure p_0 is applied to both sides of the diaphragm and is, thus, self-cancelling. As the transmitter is mounted to the side wall, the zero of the transmitter can be adjusted such that the lower range value is based on the channel floor. Naturally, communication between the device and modern process control systems is possible via an interface or a fieldbus coupler. The measuring ranges lie between 1 and 10000 kPa

The diaphragm flush-mounted to the inner wall of the flume is unaffected by deposits and contamination.

Bubbler Method

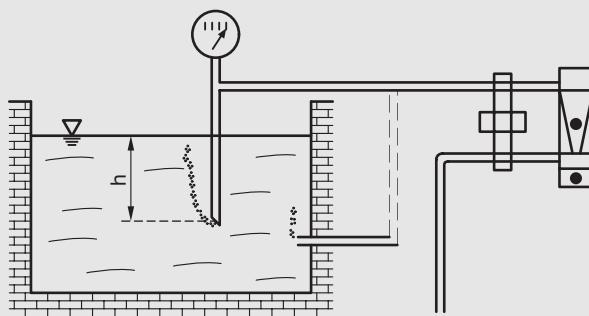


Fig. 2-125: Bubbler Method

A probe is inserted into the measuring medium either from the side or from the bottom and air or an inert gas is injected into the flume; the air bubbles to the top, thus the name bubbler method.

For injecting the gas a purgemeter type 10A6100 with needle valve and differential pressure regulator is used. After the regulator, which acts as a restriction, a pressure exists in the probe which is the same as the hydrostatic pressure at the end of the tube. The needle valve is used to set the bubble flow rate and the differential pressure regulator to maintain a constant flow rate. A pressure transmitter processes the level proportional pressure.

The advantage of the bubbler method lies in the fact that the sensitive measuring elements are not in contact with the measuring medium and are therefore not subjected to chemical or mechanical attack. Additionally, the cost for providing sufficient protection for use in hazardous areas is minimal.

Echo-sounder Method

The most successful water level measurement method is the noncontacting echo-sounder method. A sound signal is transmitted from a sound generator located above the water level which, after it is reflected from the water surface, is received. The distance between the transmitter/receiver and the water level (i.e. the headwater level) is calculated from the transit time of the sound wave. The sound velocity however is a function of the composition of the elements in the sound path, including temperature and humidity which can vary. A reference path, which is precisely defined mechanically, can be used to compensate for these disturbance factors.

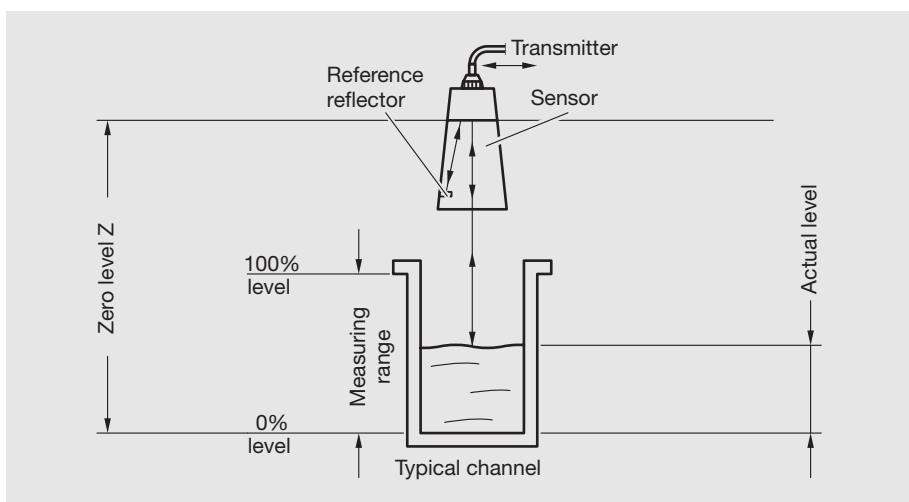


Fig. 2-126: Echo-sounder Method

A cone is installed at the sensor to protect against external influences, e.g. snow fall and to shield against undesirable wall reflections.

The connected transmitter includes a microprocessor which uses stored curves for different flume meters to calculate the flow rate proportional 0/4 ... 20 mA output signal. Naturally such transmitters provide self-monitoring functions, alarm contacts and volume totalizers.

2.3.2 Flow Measurement in Free Surface Pipelines

There are closed pipeline systems which are not continuously filled with liquid but run partially full because their size had to be selected to accommodate sporadic high flows. The most important example is in the waste water lines, in which the flow at night is small, somewhat more during the day, but is extremely high after a rain storm. This application requires a flowmeter which provides accurate measuring values under all these conditions.

The waste water containing solids prevents the installation of devices projecting into the pipeline. Therefore, the ideal measuring device is an electromagnetic flowmeter. With one minor disadvantage: the actually measured variable is the flow velocity v . The desired flow rate is available only after multiplying by the filled cross sectional area A , $q_v = v \cdot A$. Since A , as noted above, is constantly changing there are two possible solutions for the measurement. Either arrange the pipeline so that it always runs full or install the electromagnetic flowmeter FXP4000 specifically designed for these applications.

Electromagnetic Flowmeter in a Culvert

A culvert (Fig. 2-127) can be used to assure that the pipe always runs full and a correct measurement can be made. An argument against the culverts is the danger that solids will be deposited, especially in waste water applications.

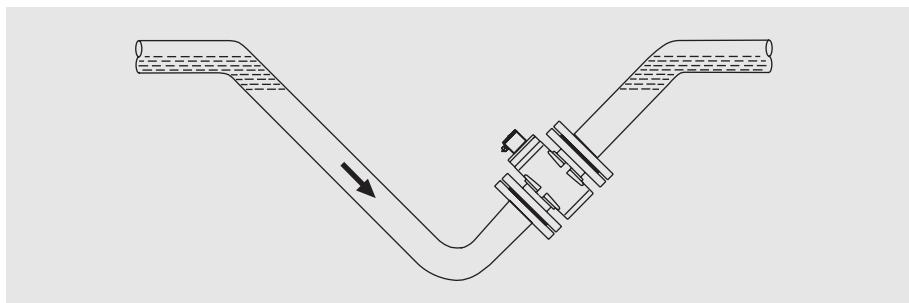


Fig. 2-127: Electromagnetic Flowmeter in a Culvert

The drag force of flowing water, which increases with increasing flow rate, is often underestimated. Deposits are flushed from the culvert when the flow is high. This condition can also be induced by damming the water ahead of the culvert for short periods of time. Another possibility is to install a separate line for flushing.

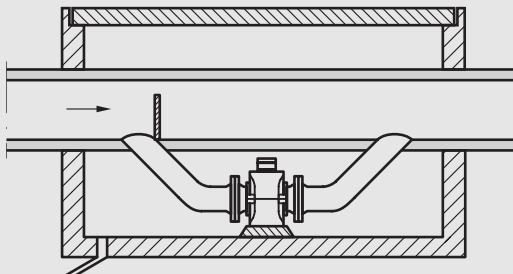


Fig. 2-128: Culvert with a High Water Bypass Line

Higher flow velocities in the culvert prevent deposits. The pipeline is designed with a cross sectional area that during periods of high water – rain storm – is actually undersized.

A solution to this problem is to install a bypass culvert and install a weir in the main pipeline (Fig. 2-121) which has the disadvantage, that during high water flows, some of the water will not be metered. In contrast to the electromagnetic flowmeter FXP4000 the culvert method has the advantage that more accurate meters can be used for partially full conditions. The cost advantage of smaller meters is usually offset by the higher construction costs.

Electromagnetic Flowmeter FXP4000 (PARTI-MAG II) for Partially Full Pipelines

It is known that the electromagnetic flowmeters described in Chapter 2.2.6 provide a signal proportional to the flow velocity v and that the flow rate q_v can be calculated by multiplying this value by the constant cross sectional area A . The device requires that in the measuring section, the pipe cross section remain full. This requirement cannot be fulfilled for free surface flows. Therefore an electromagnetic flowmeter can only measure accurately if the fill level is included in the calculation. This is the fundamental idea behind the design of the FXP4000.

For the determination of two unknown values the laws of algebra state that two independent equations, or in this case, two measured values are required.

These measured values are determined as follows:

The volume flow to be measured flows through a meter tube insulated with a liner. Using externally mounted magnet coils at the top and bottom, a magnetic field is generated in the meter tube cross section.

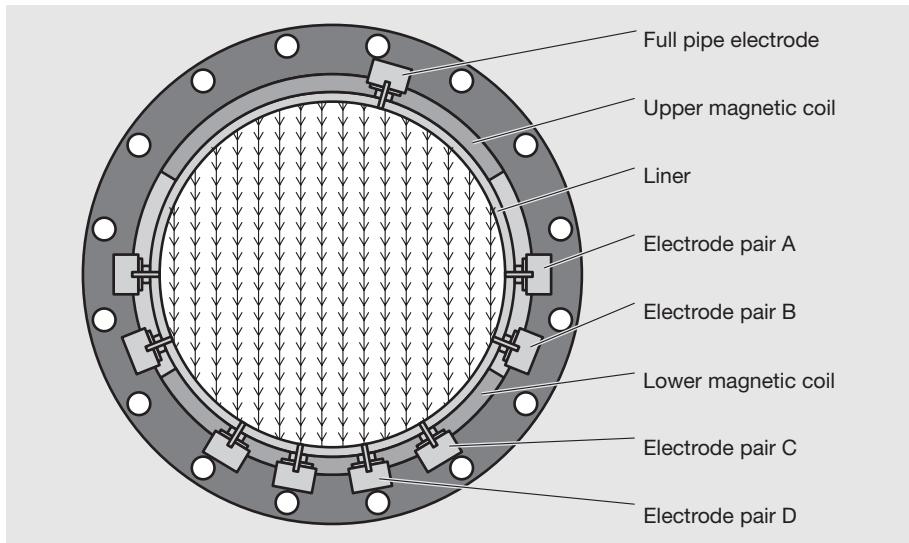


Fig. 2-129: Design of the Flowmeter Sensor

As shown in Fig. 2-129, the transmitter of the FXP4000 flowmeter contains four pairs of electrodes installed at different "levels". To measure the voltage induced in the flowing liquid the optimally placed electrode pair A, B or C, based on the fill level, is used. In this way flow rates from a fill level of 10 % all the way up to a full pipe condition can be measured. This corresponds to 5 % of the cross sectional flow area.

The electrodes are installed perpendicular to the flow direction and to the magnetic field. The induced voltages are measured at these electrodes. When the pipe is full this voltage, as in the usual electromagnetic flowmeter, is a "direct measure" for the average flow velocity.

In contrast, in a partially full pipeline the voltage measured at the electrodes must be corrected using a factor. It is determined using a curve stored in the transmitter.

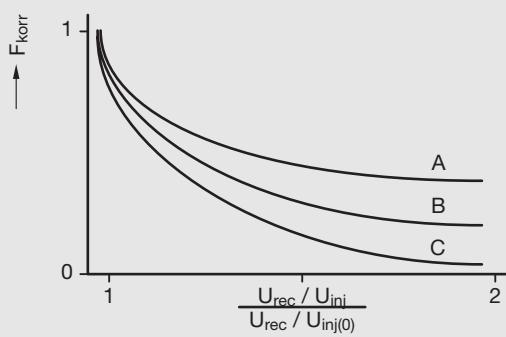


Fig. 2-130: Correction Curves for Flow Velocity Proportional Voltages Measured at Electrode Pairs A, B, C

The correction curves depicted in Fig. 2-130 show the relationship between two voltages $U_{\text{rec}} / U_{\text{inj}}$.

With the FXP4000 electromagnetic flowmeter a device has been designed that combines the advantages of the system described earlier and eliminates the disadvantages when the pipeline is partially full. There are no additional pressure drops, costly constructions are eliminated, and the smallest flow rates at low levels or large flow rates when the pipeline is full can be metered.



Fig. 2-131: FXP4000 Electromagnetic Flowmeter Sensor and Transmitter

The quality of the measurement is a function of the velocity profile in the filled state. The accuracy at a full pipeline condition is 1 % of rate; at partially full conditions an accuracy of 3 to 5 % of rate can be achieved down to a minimum fill level of 10 % DN.

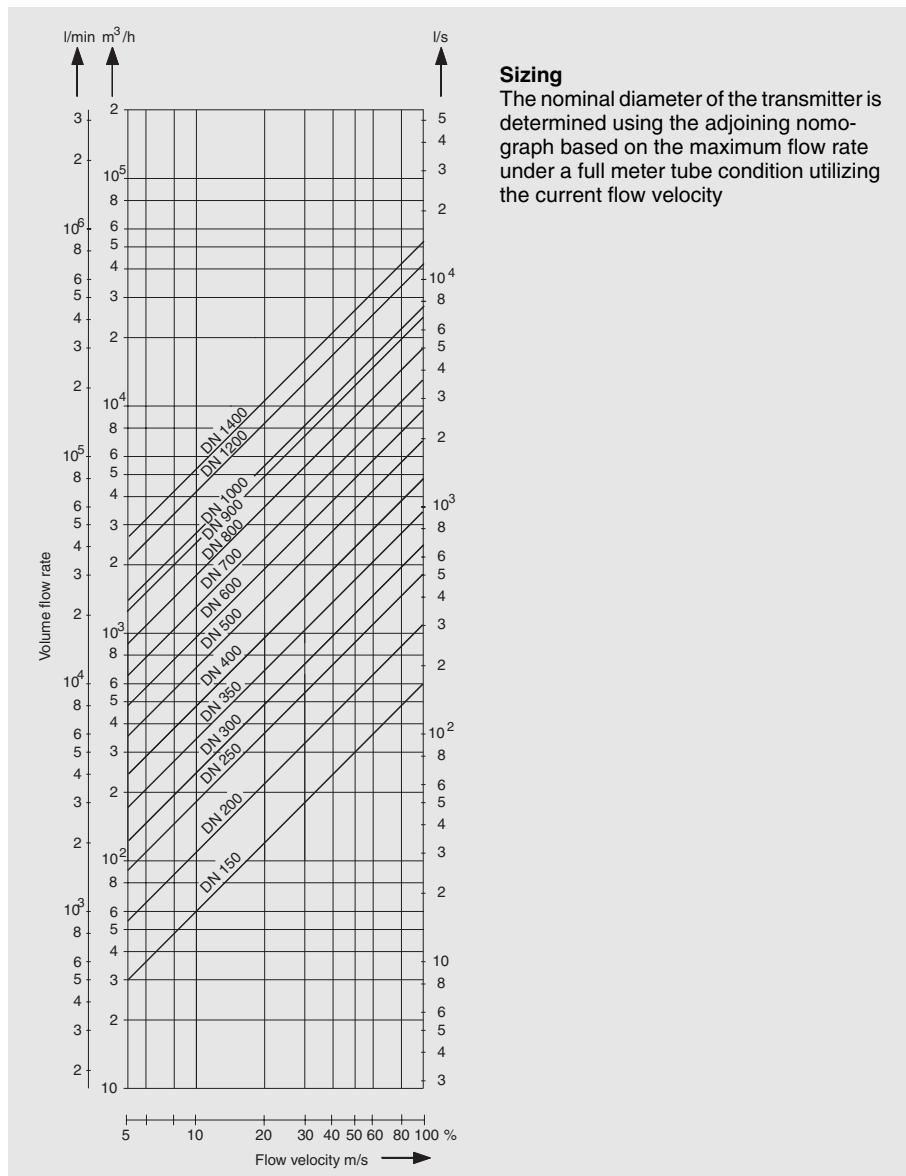


Fig. 2-132: Flow Rates as a Function of the Nominal Diameter

A special case is the sizing for sloped water and waste water pipelines. In this case the flow velocity is determined from the friction and the slope of the pipeline. The velocity can be calculated by using the resistance coefficient. According to Nikuradse the following applies for a rough wall pipe with turbulent flow:

$$v = \sqrt{\frac{h_v}{l} \cdot \frac{2g \cdot d}{\lambda}} \quad (2.42)$$

with the pipe diameter d in mm and the roughness k in mm. For steel or cast iron pipes an approximation can be calculated using $k = 1$. To calculate the flow velocity the Darcy-Weisbach equation is used and after conversion becomes:

$$\lambda = \frac{1}{\left(2 \lg \frac{d}{k} + 1.14\right)^2} \quad (2.41)$$

with the ratio h_v/l for the slope. The value v determined for the full pipe can be used for comparison with the flow rate in the nomograph (Fig. 2-118). As already mentioned, the accuracy is a function of the uniformity of the flow profile, especially when the pipe is partially full.

This condition can only be satisfied in a long pipeline with constant roughness when flow disturbances like flow profile changes in the pipeline, projections or connections in the pipe wall, deposits, and other wave and vortex producing influences are located sufficiently far from the measuring point. An ideal situation is one in which uniform flow exists. This fact is the basis for the recommendation that inlet sections of $5 \times D$ and outlet sections of $2 \times D$ should be installed.

Electrode Materials

Liner Material	Electrode Material
Hard rubber, soft rubber	Stainl. steel 1.4571 Hastelloy C or B
PTFE, PFA	Hastelloy C Hastelloy B, Ti, Ta, Pt-Ir

Nominal Diameters and Pressures

Liner Material	DN	PN
Hard rubber	150...1400	6...40
Soft rubber	150...1400	6...40
PTFE	150...600	10...40

Specifications	
Process connection	Flanges
Explosion protection	Zone 1
Upper range value	0.5...10 m/s
Max. meas. error	Full pipe: 1 % of rate Partially full pipe: 3 or 5 % of rate
Output	0/4...20 mA 0/2...10 mA
Pulse output	Active 24 V DC Passive (optoelectronic coupler) 5...25 V, 5...200 mA
Interface	RS 485
Supply power	24 V, 115 V, 230 V, 50/60 Hz

3 Regulations and Requirements Regarding Quality, Environment, Safety and Data Protection

3.1 Integrated Management System

In order for a company to be financially viable it must operate in a correct, market-oriented manner. Therefore, the highest goal must be to fulfill the customers' requirements. Optimal functionality and a long service lifetime at reasonable prices are expected for the products. Product liability requires manufacturing in compliance with the safety requirements, the applicable standards and regulations, and the generally recognized codes of good practice.

In every company there were and are organizational and procedural systems for the accomplishment of these tasks. The DIN EN ISO 9000 series of standards about quality management systems worked out and issued in 1983 has become a well-proven basis which allows for international comparability and requires constant monitoring by independent organizations.

Additionally, ABB is committed to active quality and environmental awareness, to safety at work and health protection of its staff, to compliance with the regulations concerning careful handling of personal data, and to an open information policy. The individual management systems for quality, environmental protection, safety at work, health protection and data and information protection have been united in a consistent system: the integrated management system. This system meets all requirements on a quality management system to ISO 9001, an environmental management system to ISO 14001, a management system for safety at work and health protection to BS OHSAS 18001 and all relevant national laws regarding the protection of data and information.

ZERTIFIKAT

ISO 9001:2008
ISO 14001:2004



bescheinigt hiermit, dass das Unternehmen

ABB

ABB Automation Products GmbH
Wallstraße 59 • 88520 Ladenburg
(weitere Standorte siehe Anhang)

Geltungsbereich:
Entwicklung, Projektierung, Fertigung, Service und Vertrieb
von Produkten und Dienstleistungen der Instrumentierung, Motoren & Antriebe

ein Qualitätsmanagement- und Umweltmanagementsystem entsprechend den oben genannten
Normen eingefügt und dieses System bewahrt. Der Nachweis wurde im Rahmen des Zertifizierungs-
Audits Bericht-Nr. A0811072 erbracht. Dieses Zertifikat ist nur in Verbindung mit der
erfolgigen Durchführung der Überwachungsaudits gültig.

Dieses Zertifikat ist gültig ab:	09.10.2009	Datum der Erstzertifizierung:	08.10.2006
Dieses Zertifikat ist gültig bis:	05.10.2012	Zertifikat- Nummer:	Ums-TGA-ZM-05-01-02 GMS-TGA-ZM-05-01-02
Letzte Austellung:	04.09.2009	Rezipienten-Nr.:	000001010172
		Datum:	04.09.2009


DEKRA Certification GmbH
Stuttgart, 04.09.2009



CMS-TGA-ZM-05-01-00
UMS-TGA-ZM-05-01-00

Anhang zum Zertifikat Nr. 5090310172 und 1710651922
vom 09.10.2009 gültig bis 05.10.2012

Die folgenden Standorte fallen unter das o.g. Zertifikat:

Niederlassungen/ Vertriebsbüros	Strasse	Land - Postcode	Ort
1. Ladenburg	Wallstraße 59	D-88526	Ladenburg
2. Ladenburg	Wallstraße 59	D-88526	Ladenburg
3. Alzenau	Borsigstraße 2	D-63755	Alzenau
4. Alzenau	Schlossstraße 2	D-63755	Alzenau
5. Göttingen	Oeranfelder Straße 2	D-37078	Göttingen
6. Ratingen	Oberhauser Straße 33	D-40472	Ratingen
7. Cottbus	Segewer Strasse 17/18	D-03046	Cottbus

Liste erstellt am 09.10.2009


DEKRA Certification GmbH
Stuttgart, 04.09.2009

DEKRA Certification GmbH | Headquarter 10 - DE/02005 Stuttgart | www.dekra.com/deutschland Seite 1 von 1

CERTIFICATE

ISO 9001:2008
ISO 14001:2004



hereby certifies that the company

ABB

ABB Automation Products GmbH
Wallstraße 59 • 88520 Ladenburg
(further locations see annex)

**Development, project engineering, planning, manufacturing,
service and sales of products and services of the instrumentation,
motors & drives and low-voltage switchgear systems**

has successfully implemented the above mentioned quality management system and environmental
management system according to the standards and applies it effectively. The conformity was inspected
during the certification audit documented in audit report No. A0811072. This certificate is only valid in
connection with the successful performance of the surveillance audits.

This certificate is valid from:	09.10.2009	Date of the first certification:	08.10.2006
This certificate is valid until:	05.10.2012	Certificate registration no.:	Ums-TGA-ZM-05-01-02 GMS-TGA-ZM-05-01-02
Last audit day:	04.09.2009	Signature date:	04.09.2009


DEKRA Certification GmbH
Stuttgart, 04.09.2009



CMS-TGA-ZM-05-01-00
UMS-TGA-ZM-05-01-00

Annex to the certificate no. 5090310172 and 1710651922
from 09.10.2009 valid until 05.10.2012

The following locations belong to the certificate above:

Subsidiaries/ Sales offices	Street	Country / Postcode	Location
1. Ladenburg	Wallstraße 59	D-88526	Ladenburg
2. Ladenburg	Wallstraße 59	D-88526	Ladenburg
3. Alzenau	Borsigstraße 2	D-63755	Alzenau
4. Alzenau	Schlossstraße 2	D-63755	Alzenau
5. Göttingen	Oeranfelder Straße 2	D-37078	Göttingen
6. Ratingen	Oberhauser Straße 33	D-40472	Ratingen
7. Cottbus	Segewer Strasse 17/18	D-03046	Cottbus

List written on 09.10.2009


DEKRA Certification GmbH
Stuttgart, 04.09.2009

DEKRA Certification GmbH | Headquarter 10 - DE/02005 Stuttgart | www.dekra.com/deutschland

Fig. 3-1: Certificates

ZERTIFIKAT BS OHSAS 18001:2007



bescheinigt hiermit, dass das Unternehmen



ABB Automation Products GmbH
Wallstädter Straße 59 • 68526 Ladenburg
(Weiteren Standorte siehe Anhang)

Qualitätsmanagement

Entwicklung, Projektierung, Planung, Fertigung, Service und Vertrieb von Produkten und Dienstleistungen der Instrumentierung, Motoren & Antriebe und Niederspannungschaltanlagenfirmen

einen Managementsystem für Arbeitssicherheit und Gesundheitsschutz entsprechend den oben genannten Standards eingeführt hat und dieses wissksam anwendet. Der Nachweis wird im Rahmen des Zertifizierungs-Audits Beicht-Nr. A0911073 erbracht. Dieses Zertifikat ist nur in Verbindung mit der erfolglosen Durchführung der Überwachungsaudits gültig.

Diese Zertifikat ist gültig ab: 09.10.2009
Diese Zertifikat ist gültig bis: 05.10.2012
Letzter Ausstap: 04.09.2009

Ersatzerteilung: 06.10.2009
Zertifikat-
Registrier-Nr.: 2710040162
Duplikat



TGA-ZB-A05-91-64

CERTIFICATE BS OHSAS 18001:2007



hereby certifies that the company



ABB Automation Products GmbH
Wallstädter Straße 59 • 68526 Ladenburg
(further locations see annex)

Business field:

Development, project engineering, planning, manufacturing, service and sales of products and services of instrumentation, motors & drives and low-voltage switchgear systems.

has implemented and maintains an occupational health and safety management system according to the above mentioned standard. Proof of conformity is documented in the certification audit report no. A0911073. This certificate is only valid in connection with the successful performance of the surveillance audits.

the certificate is valid from: 09.10.2009
This certificate is valid until: 05.10.2012
Last valid day: 04.09.2009

Date of the first certification: 06.10.2009
Certificate registration nr.: 2710040162
Duplicate



TGA-ZB-A05-91-64

Anhang zum Zertifikat Nr. 2710040162
vom 09.10.2009 gültig bis 05.10.2012

Die folgenden Standorte fallen unter das o.g. Zertifikat:

Niederlassungen/ Vertriebsbüros	Strasse	Land - Postcode	Ort
1. Ladenburg	Wallstädter Straße 59	D-68526	Ladenburg
2. Ladenburg	Wallstädter Straße 59	D-68526	Ladenburg
3. Alzenau	Borsigstraße 2	D-63755	Alzenau
4. Minden	Schillerstraße 72	D-32423	Minden
4. Erdingen	Dranfelder Straße 2	D-37078	Göttingen
6. Ratingen	Oberhauser Straße 33	D-40472	Ratingen
7. Cottbus	Gaglower Straße 17/18	D-03046	Cottbus

Liste erstellt am 09.10.2009

DEKRA Certification GmbH



Seite 1 von 1

Annex to the certificate no.2710040162
from 09.10.2009 valid until 05.10.2012

The following locations belong to the certificate above:

Subsidiaries/ Sales offices	Street	Country Postcode	Location
1. Ladenburg	Wallstädter Straße 59	D-68526	Ladenburg
2. Ladenburg	Wallstädter Straße 59	D-68526	Ladenburg
3. Alzenau	Borsigstraße 2	D-63755	Alzenau
4. Minden	Schillerstraße 72	D-32423	Minden
4. Erdingen	Dranfelder Straße 2	D-37078	Göttingen
6. Ratingen	Oberhauser Straße 33	D-40472	Ratingen
7. Cottbus	Gaglower Straße 17/18	D-03046	Cottbus

List written on 09.10.2009

DEKRA Certification GmbH



page 1 of 1

Fig. 3-2:

3.2 Degrees of Protection per EN 60529 (Excerpts from the Standard Sheet)

The standard EN 60529 classifies the protection of electrical equipment by housings, enclosures, or the like. It defines various degrees of protection (IP).

The standard 60529 includes:

- Protection of personnel against electric shock from parts that are energized during operation or from approach to such parts as well as protection against physical contact with moving parts within the equipment (housings) and protection of the equipment against entry of solid objects (physical contact and foreign object protection)
- Protection of equipment against damaging ingress of water (water protection)

Identification

The degrees of protection are designated by a code consisting of the two fixed code letters IP (Ingress Protection Rating) followed by two code numbers which identify the degree of protection.

The first code number indicates the degree of protection against physical contact and foreign bodies. The second code number indicates the degree of protection against the damaging ingress of water.

For designating the full IP code (letters and numbers) the standardized term “Degree of protection” is to be used.

Degree of protection	EN 60529-	IP	4	4
Name _____				
EN standard number _____				
Code letters _____				
First code number (see Tab. 3-1) _____				
Second code number (see Tab. 3-2) _____				

A housing with the code shown in the example above is protected against the penetration of solid foreign bodies with a diameter greater than 1 mm and against water spray.

If the degree of protection of a part of the equipment, e.g. the terminals, should be different from the degree of protection of the main part, the IP code of the deviating part must be specified separately. In this case, the lower degree of protection is indicated first.

Example: Terminals IP 00 – Housing IP 54

Degrees of Protection Against Contact and Foreign Bodies

First Code Number	Degree of Protection (Protection Against Contact and Foreign Bodies)
0	No special protection
1	Protection against solid foreign bodies with a diameter of 50 mm or greater (large foreign bodies) ¹⁾ . No protection against intentional access, e.g. by hand, but against contact with large surfaces.
2	Protection against solid foreign bodies with a diameter of 12 mm or greater (medium size foreign bodies) ¹⁾ . Protection against contact with fingers or similarly sized objects.
3	Protection against solid foreign bodies with a diameter of 2.5 mm or greater (small foreign bodies) ^{1) 2)} . Protection against tools, wires or similar objects with a diameter or thickness greater than 2.5 mm.
4	Protection against solid foreign bodies with a diameter of 1 mm or greater (granular foreign bodies) ^{1) 2)} . Protection against tools, wires or similar objects with a diameter or thickness greater than 1 mm.
5	Protection against ingress of damaging dust. The entry of dust is not totally prevented, but dust must not enter in sufficient quantity to affect proper operation of the equipment (protected against dust) ³⁾ . Full protection against contact.
6	Protection against the ingress of dust (dust-tight). Full protection against contact.

¹⁾ Equipment with the degree of protection 1 to 4 is protected against the penetration of regularly or irregularly shaped foreign bodies where the dimensions in three perpendicular planes are larger than the specified diameter.

²⁾ For the degrees of protection 3 and 4 the application of this table falls under the jurisdiction of the responsible technical committee when drain or vent holes exist in the equipment.

³⁾ For the degrees of protection 5 and the application of this table falls under the jurisdiction of the responsible technical committee when drain or vent holes exist in the equipment.

Tab. 3-1: Degrees of Protection for the First Code Number

Degrees of Protection Against Water Ingress

Second Code Number	Degree of Protection (Protection against Water Ingress)
0	No special protection
1	Protection against vertical water drips. The water must not have a harmful effect (dripping water)
2	Protection against vertical water drips. Vertically dripping water shall have – with the equipment (enclosure) tilted by 15° compared to its normal position – no harmful effect (slanted falling water).
3	Protection against water falling at any angle up to 60° as compared to the vertical position. It must not have any harmful effect (spray water).
4	Protection against water splashed from any angle or direction against the equipment (housing). It must not have a harmful effect (splash water).
5	Protection against a water jet from a nozzle, projected from any direction against the equipment (enclosure). The water jet must not have a harmful effect (water jet).
6	Protection against water from heavy seas or powerful jets. The water must not ingress into the equipment (enclosure) in harmful quantities (flooding).
7	Protection against water when the equipment (enclosure) is immersed in water under defined conditions in pressure and time. The water must not ingress in harmful quantities (immersion).
8	The equipment (enclosure) is suitable for continuous submergence in water under conditions which shall be specified by the manufacturer (submersion).

- ¹⁾ This degree of protection usually means that the equipment is hermetically sealed. With specific types of equipment water may ingress, but only to such an extent that it produces no harmful effect.

Tab. 3-2: Degrees of Protection for the Second Code Number

3.3 Requirements Regarding Interference Immunity (EMC)

The measuring electronics of flowmeters are constantly becoming more efficient and more compact. Digital data processing with its microprocessors has opened up new avenues for new communications, diagnostic functions, and short response times. The integral mount design also requires new ways in terms of the power supply. Advanced measuring electronics are usually provided with switch-mode power supplies. In order to ensure reliable functionality and a high immunity to interference, the measuring electronics are subjected to various tests. Electromagnetic compatibility (EMC) plays an essential role.

With the advent of the common European market, the European Union has adopted various directives. It is stipulated that all devices released to the European market must comply with the valid directives. This is visible to the customer through the CE mark that has to be attached to the devices, and the CE declaration of conformity delivered with the devices.

Over the years, the measuring electronics and, thus, the requirements on the test procedures have considerably changed. The EMC Directive has been revised to meet these new requirements. Since July 20, 2007, the new EMC Directive 2004/108/EC has been in force and applied by the manufacturers.

At national level, the new EMC Directive 2004/108/EC has been implemented, among others, through the generic standards EN 61000-6-2:2005 (Immunity standard for industrial environments) and EN 61000-6-4:2007 (Emission standard for industrial environments). EN 61326 is the product standard for Electrical equipment for measurement, control and laboratory use. All ABB flowmeters comply with these standards and directives.

Besides the requirements stipulated in EMC Directive 2004/108/EC, there are additional requirements, for example for the chemical industry, which are defined in the NAMUR Recommendations. Here, more stringent test requirements are stipulated than in the EMC Directive, for example a higher immunity test level.

Moreover, there exist special requirements from the Organisation Internationale de Métrologie Légale (OIML) (English name: International Organization of Legal Metrology) regarding the measuring accuracy under the influence of electromagnetic interference.

Types of Interference

In the context of electromagnetic compatibility (EMC) a distinction is made between two different types of interference:

- The conducted interference is transmitted directly from the interference source via the supply or signal line to the load. For example, a clicking noise that you hear on your radio may be caused by your electrical water boiler being switched off. The automatic switch-off of the water boiler's supply voltage generates a voltage pulse, the spectrum of which lies within the audible frequency range. When voltage pulses of this kind are transmitted via the radio power cord, the clicking interference occurs.
- The radiated interference is transmitted to the load via electromagnetic fields and can be received, for example, by a printed circuit board track operating as an antenna. Also, capacitive or inductive coupling of electrical or magnetic fields is possible. An example of radiated interference is a cell phone communication coupled into a radio. The reason for this may be an insufficiently shielded loudspeaker.

Interference Causes

An interference signal may be caused by a voltage variations in time or by currents, e.g. resulting from a switching operation. These produce periodic voltage or current changes. The currents and voltages of the interference source that are variable in time cause magnetic or electrical fields which may generate an interference signal at the load. Interference sources may have the following technical or natural causes:

- Variations in / interruptions of the supply voltage
- Electromagnetic fields, generated by transmitters operating in the frequency range from few kHz (long wave transmission) up to several GHz (cell phones, microwave ovens).
- Lightning electromagnetic pulses (LEMP)
- Surge voltage pulses caused by switching operations in low-voltage networks
- High-frequency, low-power burst pulses caused by switching operations of switch-mode power supplies
- Electrostatic discharge (ESD)
- High-frequency signals produced by load changes of microprocessors or frequency converters
- A nuclear electromagnetic pulse (NEMP) produced by a nuclear weapon explosion

Interference signals are often generated by electrical switches, relays, contactors, fluorescent lamps, solenoid valves, electric motors, radio transceivers or atmospheric disturbances like lightning.

Evaluation of the Interference Response

The interference response of a device is a means of evaluating how a device reacts in the event of a disturbance or interference. There are three evaluation criteria:

- No reduction in functionality.

Mainly analog devices may be affected within their error limits. Purely digital devices must not be affected at all.

- Reduction in functionality.

A certain reduction of the functionality while the device is subjected to the interference is permissible under the proviso that the device is capable of automatically resuming normal operation once the interference is over. No permanent damage may be caused.

- Loss of functionality.

Evaluated is primarily the functional failure at the onset of an interference until an automatic or manual restart occurs. When the tolerances are exceeded or underscored, the devices must be capable of restarting automatically or must remain, ready for restart, in their defined fail-safe position.

Limitation of Interferences

Interferences can be limited by EMI/RFI shielding of the interference source or by providing a sufficient interference immunity of the load.

In order to achieve an EMC compliant circuit layout, the following measures are taken:

- Avoid unnecessary switching operations
- Perform unavoidable switching operations as slowly as technically possible
- Limit unavoidable interference as far as possible by using the appropriate design elements on site (e.g. RC elements for interference shielding, shielded housings or cables)
- Choose a PCB layout that complies with the EMC requirements (e.g. adapt the length of the PCB tracks to the frequency, use grounding planes for shielding)
- Ensure sufficient interference immunity (e.g. through filters, blocking capacitors or failure-tolerant software)

Regarding the overall EMC protection independent of the individual devices, the following is aspired:

- Determine interference sources and loads through system analyses.
- Provide for sufficient shielding.
- Keep the specified distances.
- Improve the interference immunity of the load.

Electromagnetic compatibility of plants and systems can be reliably realized by introducing an interference protection concept with defined conditions for the devices to be used.

3.4 Explosion Protection

Among the variety of products and intermediate products of the chemical and industrial process industries there are many which can form explosive mixtures with other products or with the oxygen in the air. Measurement and control equipment that comes into contact with such mixtures must not cause an explosion, but must nevertheless operate effectively.

In order for an explosion to occur, a number of events must occur simultaneously:

- A sufficient degree of dispersion (degree of scattering) for mist or dust require particle sizes between 0.1 and 0.001 mm. For gases this degree is provided by nature.
- Only when the concentration of a flammable substance in air exceeds a minimum value does the danger of an explosion exist. On the other hand there is a maximum value (a too rich mixture) above which an explosion can no longer take place.
- Naturally a sufficient amount of the mixture must be available. As little as 10 liters of an explosive mixture are considered to be dangerous.
- An ignition source must provide sufficient energy in order to initiate the explosion.

Considering these criteria some measures to prevent an explosion inevitably come to mind:

Explosive mixtures are to be avoided, their quantity is to be limited, ignition must be prevented and, in a worst case scenario, the impact of an explosion must be mitigated.

These measures are considered during the design of the instruments. For example, the space in which an explosive mixture can accumulate is kept very small or the energy content of a possible spark source is minimized or the explosion is restricted to a small space.

3.4.1 International Orientation of Explosion Protection

All over the world, the explosion protection is governed by different, country-specific national standards. For ABB products this means: the same technical design, but different, country-specific approvals. Only in this way a worldwide commercialization can be achieved with little product variance, and customers throughout the world can use the same product. On the customer side, this strategy yields cost reductions, e.g. for training, project planning and maintenance of the corresponding products.

	European Union	USA	Canada	Russia	Ukraine	Australia
Directive / Standard / Approval Body	ATEX – PTB – EXAM BBG – KEMA – TÜV Nord – ZELM – IBEExU ...	FM Ex-Approval UL Ex-Approval	CSA-Certificate	GOST Russia	GOST Ukraine	IECEx
Validity	No restrictions	No restrictions	No restrictions	3 years	3 years	No restrictions
Production Supervision Auditing	yes	yes	yes	no	no	yes

Tab. 3-3: Overview of Important Country-specific Standards, Approvals and Approval Bodies

Basically, the requirements for all approvals are similar to each other and pursue the same goal: prevent, according to the state of the art, that an explosion can occur in a plant that has been instrumented in compliance with the national explosion protection requirements.

3.4.2 Terms and Definitions

Explosion

An explosion is an exothermic reaction of a substance at a very high reaction rate. It requires the presence of an explosive mixture/atmosphere and of an ignition source plus an extraneous cause that triggers the explosion.

Explosion Hazard

An explosion hazard is given if an explosive mixture/atmosphere is present, but is not ignited by an ignition source or due to an extraneous cause.

Explosive Mixture/Atmosphere

Mixture of air and gases, vapors, mists or dusts that is flammable under atmospheric conditions and in which the combustion is spread to the entire remaining unburnt mixture once an ignition has occurred.

Explosion Limits

The lower (LEL) and upper (UEL) explosion limits specify the range within which an air mixture of a substance is explosive. The explosion limits are specific to the individual substances and can be looked up in the appropriate reference literature.

Explosion Groups in Accordance with the EN Standards

The flammability and resistance to ignition flash-over of an explosive mixture are specific to a substance. These specifications are especially important for equipment engineering. For intrinsically safe electrical equipment the ignition energy is a criterion for flammability. The lower the required ignition energy, the more hazardous the mixture. The resistance to ignition flash-over provides for information relative to the maximum experimental safe gap and the width of the flameproof joint of equipment with flame-proof enclosure.

Explosion Group	Ignition Energy	Test Gas	Range
I	< 200 µJ ¹⁾	Methane in air	Firedamp protection
II A	< 160 µJ ¹⁾	Propane in air	
II B	< 60 µJ ¹⁾	Ethylene in air	
II C	< 20 µJ ¹⁾	Hydrogen in air	Explosion protection

¹⁾ Doubling the energy values is permissible if the charging voltage is < 200 V.

Tab. 3-4: List of Explosion Groups According to EN Standards

Gases and vapors are classified according to these criteria. The following table lists the classification of various materials. The equipment used for these materials must be certified accordingly.

Explosion Group	Ignition Temperature					
	T1	T2	T3	T4	T5	T6
I	Methane					
II A	Acetic acid Ethane Ethyl acetate Ammonia Benzene (pure) Acetic acid Methanol Propane Toluene	Ethyl alcohol i-amyl acetate n-butane n-butyl alcohol	Benzine Diesel fuel Aircraft fuel Heating oils n-hexane	Acetyl aldehyde Ethyl ether		
II B	Carbon monoxide	Ethylene	Hydrogen sulfide	Ethyl ether Butyl ether		
II C	Hydrogen	Acetylene				Carbon disulfide

Tab. 3-5: Classification of Materials By Explosion Groups

Flash Point

The flash point is the lowest temperature at which vapors can escape under defined conditions from the liquid to be tested in a sufficient quantity to yield a flammable air-liquid mixture above the liquid level.

Ignition Energy

The minimum ignition energy is the energy in a spark that suffices to ignite the surrounding explosive gas-air mixture.

Ignition Temperature in Accordance with the EN Standards

The ignition temperature of a combustible material is the lowest temperature of a heated wall determined with a probe at which a mixture of the combustible material and air will ignite.

The ignition temperature of liquids and gases is determined using the procedure specified in DIN 51794. For the time being, there is no standardized method for determining the ignition temperature of combustible dusts. In the relevant literature several methods are specified.

Combustible gases and vapors of combustible liquids are divided into temperature classes according to their ignition temperature. Equipment parts are classified by their surface temperature.

Temperature Class	Highest Permissible Surface Temperature of the Equipment in °C	Ignition Temperatures of Combustible Materials in °C
T1	450	> 450 ...
T2	300	> 300 ≤ 450
T3	200	> 200 ≤ 300
T4	135	> 135 ≤ 200
T5	100	> 100 ≤ 135
T6	85	> 85 ≤ 100

Tab. 3-6: Temperature Classes

Ignition Sources

In the following, the most frequently occurring ignition sources are listed:

- Hot surfaces (heatings, hot apparatuses, etc.),
- Flames and hot (combustion) gases
- Mechanically produced sparks (through friction, strokes, abrasion)
- Sparks from electrical systems,
- Compensation currents,
- Static electricity,
- Lightning, ultrasonic sound
- Optical ignition sources,
- Electrical fields through radio waves,
- ...

Primary and Secondary Explosion Protection

In the context of avoiding explosions a distinction is made between primary and secondary explosion protection.

Primary explosion protection implies avoidance of the formation of a hazardous explosive atmosphere:

- Avoidance of combustible liquids and gases,
- Increase of the flash point,
- Avoidance of the formation of explosive mixtures by limiting the concentration of substances,
- Ventilation, either technical or through use of open air systems,
- Concentration monitoring with emergency stop function

Secondary explosion protection includes all measures that can be taken to prevent the ignition of a hazardous atmosphere:

- No effective ignition source
 - Intrinsically safe equipment
 - Flameproof enclosure of the ignition source to prevent external ignition
 - Powder filling
 - Encapsulation
 - Flameproof enclosure
 - Pressurized enclosure
- ...

Zones in Accordance with the EN Standard

The hazardous area is divided into three zones. The probability of the existence of a potentially hazardous atmosphere is a criterion for the division as described below:

For Gases, Vapors and Mists (EN 60079-10)

Zone 0: Area, in which a potentially explosive atmosphere in the form of a mixture of air and combustible gases, vapors or mists *is present continuously, for long periods or frequently.*

Category: 1 G

Zone 1: Area in which, during normal operation, a potentially explosive atmosphere in the form of a mixture of air and combustible gases, vapors or mists can occur *occasionally.*

Category: 2 G

Zone 2: Area in which, during normal operation, a potentially explosive atmosphere in the form of a mixture of air and combustible gases, vapors or mists occurs *not at all or only for a short time period.*

Category: 3 G

For Dusts (EN 61241-10)

Zone 20: Area in which a potentially explosive atmosphere in the form of a cloud of combustible dust in air *is present continuously, for long periods or frequently.*

Category: 1 D

Zone 21: Area in which, *during normal operation* a potentially explosive atmosphere in the form of a cloud of combustible dust in air *can occur.*

Category: 2 D

Zone 22: Area in which, during normal operation, a potentially explosive atmosphere in the form of a cloud of combustible dust in air usually occurs *not at all or only for a short time period.*

Category: 3 D

Remark:

Layers, deposits and accumulations of combustible dust must be taken into account to the same extent as any other cause that may lead to the formation of a hazardous explosive atmosphere.

Normal operation is considered to be the state in which the plant or system is run within its specified parameters and limits.

Equipment of Category 1G/1D, Equipment Group II

The categories 1G (gas) and 1D (dust) include all equipment designed in such a way that it can be operated in compliance with the parameters specified by the manufacturer and provides a very high degree of safety.

Equipment of these categories is suited for installation in Zone 0 (1G equipment) and Zone 20 (1D equipment). Equipment in this category is required to remain functional, even in the event of rare incidents relating to equipment, with an explosive atmosphere present, and is characterized by means of protection such that:

- either, in the event of failure of one means of protection, at least an independent second means provides the requisite level of protection,
- or the requisite level of protection is assured in the event of two faults occurring independently of each other.

Equipment in this category must comply with the supplementary requirements referred to in Annex II, Number 2.1 of the EC Directive 94/9/EC.

Equipment of Category 2G/2D, Equipment Group II

The categories 2G (gas) and 2D (dust) comprise all equipment designed to be capable of functioning in conformity with the operational parameters established by the manufacturer and ensuring a high level of protection.

Equipment of these categories is suited for installation in Zone 1 (2G equipment) and Zone 21 (2D equipment). The means of protection relating to equipment in this category ensure the requisite level of protection, even in the event of frequently occurring disturbances or equipment faults which normally have to be taken into account.

Equipment of Category 3G/3D, Equipment Group II

The categories 3G (gas) and 3D (dust) comprise all equipment designed to be capable of functioning in conformity with the operational parameters established by the manufacturer and ensuring a normal level of protection.

Equipment of these categories is suited for installation in Zone 2 (3G equipment) and in Zone 22 (3D equipment) for a short time period. During normal operation equipment in this category provides the required degree of safety.

DIV Division According to NEC500 (USA) and CEC Annex J (Canada)

In addition to the division into Zone 0 and Zone 1 according to European instrumentation standards for hazardous areas, NEC500 and CEC Annex J provide a classification into Divisions. The following table is an overview of the individual zones and divisions.

IEC / EU	Zone 0	Zone 1	Zone 2
US NEC505	Zone 0	Zone 1	Zone 2
US NEC500	Division 1		Division 2
CA CEC Section 18	Zone 0	Zone 1	Zone 2
CA CEC Annex J	Division 1		Division 2

Tab. 3-7: Comparison of Zones and Divisions

IEC classification according to IEC 60079-10

EU classification according to EN60079-10

US classification according to ANSI/NFPA70 National Electrical Code Article 500 and/or 505

CA classification according to CSA C22.1 Canadian Electrical Code (CEC) Section 18 and/or Annex J

Explosion groups according to NEC500 (USA) and CEC Annex J (Canada)

Explosion Group US NEC500 CA CEC Annex J	Explosion Group US NEC505 CA CEC Section 18 EU IEC	Test Gas	Range
Mining	I	Methane	Firedamp protection
Class I Group D	II A	Propane	
Class I Group C	II B	Ethylene	
Class II Group A	II C	Acetylene	Explosion protection
Class I Group B	II B + hydrogen	Hydrogen	

Tab. 3-8: List of Explosion Groups According to US/CA Standards

Temperature Classes According to NEC500 (USA) and CEC Annex J (Canada)

Max. Surface Temperature	US NEC505 CA CEC Section 18 EU IEC	US NEC 500 CA CEC Annex J
450 °C	T1	T1
300 °C	T2	T2
280 °C		T2A
260 °C		T2B
230 °C		T2C
215 °C		T2D
200 °C	T3	T3
180 °C		T3A
165 °C		T3B
160 °C		T3C
135 °C	T4	T4
120 °C		T4A
100 °C	T5	T5
85 °C	T6	T6

Tab. 3-9: Division of Temperature Classes According to US/CA Standards

3.4.3 Types of Protection in Europe and North America

Type of protection Intrinsic Safety "i" according to EN 50020 or EN 60079-11

The equipment installed in the hazardous area contains only intrinsically safe circuits. A circuit is intrinsically safe when sparks or thermal effects cannot occur under defined test conditions (which include normal operation and certain malfunctions) which could ignite a particular explosive atmosphere.

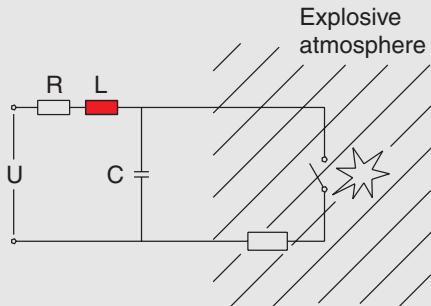


Fig. 3-3: Schematic Representation of Intrinsic Safety

There are two categories of intrinsic safety.

Category "ia" for use in Zone 0:

The devices must be so designed that in the event of a failure or under every possible combination of two failure modes an ignition is excluded.

Category "ib" for use in Zone 1:

The devices must be so designed that in the event of a failure an ignition is not possible.

Type of protection Flameproof Enclosure “d“ according to EN 50018 or EN 60079-1

Parts which can ignite a potentially explosive atmosphere are contained in an enclosure which itself will contain the pressure of an explosion of a hazardous mixture occurring in its interior and prevent the explosion from reaching the atmosphere surrounding the enclosure through a special geometry of the gap.

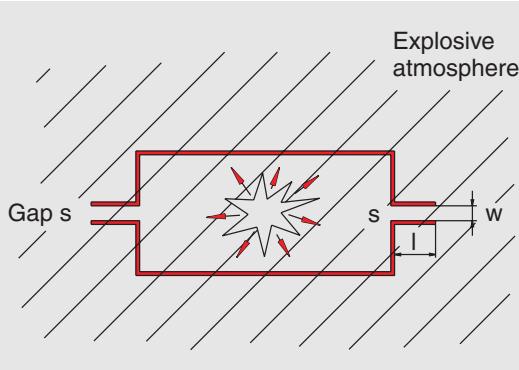


Fig. 3-4: Schematic Representation of a Flameproof Enclosure

Type of protection Increased Safety “e“ according to EN 50019 or EN 60079-7

In this case additional measures are incorporated to increase the degree of safety of an instrument by preventing prohibited higher temperatures and the generation of sparks and arcs inside or outside of the electrical equipment which during normal operation will not occur.

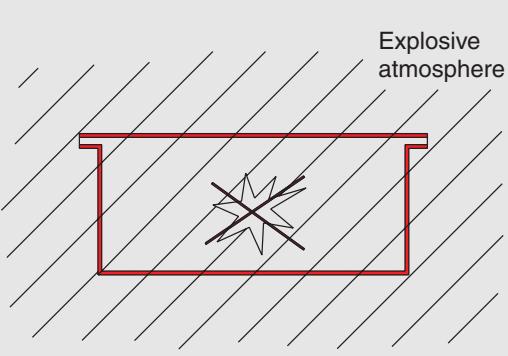


Fig. 3-5: Schematic Representation of Increased Safety

Type of protection Pressurized Enclosure “p“ according to EN 50016 or EN 60079-13

The entry of an explosive atmosphere into the housing of electrical equipment is prevented by filling the interior of the housing with an ignition protecting gas (air, inert or other appropriate gas) under a pressure greater than that of the surrounding atmosphere. The overpressure is maintained with or without constant flushing with protective gas.

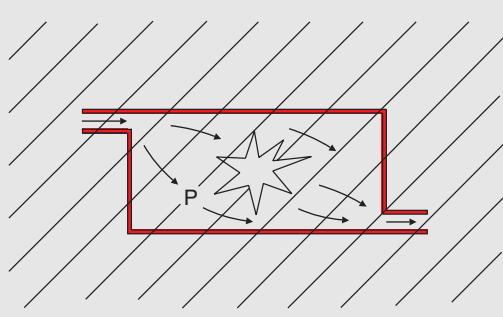


Fig. 3-6: Schematic Representation of Pressurized Enclosure

Type of protection Oil Immersion “o“ according to EN 50015 or EN 60079-6

Electrical equipment or parts thereof are made safe by surrounding them with oil so that an explosive atmosphere on the surface or outside of the housing will not be ignited.

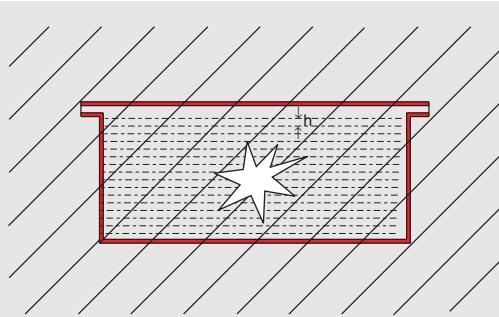


Fig. 3-7: Schematic Representation of Oil-Immersion

Type of protection Powder Filling “q“ according to EN 50017 or EN 60079-5

The housing of electrical equipment is filled with sand or some other fine grained material so that, when used as intended, an arc occurring within the housing will not ignite an explosive atmosphere external to it. Ignition may not occur either by a flame or by an increased temperature on the surface of the housing.

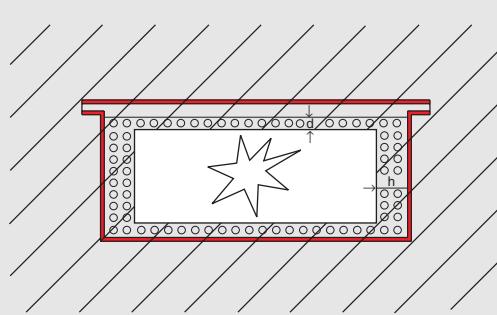


Fig. 3-8: Schematic Representation of Powder Filling

Type of protection Encapsulation “m“ according to EN 50028 or EN 60079-18

Parts which could ignite an explosive atmosphere are encapsulated in a casting material which is sufficiently resistant to the environment so that the explosive atmosphere cannot be ignited by sparks or heating within the encapsulation.

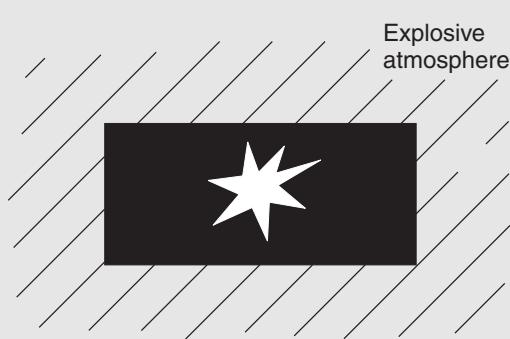


Fig. 3-9: Schematic Representation of Encapsulation

Type of protection Non-Sparking Equipment “nA“ according to EN 50021 or EN 60079-15

Non-sparking equipment is designed so as to minimize the probability of the occurrence of arcs or sparks that could raise a risk of ignition during normal operation. Normal operation excludes the removal or insertion of components while the current circuit is live.

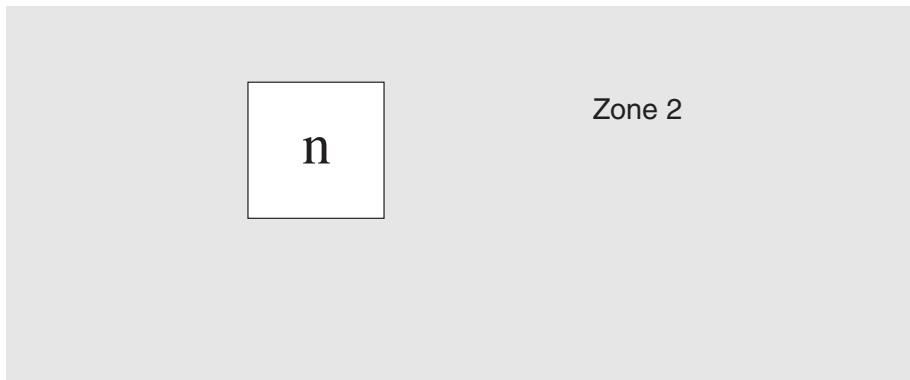


Fig. 3-10: Schematic Representation of Non-sparking Electrical Equipment

3.4.4 Approvals According to the FM Approval Standards

Flowmeters from ABB fulfill the following FM standards, depending on the certification and field of application:

- Intrinsically Safe Apparatus and Associated Apparatus for use in Class I, II and III, Division 1, and Class I, Zone 0 and 1. Hazardous (Classified) Locations. Approval Standard Class Number 3610.
- Nonincendive Electrical Equipment for use in Class I and II, Division 2, and Class III, Divisions 1 and 2. Hazardous (Classified) Locations. Approval Standard Class Number 3611.
- Explosionproof Electrical Equipment General Requirements. Approval Standard Class Number 3615.

The corresponding operating instruction and the Control Drawing must be observed when installing the device. Additionally, the National Electrical Code (NEC) must be observed for the installation.

3.4.5 Approvals in Accordance with the CSA Standards

Flowmeters from ABB fulfill one or more of the following CSA standards, depending on the certification and field of application:

- CAN/CSA-E60079-11:02 Electrical apparatus for explosive gas atmospheres - Part 11: Intrinsic safety „i“ C22.2 No.213-M1987 (Reaffirmed 1999) Non-incendive Electrical Equipment for use in Class I, Division 2. Hazardous Locations.
- C22.2 No. 30-M1986 (Reaffirmed 1999) Explosion-proof Enclosures for use in Class I. Hazardous Locations.

The corresponding operating instruction and the Control Drawing must be observed when installing the device. Additionally, the Canadian Electrical Code (CEC) Part I (Safety Standard for Electrical Installation) must be observed for installation.

3.4.6 Free Movement of Goods Related to Explosion-Proof Electrical Devices

The prerequisite for the free movement of goods within the European Community is governed by EC Directives. Since July 1st, 2003, the Directive 94/9/EC (ATEX 95, formerly 100a) must be applied.

Additionally, ATEX 95 a conformity evaluation of the Quality Assurance of the manufacturer, which includes special requirements for explosion proof equipment during development, design and manufacturing.

Device that have been tested in accordance with ATEX 95 and for which a Type Examination Certificate has been granted by the certifying body are additionally identified by a CE mark. The identification number of the test body who has evaluated the quality assurance is also added.

The specifications and the safety-relevant sections of the operating instruction must be provided in the national language of the country where the product is used.

3.4.7 Identification of Equipment

Equipment intended for use in hazardous areas must be uniquely identified by the manufacturer. To comply with EN 50014 or EN 60079-0 / EN 50020 or EN 60079-11 the equipment must be labeled with the following information:

- Manufacturer name and address
- CE mark
- Designation of the series and type
- Serial number, if applicable
- Year of manufacture
- Special identification for the prevention of explosions in conjunction with the identification of the category
- For the equipment group II the letter "G" (for areas in which potentially explosive gas, vapor, mist and air mixtures are present) and/or the letter "D" (for areas where dust may form potentially explosive atmospheres).

Example of an ABB Explosion Protection Classification and Identification

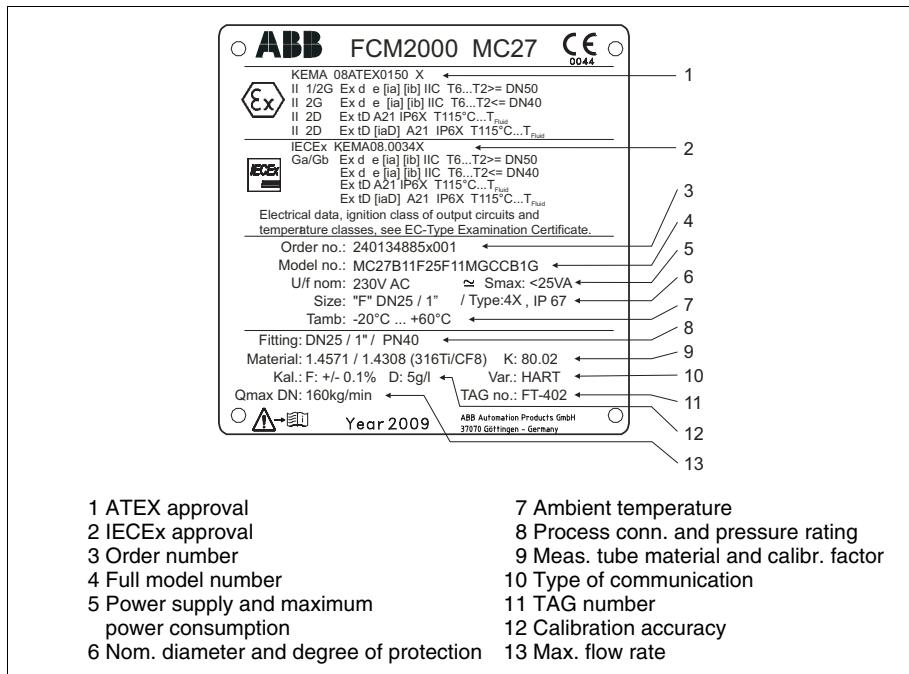


Fig. 3-11: Example of a Device Identification (here acc. to ATEX)

EC Type Examination Certificate KEMA 08 ATEX 0150 X

KEMA	= Approval body
08	= Year of approval
ATEX	= Directive 94/9 EC
0150	= Serial number
X	= Special conditions

Ex-Coding: II 1/2G Ex d e [ia] [ib] IIC T6 ... T2

II	= Explosion group
1/2	= Category 1 and Category 2
G	= Gases, vapors, mists
Ex	= Identification of the degree of explosion protection
d	= Type of protection flameproof enclosure
e	= Type of protection increased safety
ia	= Type of protection intrinsic safety, 2-fault safety
ib	= Type of protection intrinsic safety, 1-fault safety
IIC	= Explosion group IIC
T6 ... T2	= Temperature class

3.5 GOST Approvals for Flow Measurement

Note: ABB cannot assume any liability regarding possible legal amendments of the approval procedures or formalities nor for possible legal regulations that are additionally valid in Russia, Belarus, Ukraine and Kazakhstan.

3.5.1 Russia

GOST-R Certificate of Conformity

The GOST-R certificate is obligatory.

Origin

The designation “Gost-R Certificate of Conformity” has established itself in the course of time. It is a translation from the Russian word for “compliance certificate” meaning that the certified product meets the requirements of the corresponding GOST standards.

Introduction of the GOST-R Certification System

In 1989, the Russian authorities introduced preliminary regulations for the assurance of products manufactured and commercialized in Russia in order to provide for consumer protection. In the early 90ies these regulations have come into force. This was the legal and technical basis for the creation of the national certification system. From 1992 on these regulations have been put into practice.

All products that are produced or imported into the Russian Federation are subjected to obligatory certification. The GOST-R Certificate of Conformity corresponds to the CE Declaration of Conformity.

The GOST-R certificate differs from the CE declaration in that the CE Declaration of Conformity can be issued by the manufacturer himself whereas the GOST-R Certificate of Conformity can only be awarded by an external certification company.

Certification Process

First the products are inspected either in the laboratory or on site. An expert from the certification company verifies the inspection results and then decides whether a certificate can be awarded or not. The customs tariff number and the OKP code (Russian product classification code) are determined. Then the certificate is issued. Certified products are subjected to marking obligations and must be identified accordingly on the packing, on the name plate and in the product documentation.

The certificate is an important paper of the export documents when exporting products to Russia. Besides the GOST-R Certification there are other certifications and approvals. On the Russian domestic market these certificates are an essential quality feature the advertising effect of which should not be underestimated. The end user considers a certificate as a token of high quality.

There are, however, product groups that do not require the GOST-R certification. For these products so-called negative certificates are issued.

There are various types of GOST-R certificates:

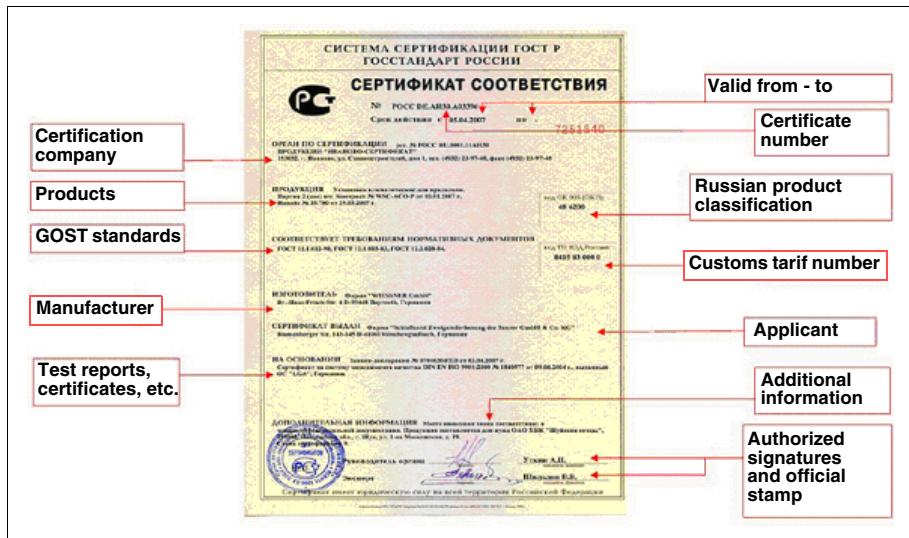
Contract-Related Certificate

This certificate is issued for a sales contract and is valid until the terms of the contract are fulfilled.

The contract must be concluded with a Russian customer who imports the products into Russia.

Certificates with a Validity Period of 1 to 3 Years

With this type of certificate the exporting company can export their products as often as required within the specified time period. For a certificate with a validity of 3 years the Russian authorities require onsite audit inspections at the manufacturer's plant.



GOST Metrology (Pattern Approval Certificate)

The measuring equipment approval also called the metrology certificate is an obligatory certificate for the flow measurement.

This certificate is a special variant and requires that a GOST-R certificate has already been issued. It mainly deals with the operational security of measuring devices. The Russian agency for technical regulation and metrology (Rostechregulierovanie) is in charge of issuing this certificate. The approval requires that the device is previously verified by accredited experts from a state-run metrological institution.

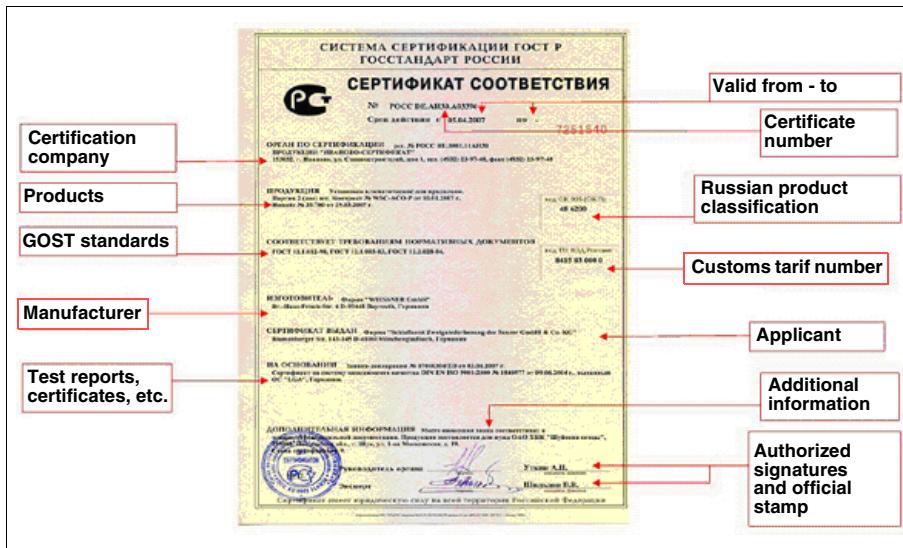
The registration includes the entry of the device in the database of the regulatory authority. The advantage is that an already registered device does not have to be re-registered.



GOST Explosion Protection

The GOST-EX certificate is obligatory for explosion proof flowmeters. GOST-EX certifications are performed by accredited Russian test laboratories. Approvals of this kind are always required when products with ATEX approval are imported into Russia. The approval is based on the valid EC type examination certificates in accordance with ATEX95.

The approval procedure includes, among other things, the inspection of the manufacturer plant and a type inspection of specific selected product types through the commissioned Russian certification agency. The certificate has a validity period of up to three years. Prolongation of the validity period must be requested in good time before its expiry. The entire approval procedure will take approximately three to four months.



GOST-RTN Permit to Use

The GOST-RTN permit to use is an obligatory certificate which provides permission to operate explosion proof flowmeters in hazardous areas. RTN permits to use are granted by the Federal Service for Ecological, Technological and Nuclear Supervision or Rostekhnadzor (RTN), previously the Federal Mining and Industrial Inspectorate of Russia, or Gosgortekhnadzor (GGTN). Rostekhnadzor is responsible for the development and observance of standards for industrial safety and quality. The Rostekhnadzor permit to use is an operating permit for machines and systems which pose a potential risk or are used in hazardous areas, for example in underground mines, smelting works or petrochemical production plants.

Among the hazardous equipment or technical devices for which RTN permits to use are required are production plants/facilities, valves, fired or non-fired pressure vessels, equipment for the chemical industry, equipment for the oil and gas production, equipment for underground mining, explosion-proof plants and equipment, gas appliances, gas grids, etc. An independent laboratory prepares an expertise for the RTN permit to use. Subsequently, all documents are submitted to Rostekhnadzor. The product-related documents and the expertise are examined by experts. An expert then decides whether all safety requirements are fulfilled and, if the results of the above checks are positive, draws up an official document.

The prerequisite of the RTN permit to use is that a GOST-R certificate and, for explosion proof device variants, a GOST EX certificate has been issued for the respective product. The permission must be granted before commissioning. The approval can be contract-related or have a validity period of five (5) years.



3.5.2 Belarus, Ukraine and Kazakhstan

Certification for Belarus

Generally speaking the certification procedure for Belarus is similar to those in the Commonwealth of Independent States (CIS) and the Russian Federation. There are, however, some differences which must be taken into account in order to provide for an unproblematic and quick exportation of products to Belarus.

The official certification institution of Belarus is the Department on Supervision of Safe Works Realization in the Industry of the Ministry for Emergency Situations of Belarus Republic (Gospromnadzor). Like its Russian counterpart Gospromnadzor grants certificates on the basis of an expertise submitted by accredited experts after having completed the accreditation procedure. In their expertise the experts confirm that the product to be imported complies with the regulatory rules of Belarus. As a rule, inspections on site are required.

Mandatory certificates for flowmeters are – similar to Russia – the metrology certificate and the EX-Promatomnadzor certificate which unites the Russian GOST-EX certificate and the RTN permit to use in a single certificate.

Certification for Ukraine

The regulatory rules for Ukraine regarding the import of foreign products are basically the same as for the Russian Federation (Russia), but may differ in details. The equivalent to the GOST-R certificate is the UkrSEPRO certificate which, for the time being, is considered as not obligatory for flowmeters. Moreover, the following certificates may be required in both Ukraine and the Russian Federation (Russia) for the importation of flowmeters in individual cases:

- Metrology certificate
- GOST-EX certificate with expert decision
- DVSC certificate (EX operating permit)

In Ukraine the certification procedure itself is more complex than in Russia and requires additional expert knowledge regarding the national decrees and laws in order to be able to successfully complete the certification process. Another difference is the proceeding of the accredited test institutes. The majority of the required tests and examinations are performed directly at the manufacturer's site. Usually, the experts must visit the company.

Certification for Kazakhstan

The regulatory rules for Kazakhstan regarding the import of foreign products are basically the same as for the Russian Federation (Russia), but may differ in details. The equivalent for the GOST-R certificate is the GOST-K certificate. Moreover, the following certificates are required in both Kazakhstan and the Russian Federation (Russia) for the import and marketing of flowmeters:

- GOST-K Certificate: may be obtained on site by own sales representatives.
- EX Permit to Use and EX Permission: unites the GOST-EX certificate and the RTN permit to use according to the Russian standard.
- Metrology Certificate: is issued by the KasInMetr authority.

The certification procedure itself is more complex than in Russia and requires additional expert knowledge regarding the national decrees and laws. Moreover, higher certification costs have to be expected. Another difference is the proceeding of the accredited test institutes. The majority of the required tests and examinations are performed directly at the manufacturer's site. Usually, the experts must visit the company.

3.6 SIL - Functional Safety Standards

The standards IEC 61508 and IEC 61511 provide methods for the risk assessment of safety-related systems. They define four safety integrity levels and describe measures for mastering the risks of plant parts. In order to determine the SIL level of a device, all field devices are subjected to the demanding test conditions and analyses of the IEC.

With the Council Directive 96/82/EC ("Seveso II Directive") the European Union has created the legal basis for the operation of plants with hazard potential. The German implementation of the Directive 96/82/EC in national legislation is the Hazardous Incident Ordinance in the Federal Act for the Protection against Immissions (12th. BlmSchV) as of April 26, 2000.

By July 31, 2004, the Hazardous Incident Ordinance referred to the standards DIN 19250 and 19251 with the requirements classes 1 - 8 for the construction of safety-related process control equipment. Since August 1, 2004, the Hazardous Incident Ordinance has referred to DIN EN 61508 and DIN EN 61511 which match the contents of the IEC 61508 / IEC 61511 standards. They define four safety integrity levels (SIL1 to SIL4) which describe the measures to be taken for mastering the risks of plant parts and to which the field devices and actuators must comply.

In order to be able to evaluate whether or not a device is suited for a safety chain with specific SIL requirements, the field devices are analyzed and verified in co-operation with an independent institution.

The hardware structure of the electronics is assessed by performing a Failure Mode, Effect and Diagnostics Analysis (FMEDA). Considering the (electro)mechanic components, the failure rates of a device, for example a flowmeter, can then be determined. Basically, three parameters are calculated from the FMEDA for this purpose: the Hardware Failure Tolerance (HFT), the Safe Failure Fraction (SFF) and the Probability of Failure on Demand (PFD).

The software development process of SIL-certified flowmeters is subject to IEC 61508 and, thus, is even beyond the requirements of IEC 61511.

Additionally, further general safety assessments of the field devices are performed. In the SIL Declaration of Conformity provided by the manufacturer in order to support the customer in selecting the appropriate devices for safety systems, the specified classification always refers to the lowest SIL level.

For the purpose of achieving safe plant operation, in another step according to the IEC regulations the entire safety systems consisting of the sensor/transmitters, control unit and actuator is considered and the SIL classification is made. Prior to the design and calculation of the safety system a SIL assessment is performed for determining the safety integrity level (e.g. SIL2) with which the safety system must comply.

ABB offers a special software which covers all aspects of plant certification from the SIL assessment to the design and calculation of the safety systems in accordance with IEC 61508. The software also logs and saves all decisions and calculation bases.

In daily operation of a plant, it is also necessary to check the safety systems in terms of their safety functions on a regular basis and record the results. To achieve this, individual test routines must be defined, executed and logged. A complex process, but a big advantage for the health, safety and environment.

In addition to its comprehensive instrumentation portfolio, ABB also offers a special software that manages the test routines and test results required in IEC 61508 for all safety systems and provides them for statistics.

3.7 Pressure Equipment Directive 97/23/EC

Introduction

The Council Directive for Pressure Equipment 97/23/EC (Pressure Equipment Directive, PED) belongs to a series of newly designed, harmonized EC directives intended to remove the technical barriers to free trade within the Community. At the same time it is a first step towards the product harmonization of pressure equipment with respect to the design, manufacturing and conformity assessment. The observance of specific safety requirements is of special importance.

The Council Directive 97/23/EC has been published on July 9, 1997 in the Official Journal of the European Community (OJ L181) and must be applied in all EC Member States since 2002, after having been implemented in national legislation.

Compliance with the provisions of this EC Directive, which includes several amendments with respect to the placement of pressure equipment on the market, is the responsibility of the manufacturer, confirmed by the attachment of the CE mark and the issuance of the EC Declaration of Conformity.

Scope

The Pressure Equipment Directive applies to the placement on the market and commissioning of pressure equipment and assemblies thereof with a maximum allowable pressure greater than 0.5 bar. It does not apply to the monitoring and repeated routine checks of this equipment during operation. Pressure equipment covered by the scope of this directive includes vessels, piping, safety accessories and pressure accessories and assemblies consisting of pressure equipment. A list of devices that are beyond the scope of the directive is found in the directive itself.

Essential Safety Requirements

According to the safety considerations of the Pressure Equipment Directive the obligations arising from the essential requirements listed in Annex I apply to pressure equipment and assemblies where the corresponding hazard exists. The safety requirements are compulsory. The manufacturer is under obligation to conduct a risk assessment in order to identify the hazards which apply to his equipment on account of pressure. The pressure equipment must be designed and constructed taking account of this analysis. The essential requirements are to be interpreted and applied in such a way as to take account of the state of the art and current practice at the time of design and manufacture as well as of technical and economic considerations. Pressure equipment must be designed, manufactured and checked, and if applicable equipped and installed, in such a way as to ensure its safety when put into service in accordance with the manufacturer's instructions.

As a result, measuring devices that are covered by the scope of the Pressure Equipment Directive but do not meet its requirements must not be placed on the market.

Conformity Assessment Procedure

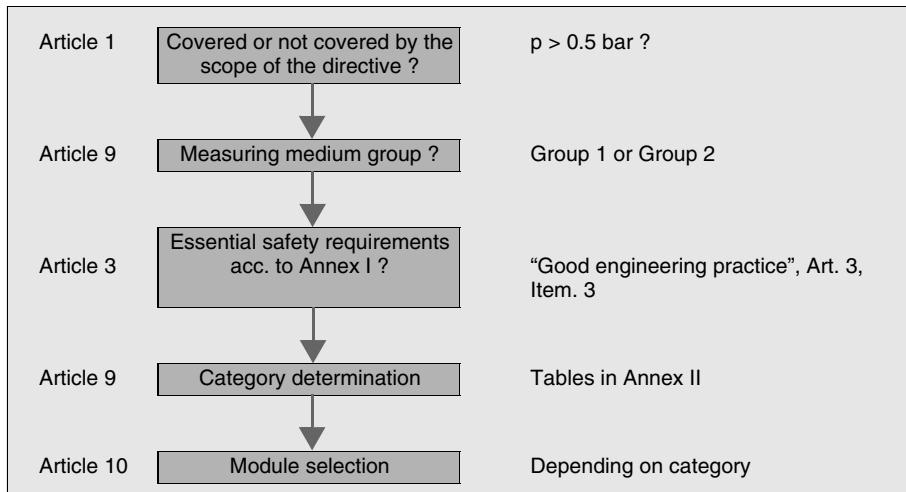
The conformity of a device that is covered by the scope of the Pressure Equipment Directive is determined by a conformity assessment procedure using individual procedure modules or a combination thereof. The selection of the modules to be used depends on the product-specific or usage-specific hazard potential of the pressure equipment.

In the Pressure Equipment Directive the pressure equipment is divided into categories I, II, III and IV, according to the increasing hazard potential. The devices are classified on the basis of their maximum allowable pressure (> 0.5 bar), the volume under pressure (for vessels) or the nominal diameter (for pipings $>$ DN 25), the physical state of the measuring medium (gas, liquid, vapor) and the potential endangerment through the measuring medium. If the pressure equipment is covered by the scope of the directive and is also classified in one of these categories, this is already a pre-selection of the possible minimum modules (or combinations thereof). The manufacturer may also choose to apply one of the procedures which apply to a higher category to be able to use a module that is more suited for his manufacturing system.

Pressure equipment that is not classified in one of the categories I - IV does not have to meet the requirements of a specific module. Instead, it must comply with the criteria of "Good Engineering Practice" (GEP) unless it is not covered by this Directive (example: $p < 0.5$ bar).

The conformity assessment tables in Annex II of the directive can be used to determine the appropriate module for the conformity assessment of the corresponding pressure equipment.

Flowchart for the Determination of the Module



Category I	Module A Internal production control
	Module A1 Internal manufacturing checks with monitoring of the final assessment
Category II	Module D1 Production quality assurance
	Module E1 Product quality assurance
Category III	Module D Production quality assurance
	Module F Product verification
	Module E Product quality assurance
	Module C1 Conformity to type
	Module B1 EC design-examination
	Module B1 EC design-examination
	Module B EC type-examination
	Module B EC type-examination
	Module H Full quality assurance

Monitoring Through Independent Bodies

The pressure equipment of Category I is solely the responsibility of the manufacturer in terms of the design, manufacturing and conformity assessment. If pressure equipment – due to the level of danger which is inherent in it – is classified in a higher category, Notified Bodies (recognized independent or manufacturer-owned inspection body) accredited by the public authorities must be involved in the procedure to the required extent.

CE Marking and Declaration of Conformity

Pressure equipment that complies with the requirements and regulations of the Pressure Equipment Directive will bear the CE marking affixed to each device, with the number of the Notified Body if applicable. Additionally, the manufacturer issues a Declaration of Conformity to document the compliance of the pressure equipment with the Pressure Equipment Directive.

Implementation of the Pressure Equipment Directive by ABB

ABB consistently implements the Pressure Equipment Directive 97/23/EC for its flowmeters, among other devices, and is therefore entitled to issue the corresponding Declarations of Conformity. Flowmeters are pressure accessories covered by the scope of the Pressure Equipment Directive.

As a rule, ABB classifies its flowmeters in Category III, independently of their specific applications. This category covers the highest potential level of danger which is possible for piping components. This ensures that the maximum safety requirements in terms of the design, manufacturing and conformity assessment procedure are taken into account. Flowmeters with nominal diameters DN 25 or smaller also fulfill the basic requirements of the Pressure Equipment Directive although they are not formally covered by its scope.

Classification Example

Piping DN 100, PS = 32 bar, TS = 180 °C, liquid of Group 1, vapor pressure > 0.5 bar above atmospheric pressure

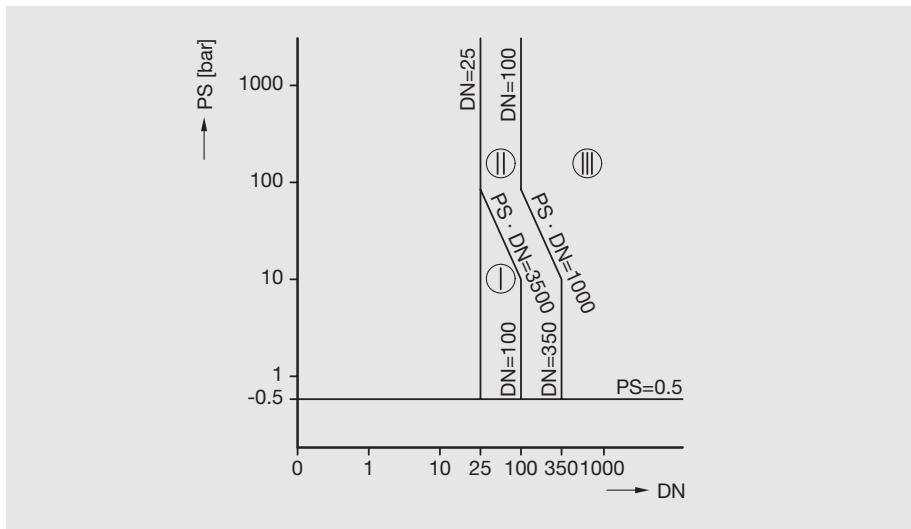


Fig. 3-12:

3.8 Corrosion

Corrosion is defined as the destruction of materials through chemical reactions. Generally, the concept is limited to a change of the structure of a metal caused by an aqueous solution. This is electrolytic corrosion for which the generation of rust is a prime example.

Metals with their free electrons are good electrical conductors. The conductivity of corrosive aqueous solutions is small, the current transport is ionic. During corrosion, a positive current flows into the liquid. This causes the positively charged metallic ions to migrate into the liquid. The intensity of this process is a function of the ionic mobility and it increases with increasing temperature and decreases with concentration increases. Also, voltage differentials augment the corrosion. That is why the non-noble metals, such as aluminum and iron, which are grouped at the negative end of the electromotive series, are severely attacked. Corrosion problems can be avoided by utilizing noble metals.

Organic chemicals, plastics, also show destructive characteristics when they come in contact with aqueous solutions. In this case it is primarily substitution processes which alter the material. Substitution is the replacement of an atom or atomic group by another atom or atomic group. A material with new chemical and physical characteristics is produced. The resistance to the solution can deteriorate. In order to evaluate the large number of organic materials it is necessary to rely on the experiences of the manufacturers which are summarized in corrosion resistance tables.

The corrosion resistance table (see Chapter 8) shows how the materials used by ABB will react when they get in contact with chemical products.

3.9 Data Transmission

The primary task of the transmitter connected to the flowmeter sensor is to produce an output signal which is proportional to the measured value and which can be used by other secondary instruments connected to the transmitter (e.g.: indicators, recorders, controllers). As these secondary devices are universally installed, the output signals must be standardized.

With the advent of intelligent transmitters, electrical data systems have forged into the forefront. For the time being, however, analog signal transmission is still preferred.

Digital technology offers appreciable advantages:

- The number of electrical interconnections decreases dramatically because every output does not require its own leads.
- Communication is not limited to the transmission of the measuring signal. The data exchange occurs in both directions which means that the access and setting of parameters can be effected from the outside. An error diagnosis is possible at any time.
- The entire system can be expanded without great effort.
- Digital signals are not affected by external interference when they are transmitted via the communication line.

3.9.1 Standardized Pneumatic Signal

Devices and systems with a pneumatic power supply are not used very often anymore. The reason for their decline is their limited capabilities when compared to digital technology coupled with the large expenses incurred in providing the air supply and costly installations.

3.9.2 Standardized Electrical Analog Signal

The most common standardized electrical signal is a direct current of 0 to 20 mA or 4 to 20 mA. It is called an impressed direct current because it is independent of the electrical resistance up to a specific maximum load. The permissible load for flowrate transmitters is 750 or 1000 Ω , respectively.

3.9.3 Switch Outputs

There are two types of switch outputs. The continuous contact is used for status signals with which an alarm condition or the reaching of a limit value can be indicated.

In the event of a dangerous condition, e.g. during a device failure or for critical measured values, an alarm is reported. The limit contact is of interest in terms of control, since its status could indicate possible changes in the course of the process. Examples are the empty pipe detector contact, the signal for flow direction reversal and the max./min. conditions.

The pulse output has a completely different function. The generated pulses are signals that are proportional to the volume and can be integrated by a totalizer. In this manner a volume signal is generated from the flow rate. The totalizer indicates the total volume that has flowed through the flowmeter during a specific time interval.

There are a number of methods to electrically design switch outputs. Relay contacts or optocoupler outputs are passive. Current outputs or voltage pulse outputs are active.

3.9.4 HART Protocol

The worldwide standardized analog signal in the measurement industry is the 4 to 20 mA signal. Since this signal can only transmit one parameter or measured value, a system has been developed with which additional information can be transmitted using an alternating current signal superimposed on this current: the HART (Highway Addressable Remote Transducer) communication protocol. This digital signal, which has become a widespread solution, allows for convenient and efficient parameterization of intelligent measuring devices. Additionally, device-specific diagnostic data can be read which provide information about the device's physical health and allow for predictable maintenance. Monitoring various device parameters is also possible.

ABB's scalable device management system Asset Vision is available for easy and cost-saving parameterization and monitoring of the measuring devices. The FDT/DTM and EDD device management and integration technologies are supported.

The FSK (Frequency Shift Keying) procedure is the basis for the HART communication. In this technology, the two digital values - logical 0 and logical 1 - are expressed as frequencies of 1200 Hz and 2200 Hz. Because the average value of the frequency is zero, the digital communication does not affect the analog signals.

A HART master transmits HART commands which then trigger parameter read or write operations of an intelligent field device. In the HART standard a distinction is made between universal commands and common practice commands which must be supported by all HART compatible device, and the manufacturer-specific commands which address the specific parameters of the device type.

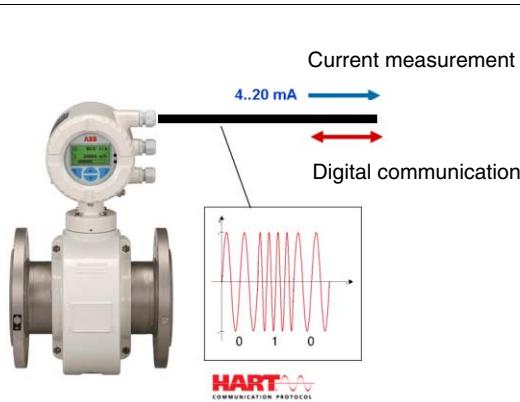


Fig. 3-13: FSK Procedure: Simultaneous Transmission of the 4 to 20 mA Signal and Digital Communication

In principle, all HART devices are connected to the process control level via I/O cards, HART multiplexers or remote I/O units (see Chapter 3.9.6). The process control level can, thus, use the analog signal, but also the digital capabilities of the field device, for further processing.

It is also possible to connect another HART master (for example a HART modem linked with a notebook, a HART handheld-terminal or a PDA microcomputer) for temporary diagnostics or for the parameterization of field devices. These devices can be connected into the 4 to 20 mA circuit at any point.

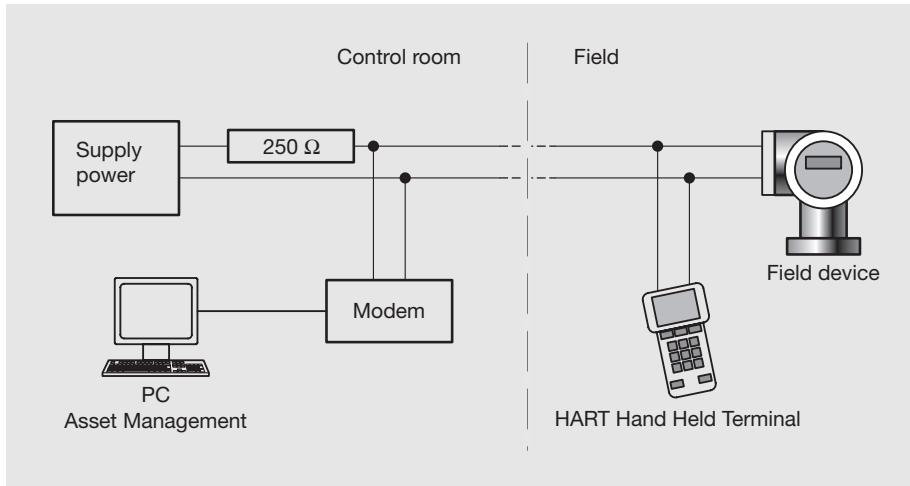


Fig. 3-14: Possibilities Offered by HART Communication

The HART standard has evolved, now offering a new stage with completely new possibilities for wireless transmission of HART information: WirelessHART. WirelessHART is the first standardized wireless communication in the field of process automation. However, as this solution does not include the connection cable, only the digital parameter range is available. The analog measuring signal is not provided.

But the digital wireless communication of parameter values does away with cabling and, thus, allows for easy and cost-saving installation of additional measuring points for diagnostic purposes. Moreover, asset management systems like, for example, ABB's Asset Vision Professional can be run in parallel with the process control systems without the need to change the existing cabling. Basically, there are two different WirelessHART solutions:

- WirelessHART Adapter for enhancing existing HART devices
- Self-powered WirelessHART transmitter.

These wireless solutions use the central element of wireless HART transmission, the WirelessHART gateway, for communication. Besides the protocol as such the standard

also defines various security mechanisms which ensure availability and tap-proof wireless signal transmission.

3.9.5 Fieldbus in Process Automation

Fieldbus systems are a communication medium for serial data exchange between decentralized devices of the field level and the input peripherals of the process control level. For process data acquisition in the field level not only intelligent measuring devices and actuators with direct connections to the fieldbus are used but also intelligent remote I/O units as interface systems for conventional field devices.

Only two wires suffice for transmitting all relevant signals like input and output data, parameters, diagnostic information and configuration schemes and - for additional applications - the operating energy. If a field device has a high energy demand, this device will be supplied separately from the signal bus, i.e. a four-wire system is used instead of a two-wire.

The use of a unique definition for the communication protocol allows the fieldbus to be open to all field device vendors who use this protocol. In this manner it was possible to achieve interchangeability and also use the standard 4 to 20 mA signal for the fieldbus technology.

Besides the considerably reduced cabling effort the fieldbus technology also provides other advantages. Every measured value is transmitted together with a status, an indicator for the reliability of the value and a module of the diagnostic capabilities of fieldbus communication systems.

Standardized diagnostics and device-specific diagnostic information are available for all devices and communication components. Additionally, the measured value have an especially high resolution as they are purely digital. Different transmission rates and configuration options for communication allow for perfect adaptation of the measurement and transmission operations to the process requirements.

After many years of successful use in industrial applications, the fieldbus technologies have become a powerful, reliable and cost-saving alternative to conventional installations with considerably more information.

The PROFIBUS Family

PROFIBUS is a vendor-independent, open, well-proven and widespread fieldbus standard for applications in production, process and building automation.

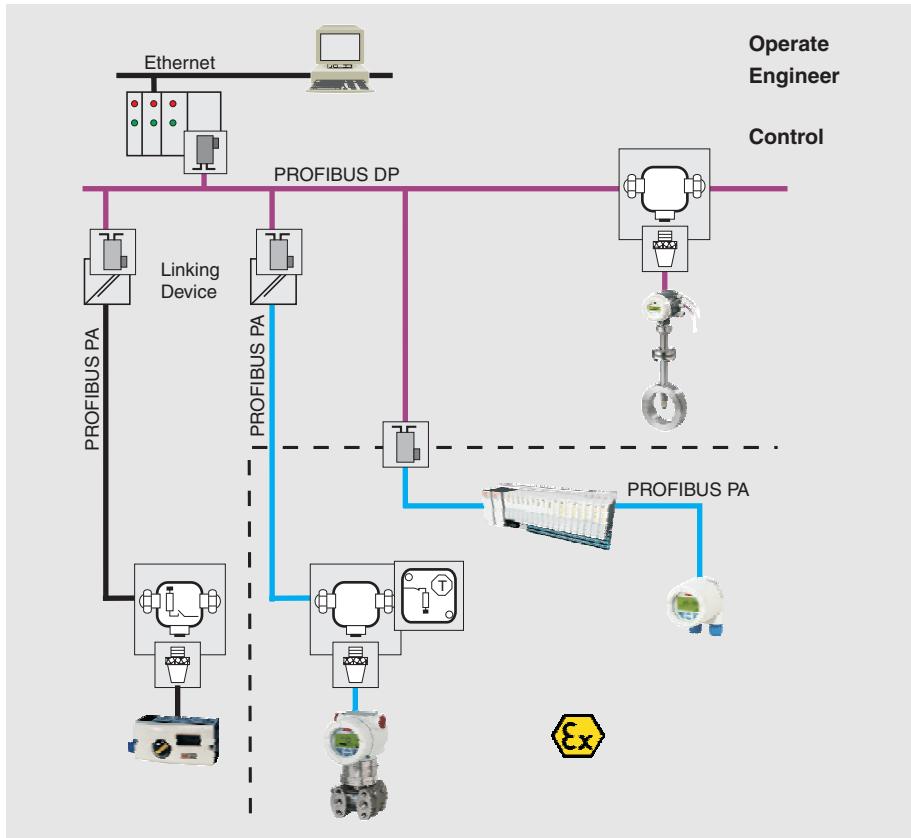


Fig. 3-15: Example of PROFIBUS Topology

The PROFIBUS family comprises two different communication protocols and profiles which enhance the protocol with application-specific features.

PROFIBUS DP Communication: The Bus for Decentralized Periphery

Both the PROFIBUS DP and PA profiles are of importance for process automation. The PROFIBUS variant DP provides the communication between the process-oriented components of a distributed control system and the decentralized peripherals in the field. PROFIBUS DP is especially suitable for high transmission rates (up to 12 Mbit/s) and is therefore often used in decentralized peripheral groups or externally supplied

field devices such as positioners or flowmeters. PROFIBUS DP/V1 additionally allows for acyclic communication and, thus, the use of FDT/DTM or EDD tools for the parameterization and monitoring of devices.

PROFIBUS PA Communication: Expansions for Process Automation

PROFIBUS PA was specifically developed for use with process technology. Intrinsic safety and supply of the field devices via the two-wire bus line are possible and comply with the IEC 61158-2 Standard (Manchester Bus Powered – MBP Physics). This variant is used for communication with two-wire supplied measuring devices and actuators in the field. PROFIBUS PA uses an expanded form of the DP protocol. The device properties and behavior are described by so-called profiles and defined in the standard. Using coupler modules (segment couplers, gateways, linking devices) the PA bus lines are integrated in the PROFIBUS DP network. This ensures that all information in the entire PROFIBUS system (with DP and PA profile devices) is available in a consistent network.

PROFINET

This additional communication protocol of the PROFIBUS family allowed for a successful start into the age of the industrial Ethernet. The technology can be used in different manners:

- As a bus system (mainly used in production automation)
- As a backbone network for heterogeneous networks with consistent basic communication (connection to different network types via a proxy server)

So far, PROFINET has not yet gained noteworthy importance in the field of process automation.

3.9.6 FOUNDATION Fieldbus

This fieldbus technology has been introduced approximately 10 years ago. It is mainly used in America and provides two variants:

- HSE - High Speed Ethernet. This variant so far has not yet been applied very often in industrial environments. Only controllers and linking devices use this protocol.
- FF-H1. Similar to the PROFIBUS PA profile this protocol uses the MBP (Manchester coding with Bus Powering) physics and, thus, allows for direct powering of the devices via the bus cable. A characteristic feature of H1 is the capability to allow the field devices to take over and process simple control tasks by themselves (“control in the field”). This means that the network intelligence is in parts transferred to the field level. This option requires deterministic operation of the H1 protocol. Another typical feature of the FOUNDATION Fieldbus is the ability to transmit alarms with a time stamp.

3.10 Calibration and Official Verification

3.10.1 Why Calibrate?

In the company the requirement for rigorous traceability of the test equipment to national standards by calibrations to assure that everyone uses the “same measurement stick”, is essential both for suppliers who manufacture the products and for users who install these parts with other parts, due to increasing national and international division of work and the resultant requirement for interchangeability.

In addition to the technical reasons, there are also legal aspects. The relevant directives and regulations must also be observed together with contractual obligations with the purchaser of the products (assurance of the quality of the product) and the responsibility to only bring products to the market place the safety of which is not compromised by faults when they are used as intended. As far as contractual responsibilities for the accuracy of the measuring devices were agreed, a nonfulfillment of these requirements is a failure of a guaranteed property.

Proof of the selection of adequate test equipment and its proper operation within the scope of product liability is of great importance within the framework of product liability, because a systematic and completely documented test equipment monitoring in combination with continuous proof of the adequacy of the test equipment for the task is essential for a possible exoneration proof.

3.10.2 Terms and Definitions

Measuring Device

A device that is to be used for measurements, either as a stand-alone unit or together with other equipment.

Standard (Reference)

Material measure, measuring device, reference material or measuring equipment intended to represent, maintain or reproduce a unit or one or more quantity values.

Measurement

The totality of activities for determining a quantity value (represented as the product of a numerical value and a unit, e.g. 1.23 m³/h).

Calibration

The determination of the relationship between the specified values of a measuring device and the values specified by standards for given conditions.

Adjustment

In the context of measurement adjustment means setting or balancing a measuring device in such a way that the measuring deviation is as small as possible.

Official Verification

Verification and marking of a measuring device and/or issuing of a calibration certificate for a measuring device to determine and confirm that the device complies with the legal requirements. This is to certify that it can be duly expected that the values measured by this measuring device will lie within the error limits (within the re-calibration period) provided that the measuring device is handled in accordance with the recognized rules of engineering.

Measurement Uncertainty

Parameter allocated to the measuring result and which specifies the spread of the (measured) values that can reasonably be assigned to the measured variable.

Traceability

Capability of a measuring device (or the values of a standard) to be related to the appropriate normals, usually international or national standards, through an uninterrupted chain of reference measurements with the specified measuring uncertainties.

3.10.3 Methods of Flow Calibration

The commonly used measurement methods are:

Volumetric Method

Procedure to measure the volume flow rate of a liquid using a calibrated volume measurement tank (bell prover) and measuring the fill time.

Gravimetric Method

This method is comparable to the volumetric method. In this case, however, the volume of the liquid is measured by weighing, taking into account the density and the displaced amount of air.

Calibrations of both methods can be conducted using either a standing START-STOP operation (opening and closing of a shutoff device) or a flying START-STOP operation (operation of a diverter device). Furthermore, a distinction is made between a static and a dynamic method, whereby the latter does not require a diverter device.

Critical Nozzles

These are used as high-accuracy reference devices for the calibration of gas flows. With this method the gas flow is accelerated to the extent that sound velocity is reached at the smallest nozzle cross-section. The adjustment of this critical flow condition limits the flow to a constant value.

Comparison Method (MASTER Calibration)

This is the calibration method most commonly used in industry. The calibration medium flow through the measuring device to be calibrated and through one or more flowmeters (masters) that have been calibrated before.

Pipe Test Section Method

The reference device is a volumetric measuring device consisting of a pipe section with a constant cross-section and a known volume. The flow rate is derived from the time that a plug - either driven by the fluid or propelled - needs to traverse the pipe section.

In test benches with the highest accuracy requirements mainly gravimetric methods are used for liquid calibration, whereas methods with critical nozzles are used for gas calibration.

3.10.4 Test Bench for Liquid Flow Measurement

When setting up a flow measurement test bench, for example using the gravimetric method, various requirements per DIN EN 29104 must be met:

- The flow must be stationary.
- The flow in an obstruction-free inlet section must be axissymmetric and free of swirl and pulsation.
- The reference flowmeters or the calibrated test equipment for the measurement of the flow rate or volume must meet the requirements of ISO 4185 and ISO 8316.
- The flow measuring range of the reference flowmeter or the calibration standard must be of the same size as the range of the flowmeter to be tested. The error limit of the reference standard should not be greater than one third of the error limit of the device to be tested.

- The measuring equipment and the reference standard must be described in detail, including the traceability of the reference standard and the uncertainty of the measuring setup. The calculation of the uncertainty of the flow measurement must comply with ISO 5168, ISO 7066-1 and ISO 7066-2.
- The sensor must be installed between a straight, undisturbed inlet section of at least $10 \times D$ and an undisturbed outlet section of at least $5 \times D$. If swirl-free velocity profiles are required, flow straighteners must be installed.
- During the measurement, the sensor must be completely filled with liquid.

Additionally, the physical characteristics of the measuring medium, for example, density and viscosity, must also be considered. Analogy calculations can be made using the Reynolds number which takes into account different flow regimes. Naturally, the other equipment on the test bench also have accuracies, which is so good that they only have minimal impact on the flow rate measurement results.

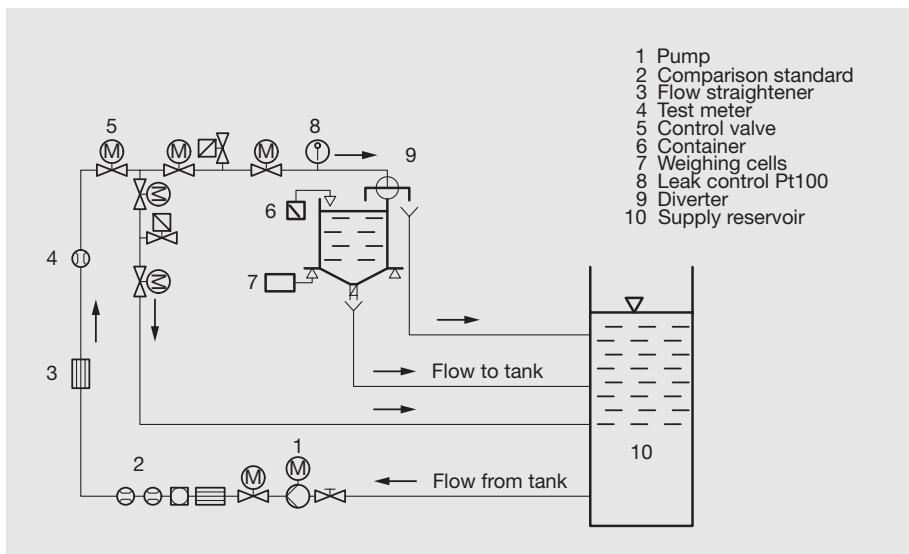


Fig. 3-16: Test Bench for Gravimetric Calibration and Comparison Calibration Methods

In the schematic diagram of a liquid test bench shown in Fig. 3-16 the water flows through two comparison standards (2) which cross-check each other. The flowmeter being calibrated (3) is installed in a long, undisturbed pipe section. The control valve (4) and the pump (1) determine the set flow rate. The water can then either be returned directly to the supply reservoir (8) or by actuating the diverter (7) into the tank (5), where its mass can be measured. The scale arrangement (6) itself is calibrated in periodic intervals with weights by the Office of Weights and Measures.

3.10.5 Test Bench for Gas Flow Measurement

Measurements for gases are for the most part realized using the differential pressure measurement method. The simple measurement setup allows for easy design and calculation of the flow measurement equipment for the specific application using standardized orifice plates, nozzles or Venture tubes.



Fig. 3-17: Calibration System for Gas Flowmeters

In the ABB calibration laboratory two test benches are used which work according to the principle of supercritically operated Laval nozzles. They work in suction mode, i.e. air as the measuring medium is taken in under atmospheric conditions from an air-conditioned calibration room. The air flow through the nozzle is increased by suction until sound velocity is reached in the nozzle throat. The pressure condition above the nozzle at the time when the sound velocity is reached is called the critical pressure condition. Another pressure reduction on the suction side will not change the flow any more. A stable flow is achieved.

Each calibration system has two test chambers, to which the test meter can be adapted by using the appropriate inlet / outlet sections, depending on the nominal diameter. The test chambers lead to a collecting tank, to which the inlet sections of the nozzles are also connected. The outlet sections are flanged to a second collecting tank. The two collecting tanks with the flanged nozzle sections are attached to a stable frame. A piping branches off the second collecting tank and leads to a blower station. In the blower station three roots blowers are installed which also provide for the supply of the calibration system. The two test benches are largely independent of each other. The flow ranges overlap.

Both systems consist of up to 10 nozzle sections representing a constant mass flow, each. Measurement and control of the pressure conditions upstream and downstream of the nozzles ensure that the nozzles are always operated supercritically. By means of temperature and pressure measurements of the measuring medium upstream of each nozzle and a calibration measurement in the calibration room the known standard values of the nozzles are converted to the actual nozzle values under calibration conditions.

A separate setup of the individual nozzle sections ensures that the nozzle do not influence each other. The feed line from the blower station, the two test chamber sections and the individual nozzle sections can be switched using butterfly valves. The nozzle sections can be switched individually or as a combination of up to three sections. With this calibration points with small steps can be realized.

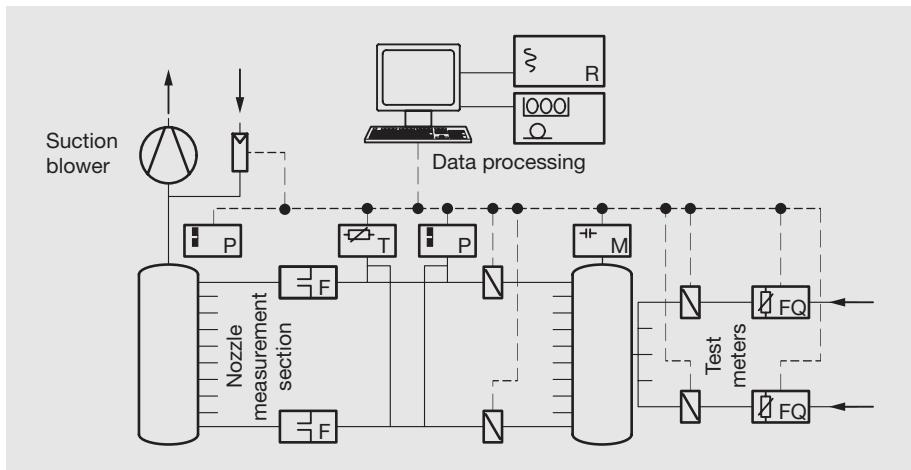


Fig. 3-18: Basic Test Bench Setup

3.10.6 Approvals of Test Benches and Products

DAkkS Accreditation

ABB has a DAkkS calibration laboratory for flow measurement. This calibration laboratory is accredited and monitored by Deutsche Akkreditierungsstelle GmbH (DAkkS, formerly DKD). DAkkS has been founded by the Federal Republic of Germany, represented by the BMWi (Federal Ministry of Economics and Technology). The issued DAkkS calibration certificates are proof of the traceability to the national standards as required in the DIN EN ISO 9000 and DIN EN ISO 17025 series of standards. Calibrations in DAkkS laboratories provide the user assurance of the reliability of the measurement results, increase the confidence of the customer and provide competitiveness in the national and international markets. They are the technological basis for the measurement and test equipment monitoring within the framework of quality assurance.

In the course of globalization the international reciprocal recognition of calibration certificates is getting more and more important. Within in Europe, this is governed by a multilateral agreement (MLA) of the European Co-operation for Accreditation (EA), worldwide through the International Laboratory Accreditation Cooperation (ILAC). DAkkS calibration certificates are recognized by all signatory states of this agreement.





Deutsche Akkreditierungsstelle GmbH German Accreditation Body

Entrusted according to Section 8 subsection 1 AkkStelleG in connection with Section 1
subsection 1 AkkStelleGBV

Signatory to the Multilateral Agreements of
EA, ILAC and IAF for Mutual Recognition

Accreditation



The Deutsche Akkreditierungsstelle GmbH (German Accreditation Body) attests that the calibration laboratory

ABB Automation Products GmbH
Dtransfelder Straße 2, 37079 Göttingen

is competent under the terms of DIN EN ISO/IEC 17025:2005 to carry out calibrations in the following field:

Fluid Quantities

- Gas and liquid flow rate
- Volume of flowing gases and liquids

The accreditation certificate shall only apply in connection with the notice of accreditation of 2011-05-16 with the accreditation number D-K-15081-01 and is valid until 2012-03-31. It comprises the cover sheet, the reverse side of the cover sheet and the following annex with a total of 3 pages.

Registration number of the certificate: **D-K-15081-01-00**

Braunschweig, 2011-07-06

A handwritten signature in blue ink, appearing to read "M. Wolf".
Dr. Michael Wolf
Head of Division

This document is a translation. The definitive version is the original German accreditation certificate.

See notes overleaf.

Fig. 3-19:

Testing of Measurement Devices for the Volume Measurement of Flowing Liquids (Certification Approval)

Various ABB test benches have received from PTB (German National Institute of Technology and Science) the approval to calibrate approved certified measuring devices (see next section) as well as to perform technical tests in the presence of an official from the Office of Weights and Measures. The calibration certificates issued (without measurement specifications, according to the calibration regulations) or test certificates MEN (with measurement specifications) are proof of the traceability to national standards.

Type Examination Approval for Intrastate Certified Calibrations (Germany)

In order to be able to calibrate a measuring device, it is not enough to have an approved test bench. The flowmeters themselves must also be approved by PTB for intrastate official verification in order to certify that they comply with the requirements of the calibration regulations. The Calibration Regulation EO 5 makes a distinction between different measuring media and evaluates them individually. For this reason, the approval includes not only the device type, but also the nominal diameter, flow range and measuring medium. ABB has received the following approvals:

Approval Range	Device Type	Nominal Diameter Range
Cold water/waste water	6.221 Electromagnetic flowmeter	DN 25...DN 2000
Liquids other than water for example: • Milk • Brine • Beer • Wort • Beverage concentrate • Chemical liquids	5.721 Electromagnetic flowmeter	DN 25...DN 40, DN 65, DN 80 DN 100...DN 150 DN 25...DN 100 DN 50...DN 100 DN 25 DN 25...DN 150

Approved and calibrated devices can be identified by their special name plate:

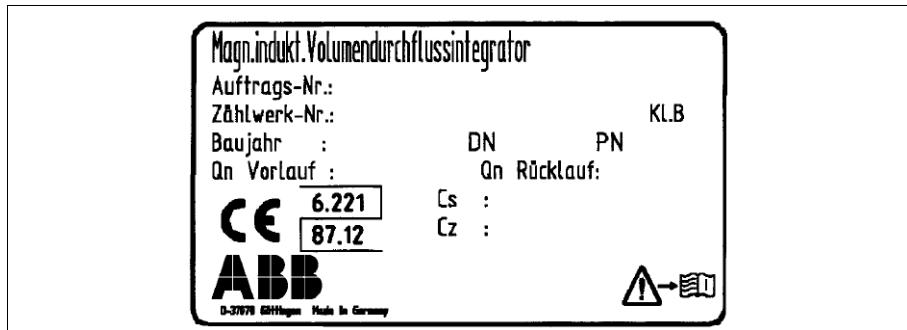


Fig. 3-20: Name Plate of Measuring Device with Approval for Certified Calibration of Water/Waste Water (Germany, only)

3.10.7 Calibration Possibilities at ABB

Factory Calibrations

Measured variable	Volume flow rate
Measuring medium	Water
Nominal diameter range	DN 1...DN 2400
Measuring range ¹⁾	$q_v = 0.2 \text{ l/min} \dots 6,000 \text{ m}^3/\text{h}$

Measured variable	Volume flow rate
Measuring medium	Atmospheric air
Nominal diameter range	DN 15...DN 300
Measuring range ¹⁾	$q_v = (2\dots4600) \text{ m}^3/\text{h}$

Factory Calibrations (also Onsite Calibrations)

Measured variable	Volume flow rate
Measuring medium	Atmospheric air
Measuring range ¹⁾	(0.1...25) m^3/h (10...1000) m^3/h
Measuring accuracy	< 0.5 % of rate
Peculiarities	p_{\max} 16 bar

¹⁾ Specified is the maximum range over all nominal diameters.

Special Calibration with Process Gas

The unique process gas measurement system is used for calibrating gas mass flow-meters with or without explosion protection approval for combustible and non-combustible gases. Gases that are corrosive to the used materials or noxious are excluded.

Measured variable	Volume flow rate
Measuring medium	Process gas
Nominal diameter range	DN 25...DN 100
Measuring range ¹⁾	1...700 m ³ /h (standard condition)
Pressure range	0.5...20 bar abs.

1) Specified is the maximum range over all nominal diameters.



Fig. 3-21: Pictures of the Process Gas System

Certified/Special Calibrations MEN

Measured variable	Volume flow rate
Measuring medium	Water
Nominal diameter range	DN 10...DN 2000
Measuring range ¹⁾	$q_v = \text{max. } 6000 \text{ m}^3/\text{h}$

DKD Calibrations

Measured variable	Volume/mass flow Volume/mass of flowing liquids	
Measuring medium	Water	
Nominal diameter range	DN 50...DN 600, DN 800	
Measuring range ¹⁾	$q_v = 5 \dots 3000 \text{ m}^3/\text{h}$	$V = 1.5 \dots 60.0 \text{ m}^3$
	$q_m = 5 \dots 3000 \text{ t/h}$	$m = 1.5 \dots 60.0 \text{ t}$
Smallest specifyable meas. error ²⁾	0.15 %	0.1 %
Meas. inputs	Current Frequency	0/4...20 mA 0...10 kHz

Measured variable	Volume/mass flow Volume/mass of flowing gases		
Measuring medium	Atmospheric air		
Measuring range	$q_v = 0.8 \dots 1000 \text{ m}^3/\text{h}$		
	$q_v = 1000 \dots 7300 \text{ m}^3/\text{h}$		
	$m = 1 \dots 1200 \text{ t/h}$		
		$m = 1200 \dots 8800 \text{ kg/h}$	
Smallest specifyable measuring error	0.3 %	0.4 %	

1) Specified is the maximum range over all nominal diameters.

2) The smallest specifyable measuring error is defined in acc. with DKD-3 (EA-4/02). These are extended measuring errors with a coverage probability of 95 % and an extension factor $k = 2$. Measuring errors without units are relative values related to the measured value.

3.10.8 Measuring Instruments Directive (MID)

The Measuring Instruments Directive MID is a European directive that describes the prerequisites for placing on the market and putting in use measuring devices for legal metrology (calibration). The directive was adopted by the European Parliament and incorporated by the Member States of the European Union into national legislation. In Germany this resulted in the amendment of the already existing Verification Act.

Due to the harmonized standards in Europe, an approval is recognized in all Member States of the EU. The requirements in terms of the device technology are only roughly outlined in the MID, in order not to enforce technological restrictions. For detailed information please refer to the recommendations of the OIML (Organisation Internationale de Métrologie Légale).

For the conformity assessment different module combinations are possible:

Manufacturer Production Phases	Conformity Assessment			
	Modules B + F	Modules B + D	Module G (not for Water Meters)	Module H1
Development Design				
Type	Type Examination (B)	Type Examination (B)		Design Examination
Series Production		Quality Assurance of Production Process (D)		Unit Verification
Final Product	Product Verification (F)			Full Quality Assurance
Declaration of Conformity and CE Marking				

Tab. 3-10: Overview of Module Combinations

MID Chronology and Transitional Period

The MID was adopted by the European Parliament in 2004 and had to be incorporated into national legislation within two years (by October 30, 2006, at the latest).

Type examination approvals issued before this date will be recognized for re-calibration for up to ten years after this deadline (i.e. until October 29, 2016).

3.10.9 OIML (Organisation Internationale de Métrologie Légale)

The OIML is the International Organization for Legal Metrology having seat in Paris, France. It has already been existing for many years and has published various recommendations and documents for the worldwide standardization of the legal metrology. The OIML has a close cooperation with the PTB (German National Institute of Technology and Science).

OIML Recommendation R49 is valid for cold water meters, whereas flowmeters for liquids other than water fall under OIML Recommendation R117.

OIML R49 - Flowmeters for Cold Water

This directive describes the technical requirements on the device, the prerequisites for approval and the tests to be performed (type examinations and routine tests). These include, for example:

- Accuracy classes (1 % and 2 %)
- Measuring ranges in fixed steps
- Flow ranges Q1 to Q4 (minimum flow to overload flow)
- Flow measurement points, mounting position, inlet/outlet sections
- Volume indication
- Functional tests of devices with electronic equipment (e.g. EMC, vibration, temperature)

OIML R117 - Flow Measurement of Liquids other than Water

This directive describes the technical requirements on the flowmeter and the entire measuring system, the prerequisites for approval and the tests to be performed (type examinations and routine tests). These include, for example:

- Various accuracy classes, depending on the measuring medium and application
- Measuring ranges in fixed steps
- Flow ranges Q_{\min} to Q_{\max} , with fixed ratio
- Flow measurement points, mounting position, inlet/outlet sections
- Indication of volume flow and mass flow (conversion requires special approval procedure)
- Functional tests of devices with electronic equipment (e.g. EMC, vibration, temperature)
- Suitability of the entire measuring system (e.g. pump, filter, gas separator)

4 Device Selection Criteria

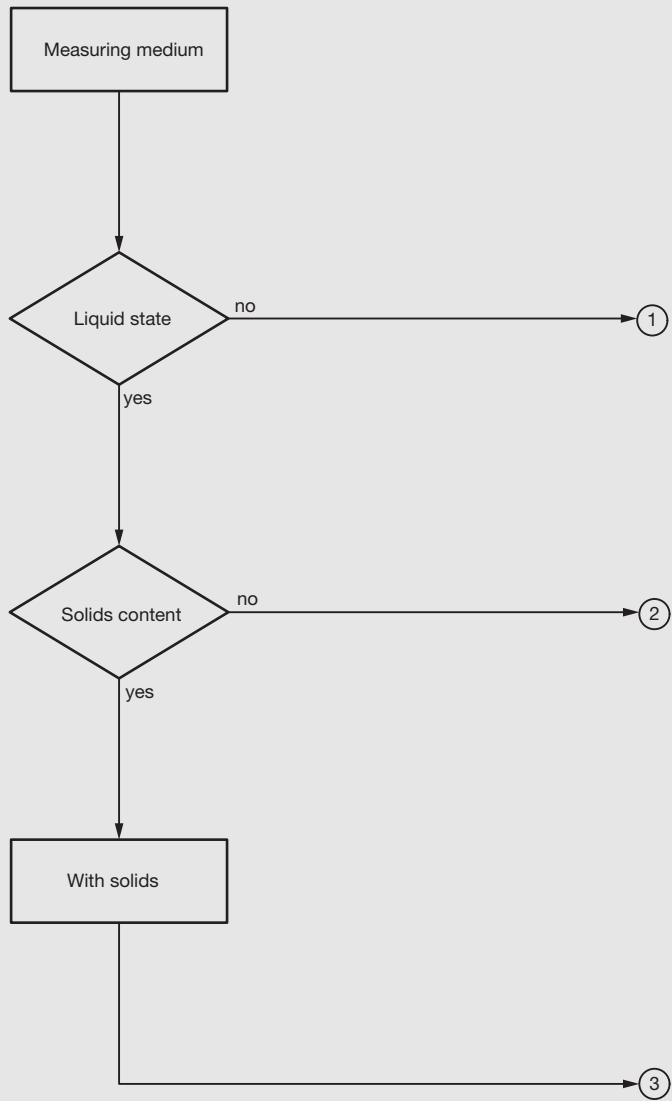
By comparing the individual characteristics of volume totalizers and flowmeters, which must be considered from different points of view, this section of the manual attempts to compile the most interesting aspects for instrument selection in order to provide a guide to the user. The various criteria are assembled in tables so that the applicability may be readily ascertained for a particular situation.

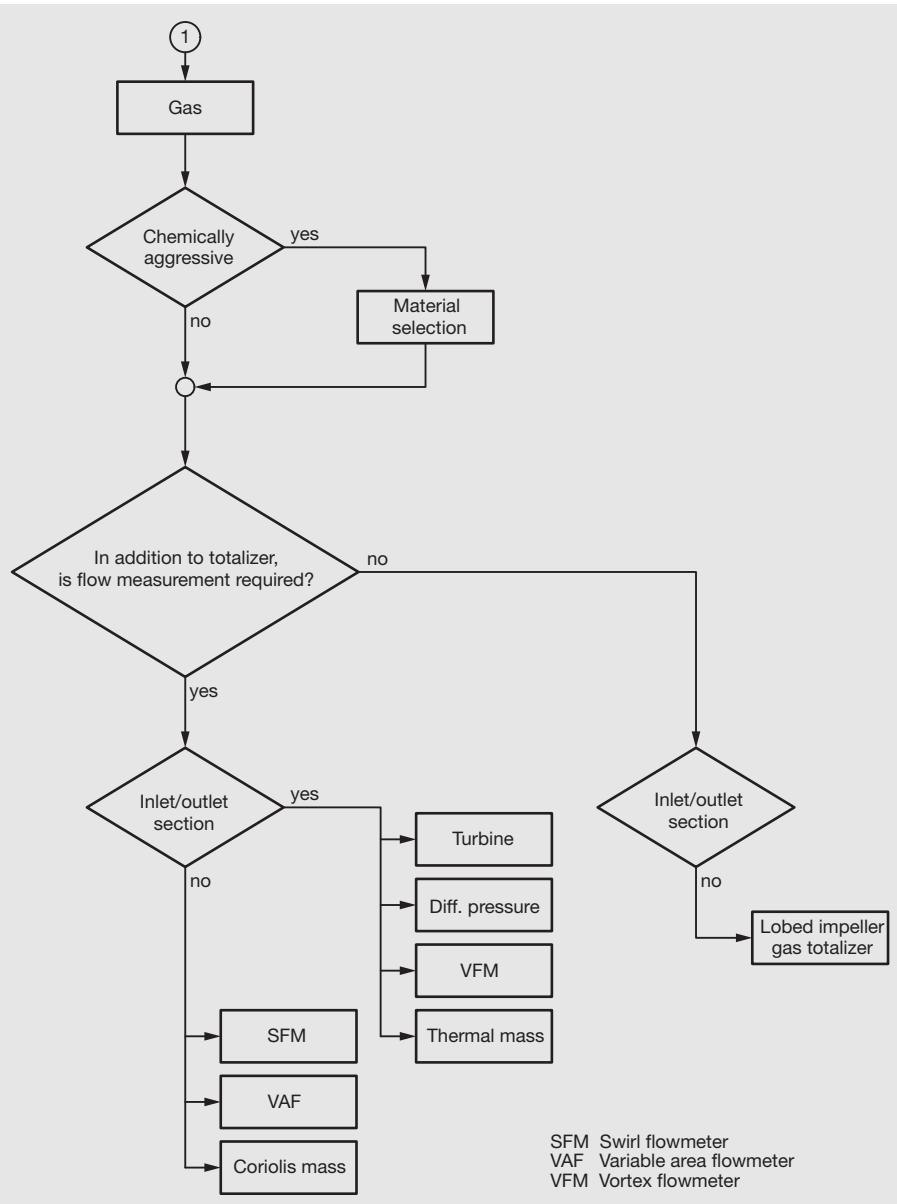
Naturally it is not possible within the framework of this publication to be all encompassing. There are always special designs for individual applications, and the sizes and values listed here are merely snapshots representing the current state of the art. They will certainly be updated as technology continues to evolve.

Unfortunately, the initial cost is often the essential selection criterion. Lifecycle costs, for example for the preparation of the installation site, installation and maintenance, are often considered as being of low priority or neglected for the most part. Additionally perhaps, considerations in terms of the long-term stability may play an important role in device selection. The following comparison is intended to provide assistance in this regard.

4.1 Flowmeters for Closed Pipings

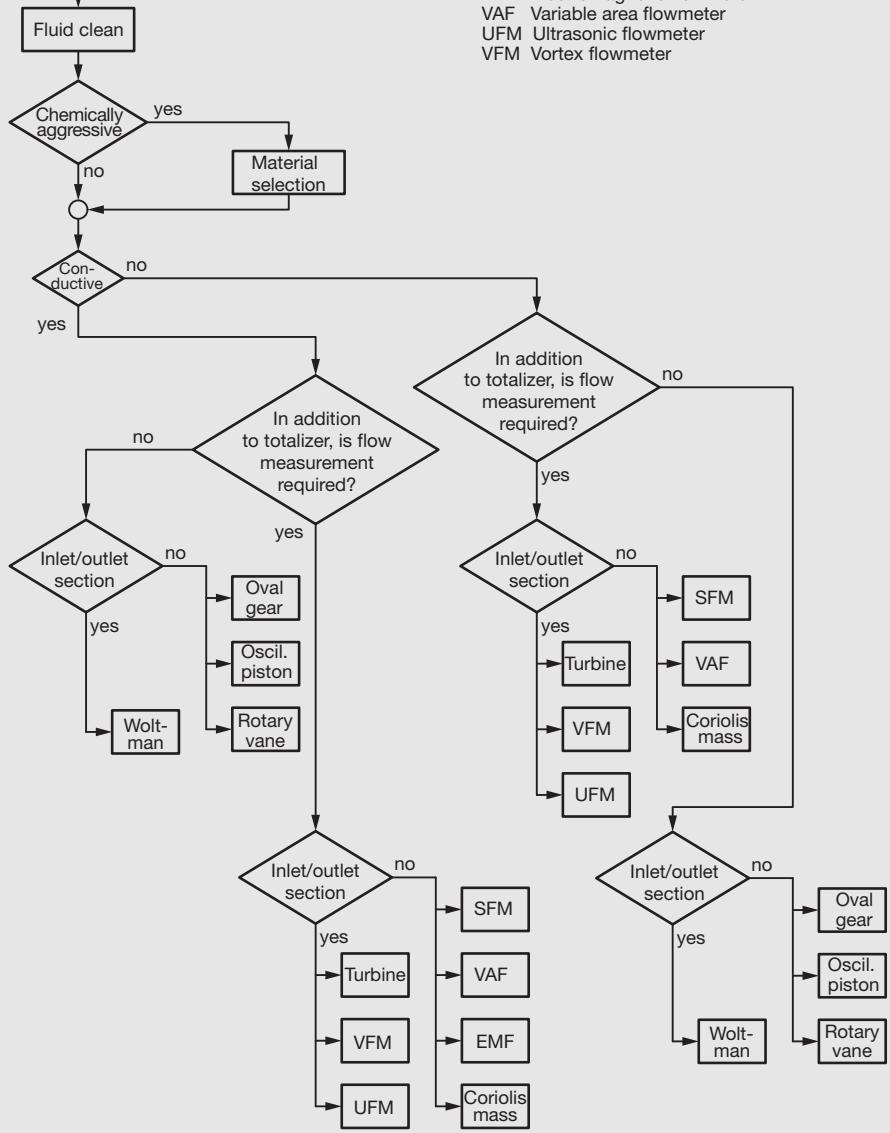
Flow charts for device selection with a number of important selection criteria



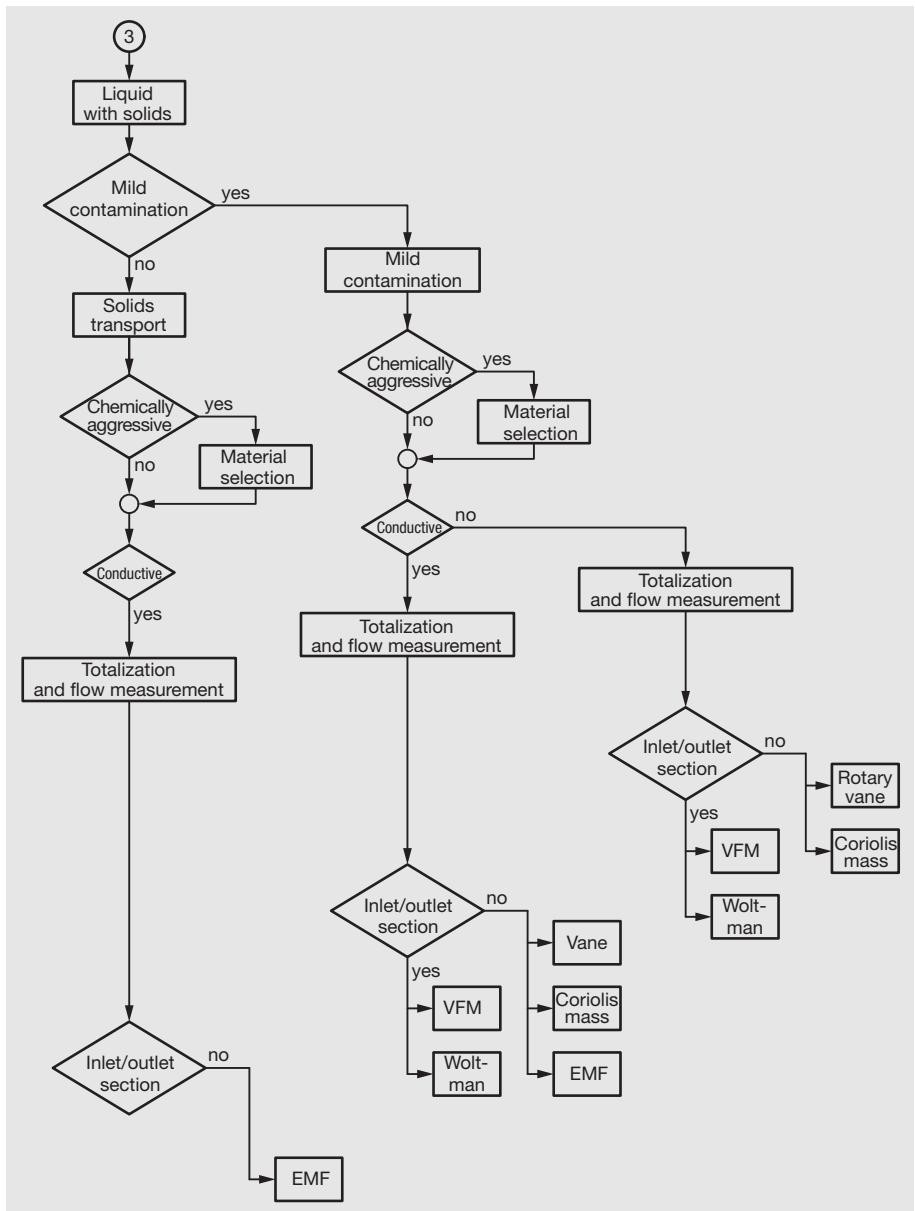


SFM Swirl flowmeter
 VAF Variable area flowmeter
 VFM Vortex flowmeter

2



SFM Swirl flowmeter
 EMF Electromagnetic flowmeter
 VAF Variable area flowmeter
 UFM Ultrasonic flowmeter
 VFM Vortex flowmeter



4.1.1 Influences of the Measuring Medium Properties

In the first place is the measuring medium itself. Its volume and flow rate are to be determined. Before the appropriate device type can be selected, the type of the medium to be measured and its properties have to be analyzed. This represents an appreciable portion of the meter sizing effort.

	Measuring Medium	Aggreg-ate State	Upper Viscosity Limit [mPas]	Solids in Measuring Medium		Electrical Conductivity	Gas Content in Liquid	Changes of Pressure, Density, Temperature	Chemically Aggressive Measuring Medium, Risk of Corrosion
				Mild Contamina-tion	Solids Transport				
Volume Totalizer	Oval Gear Totalizer	L	$1 \cdot 10^5$	Increased wear, Risk of blockage	u	n	Error	Minor error	Housing and gears of stainl. steel, carbon bearing
	Oscillating Piston Totalizer	L	$2 \cdot 10^4$		u	n	Error		Stainless steel housing PTFE piston, carbon bearing, PTFE bearing
	Lobed Impeller Totalizer	G	No effect		u	n	-		Cast steel housing alumin., steel cast piston, oil seal
	Rotary Vane Totalizer	L	5		u	n	Error		Plastic parts, brass housing
	Woltman Totalizer	L	3		u	n	Error		Cast housing, plastic rotary vane, parts of stainless steel
Indirect	Turbine Totalizer	L (G)	700	u	u	n	Risk of over speed		Nickel rotor, housing and other parts of stainless steel

n = no effect
 u = unsuitable
 L = Liquid
 G = Gas
 S = Steam

Tab. 4-1: Effect of the Measuring Medium Properties

	Measuring Medium	Aggregate State	Upper Viscosity Limit [mPas]	Solids in Meas. Medium		Electr. Conductivity	Gas Content in Liquid	Changes of Pressure, Density, Temperature	Chemically Aggressive Measuring Medium, Risk of Corrosion
Flowmeter	Vortex Flowmeter	L, G, S	7.5	Essentially insensitive to contamination	u	n	Cavitation effects possible	Gas measurement affected, liquid measurement unaffected	Stainless steel (Hastelloy)
	Swirl Flowmeter	L, G, S	30 (indep. of nominal diameter)		u	n			Stainless steel (Hastelloy)
	Differential Pressure Measurement	L, G, S	see Table 2.4	Damage to metering edge, plugging of pressure tap connector	u	n	Error	Effect on Δp	Stainless steel
	Variable Area Flowmeter	L, G, S	100 (700)	Damage to metering edge	u	n	Error	Density changes buoyancy	Stainless steel Hastelloy, PTFE, glass
	Electromagnetic Flowmeter	L	No effect	n	n	$\geq 0.5 \mu\text{s}/\text{cm}$	Error	n	PTFE, PFA, platinum
	Ultrasonic Flowmeter	L (G)	Re-effect	Only allowed for Doppler, damping for transit time	u	n	Error for Doppler, damping for transit time	Sound velocity changes for Doppler	Stainless steel, PTFE
	Mass Flowmeter, Coriolis	L (G)	No effect	Possible with restrictions	u	n	Error	Density is measured variable	Stainl. steel Hastelloy
	Mass Flowmeter, Thermal	G	No effect	Essentially insensitive to contamination	u	n	—	n	Stainl. steel, Hastelloy, ceramic

n = no effect
 u = unsuitable
 L = Liquid
 G = Gas
 S = Steam

Tab. 4-2: Effect of the Measuring Medium Properties

Viscosity Effects

Viscosity is a property of the measuring medium. Through use of the Reynolds number it is possible to coordinate the viscosity effects and the dimensions of the measuring point. For $Re < 2300$ laminar flow exists with a large viscosity effect. The transition region exists between approximately $2300 < Re < 3000$ above which turbulence exists. In the turbulent region there are no limitations due to viscosity. Small Re values have varying effects, depending on the measuring method.

For gas totalization or flow measurement the viscosity effect is hardly noticeable. Only for small variable area flowmeters with light-weight floats does the effect increase slightly in the lower measuring ranges.

The situation for liquids is quite different. Completely viscosity-independent are the electromagnetic flowmeters and the mass flowmeters, although the pressure drop in the latter is affected as a function of the length of the measuring section. Ultrasonic flowmeters have difficulties in the transition region from laminar to turbulent flow.

In Vortex, swirl and turbine flowmeters an increasing viscosity raises the lower range value, thus reducing the span.

Oval gear and oscillating piston meters are ideal devices for high viscosities. At higher viscosity they become more accurate because of the decrease in gap losses.

A special float design helps to minimize the effects of viscosity in flowmeters of this type.

Solids in the Measuring Medium

The presence of solids in the medium has various effects. First there is the usually undesirable contamination, then there are mixtures such as pastes and slurries, and finally there is the hydraulic transport of solids. Contamination is undesirable because its amount and effects are difficult to predict. Gases can convey liquids or dust particles. Solid particles in a gas are dangerous because the gas flow velocities are high and therefore the kinetic energy of the particles can be appreciable, so that they may become destructive or cause deposits .

The lobed impeller gas totalizer requires that the gases is filtered. In the startup phase a screen with 0.1 to 0.2 mm of mesh is recommended. Additionally, a flushing system can be used to remove dirt. In differential pressure and variable area flowmeters dust particles may damage the highly sensitive metering edges.

Unclean liquids may cause a higher wear of rotary totalizers. In the worst case the rotating parts may become stuck. Vortex and swirl flowmeters flush minor contamination through the meter.

If a non-conducting coating (oil, grease) in an electromagnetic flowmeter isolates the electrically coupled electrodes from the liquid, then a meter with capacitively coupled electrodes must be installed. A conductive coating, e.g. from magnetite, only results in measuring error when the medium (in this case water) has a conductivity of less than 100 $\mu\text{S}/\text{cm}$. Otherwise, the electromagnetic flowmeters is the least affected meter.

A special case is the ultrasonic flowmeter, because the Doppler principle requires some foreign bodies as reflectors. The transit time principle can only tolerate a minor amount of dirt particles and will not operate if gas bubbles are present. Deposits affect the sound path and cause measuring errors.

A prerequisite for proper functioning of the mass flowmeter is that the solid particles follow the vibrations, which again is a function of the fluid viscosity. Therefore, with an increasing mass and inertia of the particle the risk of incorrect measurements increases.

Hydraulic Solids Transport

For hydraulic solids transport, e.g. for coal or dredging slurries, a piping system without any constrictions or obstructions is required. Increased abrasion is also always present. The flow measurement in sections of this kind is only possible with electromagnetic flowmeters. The abrasion effect can be minimized by selecting the appropriate materials for the liner (ceramic carbide, PU, soft rubber) and electrodes (Hastelloy). The mass flow rate of the moving solids is generally the variable which is desired for hydraulic solids transport. Therefore a density meter (radioisotope density meter) and a volume flowmeter are combined and the mass flow rate is calculated from the product of the two values.

Deposits

Undesirable deposits in the pipings are removed with scrapers. The effectiveness of the scraper requires, among other things, a constant inside diameter along the entire length of the piping. The flowmeter installed in the piping is of course subjected to the same requirements, i.e., matching of the inside diameter without steps. Only electromagnetic and ultrasonic flowmeters can be individually adapted. Multipipe mass flowmeters cannot be scraped at all.

Gas Content in a Liquid

The devices used for the flow measurement of liquids are volume flowmeters that are not capable of differentiating between a gas and a liquid. For this reason, gaseous components in a liquid cause errors the magnitude of which is equal to the proportion of gas in the mixture. A correct measurement can be expected to be obtained with a Coriolis mass flowmeter. But here also errors occur because of the damping characteristics of the gases.

Beyond these there are some side effects which must also be considered. For turbine flowmeters it might happen that larger gas bubbles could cause over speeding. Cavitation is readily generated at higher flow velocities particularly in Vortex and swirl flowmeters. In the Ultrasonic flowmeters using the transit time principle both the transit time and the damping are changed so that even small gas bubbles can cause an effect. Errors are noted with as little as a 0.2% volume of gas.

Risk of Corrosion due to Aggressive Measuring Media

The effects of corrosion can only be avoided by proper material selection. A slight inattention, for example, in selecting the material for a gasket can result in an inoperative measuring device.

The complicated elements of volume totalizers are disadvantaged when it comes to material selections. Therefore, these meters are not favored for applications with corrosive media. Rotary vane and Woltman meters are preferred for water measurements.

The flowmeters offer a variety material choices. For differential pressure flowmeters it is important to consider that not only the orifice must be corrosion resistant, but also the pressure lines and fittings. In certain installations an isolating fluid or gas is injected into the pressure line in order to prevent the entry of dangerous fluids.

Variable area flowmeters made of special materials are expensive and, therefore, rarely deployed. The same holds true for the mass flowmeters.

Suitable solutions to the problems are offered only by the electromagnetic and ultrasonic flowmeters. The smooth meter tube can be coated with a corrosion resistant liner such as PTFE, for example. Ultrasonic probes in ultrasonic flowmeters and electrodes in electromagnetic flowmeters are process-wetted, i.e. they extend through the pipe or liner and are, thus, in direct contact with the measuring medium. The ultrasonic probe can be protected with a stainless steel or Hastelloy coating. There are better alternatives available in the electromagnetic flowmeters. A wide variety of electrode materials are available, ranging from stainless steel over Monel, Titanium, Hastelloy and Platinum to Carbon.

4.1.2 Flow Regime Effects

The measuring medium flowing through the piping has characteristics which effect the flow regimes, particularly in combination with the pipeline configuration. On the other hand, the measuring devices only have a limited ability to process these effects without errors. In other words, there are limitations which are characterized by the velocity profile and the Reynolds number.

The ideal condition is flow with a turbulent axisymmetric flow profile. The two-dimensional velocity profile shown in Fig. 1-2 should be considered in three dimensions. All devices operate correctly. Similarly most devices operate correctly with axisymmetric laminar flow profiles with the restriction that the spans of the indirect volume totalizers, the differential pressure and variable area flowmeters decrease with increasing viscosity.

The least affected by flow profile irregularities are the direct volume totalizers. And for measuring media with lower Reynolds numbers they are the most accurate.

		Flow Regime			Steadying Section		
		Laminar	Transi-tion	Turbu-lent	Inlet	Outlet	Shock Type Operation
Direct	Oval Gear Totalizer	n	n	n	n	n	Wear
	Oscillating Piston Totalizer	n	n	n	n	n	Wear
	Lobed Impeller Totalizer	n	n	n	n	n	Risk of resonance
Indirect Volume Totalizer	Rotary Vane Totalizer	n	n	n	n	n	n
	Woltman Totalizer	n	n	n	5 x D	3 x D	n
	Turbine Flowmeter	n	n	n	15 x D	5 x D	Over speed, wear
	Vortex Flowmeter	X	X	X	n	15...25 x D	5 x D
	Swirl Flowmeter	X	X	X	n	3 x D	1 x D
	Differential Pressure Measurement	n	n	n	Tab. 2.5	Tab. 2.5	Error
Flowmeter	Variable Area Flowmeter	n	n	n	n	n	Error
	Electromagnetic Flowmeter	n	n	n	3 x D	2 x D	n
	Ultrasonic Flowmeter	n	X	X	n	Same as orifices, Tab. 2.5	5 x D
	Coriolis Mass Flowmeter	n	n	n	n	n	Error
	Thermal Mass Flowmeter	n	n	n	15 x D	5 x D	n
n = no effect; X = unsuitable 1 x D = inlet/outlet section of 1 x D in length							

Tab. 4-3: Flow Regime Effects

Type of disturbance	Velocity profile (turbulent)	
Concentric reducer		
Concentric square edge reducer		
Concentric expander		
Concentric square edge expander		
Eccentric gate		
90° elbow		
Tee		
Two 90° elbows in different planes		
Eccentric side entry		

Tab. 4-4: Velocity Profiles in Piping 1...2 x D After the Disturbance with Turbulent Flow

Disturbed flow profiles in turbulent flows must be considered independently of the device type. Tab. 4-4 shows a number of examples of disturbances and their influence on the velocity profile cross sections. Direct volume totalizers have no difficulty with such changes. The same holds true for variable area and Coriolis mass flowmeters as well as for swirl flowmeters.

The differential pressure flowmeters are very sensitive to disturbances. Long, disturbance-free straight pipe sections should provide for equilibration (Tab. 2-4). The ultrasonic flowmeter is affected when its very narrow sound beam does not sense all the velocity differences, which is very seldom the case. Therefore, requirements similar to those for the differential pressure flowmeters are valid. The two or more beam ultrasonic flowmeters are better suited for such conditions.

Axissymmetric flow profiles are good-natured disturbances that lose their effects after even short inlet sections. The step changes can, however, carry along wall vortices. Indirect totalizers, electromagnetic flowmeters and mass flowmeters do not encounter any problems.

The situation is quite different with non-symmetric profiles. Direct volume totalizers require an inlet section of $10\ldots15 \times D$ (inlet and outlet sections are straight pipe sections that have the same diameter as the measuring device; flow straighteners provide a means for shortening the required section length), whereas electromagnetic flowmeters demand only sections of $3\ldots5 \times D$. Swirl and transverse vortices persist in straight sections over long distances. Since their effects on the measuring accuracy are appreciable, flow straighteners must be used to eliminate their effects.

The inlet sections listed in Tab. 4-3 should be installed upstream of the meters. Additional outlet sections should be provided to prevent feedback from disturbances downstream of the sensor. Their lengths are between $3 \times D$ and $10 \times D$.

4.1.3 Ranges of Application and Technical Limit Values

The installation site must also be taken into account in the selection of the meter because the ambient conditions can only be adjusted to a limited degree to the requirements of the particular flowmeter.

If, for example, solids are to be transported hydraulically, oscillating piston meters are not suitable. The same is valid for electromagnetic flowmeters that are unusable for gas flow measurement, as gases are not electrically conductive.

Tab. 4-5 shows a number of criteria which may be given by the measuring point. The specifications in the tables are taken from manufacturers' publications. There are certainly device variants with specifications and limits beyond the limits listed in the table.

		Nominal Diameter DN	Mounting Position	Max. Perm. Meas. Point Temp.	Highest Pressure Rating PN	Vibration	Pulsation	Response to Reverse flow	Power Supply	
Volume Totalizer	Direct	Oval Gear Totalizer	6...400	Horizontal	300 °C	100	Increased wear	Minor effect	Reverse Totalizing	Not required, only for conversion and measured value transmission
		Oscillating Piston Totalizer	15...800	Any	300 °C	100		Strong effect		
		Lobed Impeller Totalizer	40...300	Horizontal	40 °C	25		Effect		
	Indirect	Rotary Vane Totalizer	15...50	Horizontal (vertical)	130 °C	16		Little effect	No defined measurement	For supply of the transmitters
		Woltman Totalizer	40...400	Horizontal (vertical)	130 °C	40				
		Turbine Totalizer	5...600	Horizontal (vertical)	250 °C	100				
Flowmeter		Vortex Flowmeter	15...300	Any	400 °C	100	Effect*)	No effect	Compl. meas. for reverse flow	Required
		Swirl Flowmeter	15...400	Any	280 °C	100	Effect*)			
		Differential Pressure Measurement	<50...2000	Any	1000 °C	630	Little effect	Little effect		
		Variable Area Flowmeter	3...100	Vertical	360 °C	250	Strong effect	Strong effect	Minor effect	Same as totalizers
		Electromagnetic Flowmeter	1...3000	Any	180 °C	250	No effect	No effect		Measurement possible
		Ultrasonic Flowmeter	10...3000	Any	200 °C	100		Minor effect		
		Coriolis Mass Flowmeters	1.5...150	Any	200 °C	100	No effect	Insignificant effect	Compl. meas. for reverse flow	Required
		Thermal Mass Flowmeter	25...3000	Any	300 °C	40	No effect	Little effect		

*) Compensation for swirl and Vortex flowmeters

Tab. 4-5: Fields of Application

Pressure and Temperature

Housing strength due to its wall thickness and material selection, mechanical tolerances for temperature expansion, gasket type and material, sensors limits and the effects on the transmitting element; these are some of the considerations that have an effect on the device selection for high temperatures and pressures. For variable area flowmeters a distinction is made between devices with glass tube and those with a metal tube. The pressure and temperature limitations for glass tube meters naturally lie far below those for metal tube meters.

Differential pressure flowmeter selection includes the fittings, pressure lines and transmitters. These parts must be designed appropriately. The limiting values for the transmitter are decisive for the entire system. As the maximum temperature limit for transmitters is usually around 120 °C, higher temperatures must be reduced accordingly by isolators in the pressure line.

Vibration

Piping vibrations primarily cause wear on the moving parts and bearings in volume totalizers. In the oscillating elements in Vortex and mass flowmeters, the vibration frequencies are superimposed on the measurement frequencies, thus causing errors. If resonance occurs, parts may fracture. The ABB Vortex flowmeter is substantially insensitive to vibrations because of the separation of the sensor from the bluff body and the oscillation compensation in the sensor.

Because of its S-shape double tube design the CoriolisMaster mass flowmeter measures differential signals which are essentially decoupled from external vibrations. Additionally, the digital filter technology assures wide insensitivity to external vibrations. Should the vibrations be the same as the excitation frequency, then the measurements could be affected.

The relatively large mass of its float makes the device sensitive to vibrations. Therefore, snubbers should be used and the devices should be fixed to the wall.

Pulsation

Pulsation effects are a function of the inertia of the measuring system. Only when the measuring element can follow the pulsations without lag will the measurement be unaffected.

Measuring devices with moving parts are, thus, subjected to increased wear. Therefore, it is essential to use the appropriate snubbers. Oval gear and oscillating piston meters have so much inertia that they provide a degree of self damping sufficient for averaging purposes. The measuring error will slightly increase.

In Chapter 2.1.3 the dangerous effect of pulsation on lobed impeller totalizers has already been described. Turbine, vortex and swirl flowmeters measure the flow essentially without inertia, but they include time constant elements in the connected transmitters. Again the average is obtained with slightly larger errors. Gas turbine flowmeters are in danger when the rotational speed increases too quickly resulting in more bearing wear if over speeding occurs.

As a result of the nonlinear relationship between the flow rate and the differential pressure, the error in differential pressure flowmeters caused by pulsation also changes nonlinearly. Therefore, a damping device is definitely recommended, preferably using storage volumes or expansion tanks in the measuring medium line. The Hodgson number can be used to calculate the required volumes. The damping elements in differential pressure transmitters compensate for small pulsations.

The float of a variable area flowmeter tends to dance when pulsations are present. Therefore, damping elements must also be used here. Metal cone variable area flowmeters can be equipped with the appropriate damping elements.

Reverse Flow Measurement

An extreme form of pulsation can lead to reverse flow. On the other hand, many pipings are specifically designed and used for bidirectional flow. Are there flowmeters which can also measure reverse flow?

Direct volume totalizers can naturally reverse their direction and totalize backwards when their secondary sides include appropriate provisions. The best solutions are provided by the electromagnetic and mass flowmeters which provide all measurements for both flow directions and can switch automatically.

Power Supply

Measurement and control technology operates with measurement signals which must be transmitted over long distances. Therefore, all totalizers and flowmeters provide appropriate output signals the generation of which requires electrical power. The flowmeters additionally require power supply for their operation.

When only local indication is needed, totalizers and variable area flowmeters do not require electrical supply cables.

In very few cases 0.2 to 1 bar pneumatic standard signals are used. For this purpose the measuring devices must be equipped with the corresponding transmitters the power of which is provided by a compressed air supply of 1.4 bar. Pneumatic transmitters are found in differential pressure and variable area flowmeters.

Grounding the Electromagnetic Flowmeters

Grounding per VDE 0100 is not only required because of safety considerations but also to assure proper operation of the flowmeter sensor. The signals measured at the electrodes are only a few millivolts in amplitude and can be affected by stray ground currents which may flow through the flowmeter or measuring path and may exceed a tolerable degree. To comply with VDE 0100, Part 540, the sensors' grounding screws must be connected to functional ground (for explosion-proof designs per VDE 0165 to a potential equalization bonding conductor). For measurement reasons the ground potential and the signal potential of the measuring medium should be identical, if possible. No additional grounding via the terminals (power supply) is required. Plastic pipes or pipes with insulated liner are grounded by using a grounding plate or grounding electrodes. If the piping section is not free of stray currents, it is recommended that a grounding plate be installed on each side, i.e. upstream and downstream of the flowmeter.

Grounding electrodes are used when price considerations are decisive and no stray currents are present. It should be noted that not all device variants can be specified with grounding electrodes.

One grounding plate is installed when plastic or insulated pipings are used and for device designs, which are not available with grounding electrodes.

Two grounding plates are installed for insulated pipings when stray potentials may exist in the piping. This is also true when cathodic protection is used and the flowmeter sensor is to be installed electrically insulated in the piping so that the cathodic potential can be shunted around the sensor.

4.1.4 Performance Specifications and Properties of the Flowmeters

		Span	Measuring Error in % of Rate	Pressure Drop at q_{vmax} [bar]
Direct Volume Totalizers	Oval Gear Totalizer	1:2...1:10	0.1...0.3	4
	Oscillating Piston Totalizer	1:5...1:250	0.2...2	3
	Lobed Impeller Totalizer	1:20 (1:50)	1	0,03
Indirect Volume Totalizers	Rotary Vane Totalizer	1:100...1:350	2...3	0.25...0.75
	Woltman Totalizer	1:100...1:12500	2...3	0.005...0.5
	Turbine Totalizer	1:5...1:20	0.5 (liquid) 1 (gas)	0.5...1
	Vortex Flowmeter	1:15...1:20	0.75 (liquid) 1 (gas)	0.9 (water) 0.06 (air)
	Swirl Flowmeter	1:15...1:25	0.5	0.7 (water) 0.07 (air)
Flowmeters	Differential Pressure Measurement	1:5 (1:10)	2	0.005...1 depending on differential pressure and area ratio
	Variable Area Flowmeter	1:12	Class 1.6/2.5/6	0.005...0.2
	Electromagnetic Flowmeter	1:50	0.2	Same as piping
	Ultrasonic Flowmeter	1:10	1	Same as piping
	Coriolis Mass Flowmeter	1:100	0.1	0.5...2
	Thermal Mass Flowmeter	1:40...1:150	1	0.002

Tab. 4-6: Performance Specifications

		Moving Parts	Wear, Wear Parts	Material Selection for Process-Wetted Parts	Cleaning Sterilization
Direct Volume Totalizers	Oval Gear Totalizer	Oval gears, gear train	Bearing, gear teeth	Oval gears and housing of gray cast iron, stainless steel, bronze, bearings of hard carbon, stainless steel	-
	Oscillating Piston Totalizer	Oscillating piston, gear train	Bearing, oscillating piston	Housing and meas. chamber of gray cast iron, stainless steel, bronze, thermosets, oscillating pistons of gray cast iron, hard rubber, carbon, PCTFE, Tantalum, plastic	+
	Lobed Impeller Totalizer	Lobed impeller, gear train	Bearing, lobed impeller	Impellers and housing of aluminum alloy or gray cast iron, bearings of stainless steel	-
Indirect Volume Totalizers	Rotary Vane Totalizer	Rotary vane, gear train	Bearing	Housing of brass, measuring inset of plastic, axles of stainless steel	-
	Woltman Totalizer	Rotary vane, gear train	Bearing	Housing of gray cast iron or spheroidal graphite iron, vane and measuring inset of plastic, brass, stainless steel	-
	Turbine Totalizer	Rotor	Bearing	Rotor and housing of stainless steel, bearing of sapphire, tungsten carbide	-
	Vortex Flowmeter	None	Insignificant Wear	Stainless steel, optionally Vortex element, sensor and complete housing of Hastelloy C	+
	Swirl Flowmeter	None		Stainless steel, optionally inlet and outlet body, sensor and complete housing of Hastelloy C	+
Flowmeter	Differential Pressure Measurement	None	Metering edges	Stainless steel 1.4571	
	Variable Area Flowmeter	Float	Metering edges	Stainless steel 1.4571, Hastelloy C, PTFE, PVDF, glass	+
	Electromagnetic Flowmeter	None	Insignificant wear	Liner of hard or soft rubber, PFA, PTFE, electrodes of stainless steel 1.4571, Hastelloy, tantalum, platinum	++
	Ultrasonic Flowmeter	None		Stainless steel 1.4571, Hastelloy C	++
	Coriolis Mass Flowmeters	None		Stainless steel 1.4571, Hastelloy C, stainless steel 1.4435	++
	Thermal Mass Flowmeter	None		Stainless steel, Hastelloy C, ceramic	++

Tab. 4-7: Performance Specifications (Continued)

		Measured Value Indication and Transmission								
		Local Indicator	Limit Contact	Current Output	Two-Wire	Pulse	Interface	HART	Expl. Prot.	Certif. Approval
Direct Volume Totalizers	Oval Gear Totalizer	yes	yes	n	n	yes	n	n	Not requ.	Liquids
	Oscillating Piston Totalizer	yes	n	n	n	yes (Ex)	n	n	Not requ.	Liquids
	Lobed Impeller Totalizer	yes	yes	n	n	yes	n	n	Not requ.	Gases
Indirect Volume Totalizers	Rotary Vane Totalizer	yes	n	n	n	yes	n	n	Not requ.	Water
	Woltman Totalizer	yes	n	n	n	yes	n	n	Not requ.	Water
	Turbine Totalizer	n	n	n	n	yes	n	n	yes	Liquids, gases
	Vortex Flowmeter	yes	yes	yes	yes	yes	yes	yes	yes	n
	Swirl Flowmeter	yes	yes	yes	yes	yes	yes	yes	yes	n
Flowmeter	Differential Pressure Measurement	yes	n	yes	yes	n	yes	yes	yes	n
	Variable Area Flowmeter	yes	yes	yes	yes	yes	n	yes	yes	n
	Electromagnetic Flowmeter	yes	yes	yes	yes	yes	yes	yes	yes	Water, food, chemicals
	Ultrasonic Flowmeter	yes	n	yes	yes	yes	yes	yes	yes	Heating water
	Coriolis Mass Flowmeter	yes	yes	yes	n	yes	yes	yes	yes	yes
	Thermal Mass Flowmeter	yes	yes	yes	n	yes	yes	yes	yes	n

Tab. 4-8: Performance Specifications (Continued)

Span

The spans for oval gear and oscillating piston meters are a function of the viscosity of the measuring medium. They are 1 : 10 for viscosities up to approx. 300 mPas and increase to 1:20 for viscosities of $1 \cdot 10^4$ mPas. The conditions are exactly the opposite for indirect totalizers and flowmeters. With increasing viscosity the linear lower range value increases and reduces the span.

Because of the square root relationship which exists in the differential pressure measurement between the measured variable, the differential pressure and the flow rate, the span depends on the required measuring accuracy. A span of 1:3 promises a very high measuring accuracy.

Electromagnetic and ultrasonic flowmeters represent a special situation in that their upper range values can be set and, thus, optimized. Thermal mass flowmeters (gas measurement) achieve spans up to 1:150.

Error Limits

The error limits represent controversial specifications, because they are values published by the manufacturers for ideal boundary conditions. In practice deviations from the ideal conditions are common, so that additional stipulations must be made for the instrument accuracies. It is important to realize that the accuracy may be based on the currently measured value (% of rate) or on the upper range value (% of max.). In the VDI/VDE Directive 2600 (4) the types of errors, reference values, and error conditions are defined. Through special calibrations better accuracies can be achieved, which are generally valid only for a specific time period. Generally speaking, the error limits can be affected by contamination, wear and physical changes.

The values listed in the table are based on the currently measured values [% of rate]. An exception is made for the specifications regarding the variable area flowmeters, since in VDI/VDE 3513 Sheet 2 a classification class system is defined which is based on a combination of errors related to either the rate or the upper range value. 75% of the error values for an accuracy class are percent of rate values and the other 25% are percent of max. values.

The sum of the two values yields the accuracy class: 1 - 2.6 - 2.5 - 4 - 6 - 10.

The accuracy is defined by two parameters, G and qG: Error limit G: Constantly permissible error in % of rate that is valid above the linearity limit qG. Linearity limit qG: Flow limit in % of the max. value, above which the permissible relative error is constant. Below the linearity limit the permissible measuring error increases with decreasing measured value in inverse ratio.

Wear

Understandably, long-term reliability of the measurement is one of the major user requirements. Therefore, the mechanical wear must be kept to a minimum.

Wear is caused primarily by abrasion of the metering elements (through the measuring medium) and by the bearing friction of the moving parts. Electromagnetic flowmeter can be considered to be ideal because the smooth inside wall only shows wear when highly abrasive media are measured such as lime slurries, sand-water mixtures, or coal-water mixtures in hydraulic solids transport. If the walls are lined with polyurethane or soft rubber then even these measuring media rarely cause difficulties.

Even though Vortex and swirl flowmeters have no moving parts, they do have parts which extend into the measuring section. A specific size, hardness and edge sharpness of solid particles in the measuring medium must not be exceeded. A low dust content in gases or plastic suspensions, however, is permissible.

In orifice metering the metering edge must remain sharp because, otherwise, even minor changes may cause measuring errors. In extreme cases a nozzle can be used for low concentrations of solid particles in the measuring medium. Even then the pressure connections can create problems because they may become plugged. The metering edge of a variable area flowmeter float is also precisely machined and must not be damaged.

Bearing wear in totalizers with rotating meter bodies can be added to the difficulties mentioned above. Even a very small quantity of solid particles in the measuring medium may considerably damage these devices. Ideally, the measured medium should feature a certain tendency to lubricate.

Materials

Material selection always requires information about corrosion problems. Some measuring media are chemically harmless, but can become corrosive when small amounts of other

materials are present, perhaps only contamination. Therefore care must be exercised. The variety of possible materials is especially restricted where complicated and difficult to manufacture parts are required. This is particularly true for volume totalizers and, to a certain extent, for swirl, vortex and mass flowmeters.

At first glance, differential pressure measurement would seem to present no problems. But not only the orifice plate or the nozzle must be manufactured of resistant materials. It is also important that the pressure line, fittings and transmitters are made of a material that is suitable for the measuring medium. Sometimes constant flushing of the pressure lines is used to help.

The price issue comes up for variable area flowmeters made of stainless steel. They are only installed if no supply power is available at the measuring point. The material selection problem is solved almost ideally for electromagnetic flowmeters because the PTFE liner material can be used for almost all measuring media. Platinum is exceptionally good as an electrode material. It may also be possible to solve the electrode material problem by using the capacitive electrode design.

The ultrasonic flowmeter requires the proper protective tube material for the sound transducer (transmitter/receiver).

Cleaning, Sterilization

Why must a closed piping be cleaned? There are various answers: deposits due to sedimentation or adhesion reduce the cross sections, crystal formations block the flow, residue can contaminate the product. The ability to clean is a determining factor for flowmeter selection.

Where deposits are to be expected meters with moving parts are seldom installed. Difficulties can also be encountered in installations of swirl, Vortex and thermal mass flowmeters. In the ultrasonic flowmeters the sound path is altered so that erroneous measurements may occur. In the Coriolis mass flowmeters deposits may cause a zero shift. Nonconducting deposits affect the electromagnetic flowmeters unless the same meter type with capacitive electrodes is installed. Electrically conductive deposits short out the measuring signal and cause erroneous measurements.

Deposits are removed by flushing, dissolving, or by mechanical cleaning using a brush or scraper. An unobstructed cross-section is a big advantage for this method. Using a scraper even requires a piping with a defined diameter without internal steps. This requirement can only be met by the electromagnetic flowmeter, and perhaps by the ultrasonic flowmeter. Residues remaining in the piping are a special problem in the food and beverages industries, where bacteria may contaminate the final product. Thorough cleaning and sterilization using steam, liquid cleaning agents, acids and bases are mandatory. This is usually accomplished using CIP (Cleaning In Place) and SIP (Sterilisation in Place) procedures, in which all elements in the system remain in place. The CIP capability is determined by testing and confirmed by certificates. The oscillating piston meter must be disassembled for cleaning.

4.1.5 Installation and Maintenance

The user of measurement information expects a problem free installation of the meter and thereafter only wants to see accurate measurement values, the meter itself is no longer of interest. Even though modern technology comes close to fulfilling these expectations, regular monitoring can prevent failures. Therefore included in the selection of a meter is the question regarding the capabilities of the maintenance personnel.

The flowmeter, e.g. a Vortex or thermal mass flowmeter, is installed in the piping in a relatively straightforward manner using flanged or threaded connections while giving consideration to the inlet and outlet sections. At this point the requirement for stress free installation must be emphasized because very often the meters are installed in existing pipings, and existing stress is transferred to the meters. Wafer-type design requires exact centering. And there are ultrasonic flowmeters the measuring elements (transmitter/receiver) of which are welded into the piping wall. This method produces error free measurements only when an on-site calibration is conducted which takes into account the actual piping geometry.

The work is essentially completed when totalizers and variable area flowmeters which operate without an external power supply are installed . Flowmeter sensors and separate transmitters communicate with each other with low-level signals that are sensitive to interference. For this reason special shielded cables are used. Flowmeters with integral mount design do not require this effort.

An appreciable expense is required for differential pressure flowmeter installations. In this case, the pressure lines and various fittings must be installed and connected. Also, differential pressure transmitters require an external power supply.

All measuring devices are designed such that maintenance personnel can monitor their proper functional operation using a simple tests. The majority of these devices are self-monitoring and report errors.

The wear in bearings and measuring elements of rotating totalizers can usually be best determined by a visual examination. That is why these totalizers are designed such that they can be opened on site.

When installing electromagnetic flowmeters, it must be ensured that they are axissymmetrically fitted, that they are filled with the medium to be measured and that they are not operated when empty. An exception is the FXP4000 flowmeter. This electromagnetic flowmeter is suitable for use in partially filled pipings. If it cannot be avoided that a system is sometimes run empty, the signal outputs are switched off accordingly, either via an external contact, for pipe sizes greater than DN 10 and cable lengths of up to 50 m (remote mount design), or automatically by means of an empty pipe detector function. This avoids measuring errors in the measuring section when the pipe is empty.

For the majority of installations it is fully sufficient to realize a straight inlet section of $3 \times D$ of the nominal diameter and an outlet section of $2 \times D$ of the nominal diameter of the flowmeter sensor. These are the manufacturers' specifications. According to the reference conditions stipulated in EN 29104, for systems to be approved by the Weights and Measures Office, and to comply with the DVGW Directives other straight section lengths are specified and must be observed.

Valves or other shut-off elements should be installed in the outlet section. A slight slope of approx. 3 % is advantageous for degassing. It should be ensured that the imaginary line which connects the two electrodes is horizontal if possible or no more than 45° from the horizontal, so that any air or gas bubbles cannot affect the measurement voltage.

The monitoring and test system for the electromagnetic meters is optimally structured. In addition to internal test functions, simulators are available with which practically all parameters can be checked.

		Tasks On Site	Piping Upstream of Meter	Maintenance During Operation	Self-Monitoring	Service
Direct Volume Totalizers	Oval Gear Totalizer	Flanged connection	Filter	Maintenance-free	Not possible	Local disassembly possible
	Oscillating Piston Totalizer	Flanged connection, threads	Filter recommended, no steadyng section	Maintenance-free	Not possible	
	Lobed Impeller Totalizer	Flanged connection	Filter	Lubrication monitoring	Not possible	
Indirect Volume Totalizers	Rotary Vane Totalizer	Flanged connection, threads	No steadyng section	Maintenance-free	Not possible	Exchange of measuring inset possible
	Woltman Totalizer	Flanged connection	No steadyng section	Maintenance-free	Not possible	
	Turbine Flowmeter	Flanged connection, electrical installation	No steadyng section	Maintenance-free, monitoring of possible external lubrication	Not possible	Sensor replacement
	Vortex Flowmeter	Flanged connection or wafer-type design, electrical installation	Long steadyng section	Maintenance-free	Permanent plausibility checking and error monitoring/reporting	Electronic control function and test values, sensor is exchangeable
	Swirl Flowmeter	Flanged connection, electrical installation	Short steadyng section	Maintenance-free		

Tab. 4-9: Maintenance Requirements

		Tasks On Site	Piping Upstream of Meter	Mainte- nance During Operation	Self- Monitoring	Service
Flowmeter	Differential Pressure Measurement	Center meter in flange, pressure line, fittings, transmitter, power supply	Long inlet and outlet sections	Regular inspection required	Not possible	Direct measurement at transmitter
	Variable Area Flowmeter	Flanged or threaded connection	No regulations	Maintenance-free	Permanent plausibility checking, error monitoring and reporting	Glass flowmeter with "SNAP-IN" design
	Electromagnetic Flowmeter	Flanged connection, electrical installation	Short inlet and outlet sections	Maintenance-free		
	Ultrasonic Flowmeter	Flanged connection, or weld-in socket, el. installation	Long inlet and outlet sections	Maintenance-free	Signalling few failures	
	Coriolis Mass Flowmeter	Flanged connection, wall-mounting, electrical installation	No regulations	Maintenance-free	Permanent plausibility checking, error monitoring and reporting	Electronic control functions and test values
	Thermal Mass Flowmeter	Flanged, wafer-type mounting and plug-in sensors	Inlet/outlet sections	Maintenance-free	Error reporting	Measuring sensor can be exchanged

Tab. 4-10: Maintenance Efforts, Continued

4.2 Flowmeters for Channels and Free Surface Pipings

The comparison (Tab. 4-11) is not as extensive as those for meters in closed pipings. A large number of parameters exclusively refer to closed pipings, and the application range of the devices considered here is considerably restricted. As channels and free surface pipings are mainly used for water or waste water applications, only these measuring media will be considered here.

Waste water often includes a variety of nonwater components which must be taken into account when making comparisons. Chemically aggressive components play an important role in material selection. Solid components can cause errors or hamper measurements. Therefore, it is important that the sweeping forces of the water are sufficient to carry the solids.

	Meter Sizes	Max. Flow Rate	Meas. Span	Error Limit	Meas. Value Indication and Transmission	Solids in Measuring Medium	Air in Water	Flow Regime Effects
Open Channel	Weir	Practically unlimited	Unlimited	1:20 (1:100)	> 3 %	With appropriate sensor selection all types are possible, from local indicator to HART communication	Risk of deposit build-up upstream of weir and on overflow edge	Ventilation required so that the stream separates at the metering edge
	Venturi Flume	Width in mm 220...3514	13,990 m ³ /h	1:10 to 1:20	(Design type calibration) ± 6 % of rate		No sedimentation if minimum velocity is maintained	Degassing in inflow
Free Surface Piping	EMF in Culvert	All DN up to DN 2500	267,000 m ³ /h	1:50	± 0.25 % of rate	Electromagnetic flowmeters offer all possibilities, from local indicator to interface and HART communication + PROFIBUS + FF	Risk of sedimentation at low flow velocity and with heavy solid particles	Avoid air, otherwise measuring errors
	FXP4000	DN 150 to DN 2000	171,000 m ³ /h	1:100	TF: 5/3 % of rate VF: 1 % of rate		No sedimentation	Degassing in inlet

Tab. 4-11: Flowmeters for Channels and Free Surface Pipings

4.2.1 Solids in the Measuring Medium

When the flow velocity in the dammed area ahead of a weir decreases the solid particles carried along with the fluid will settle. The deposits change the geometric conditions and cause measuring errors. Floating particles change the geometry even more and may plug the meter overflow.

The Venturi flume accelerates the fluid in its constricted areas and drives the solids through. The floating particles may have a negative impact on the level measurement. Foam build up causes measurement errors which are a function of the type of sensor used.

In pipe culverts extremely low velocities can be present, leading to the formation of deposits which, however, have little or no effect on the measurements. When the velocity increases, the culvert is flushed (sand deposits in straight pipes are already carried along at velocities $> 0.25 \text{ m/s}$).

4.2.2 Gas Content

The gas content is usually due to entrained air. Since all the devices discussed in this chapter measure the volume flow, the air content in the water is considered as fluid and causes an error as large as the volume of the entrained air.

The weir requires ventilation through air entry at its sides so that the overflow stream can separate from the metering edge and does not attach to the outer side of the weir due to the presence of a vacuum. Air resulting from this ventilation causes no errors because the level measurement is made approx. $4 \times h$ upstream of the weir. Basically open channel measurements are rarely affected by entrained air.

The FXP4000 also allows the measuring medium to deaerate within the inlet section. It is, however, possible that in fully filled pipings air remains in the water and cannot escape before reaching the measuring section. This may result in measuring errors.

In culverts air can be sucked in due to vortices in the inlet. This effect can be avoided by increasing the air level upstream of the culvert (inlet shaft). When the incoming fluid falls into the inlet shaft as a free stream the same air injection effects occur.

4.2.3 Flow Regime Effects

The flow regime effects in closed pipings have already been discussed in Chapter 4.1.2. What is said there also applies in this situation, especially for electromagnetic flowmeters in culverts. An additional parameter complicates the measurements in open channels and that is the nature of the upper surface of the liquid because wave motion as the sensor seat will be included in the measurements. The weir is not as affected as the Venturi flume.

The Venturi flume dams the flow in the water inlet section and thereby quiets the surface when subcritical flow is present. The inlet section should be straight with a constant cross sectional area without any unevenness.. The location of any hydraulic jump should be at least $20 \times w$ (flume width) upstream of the Venturi flume. On the outlet side there is a requirement that in no case may backflow be present in the Venturi flume which could produce a level at the measuring point that corresponds to a higher flow rate. The Parshall flume allows for a slight backflow.

This backflow can be ideally handled in the FXP4000 electromagnetic flowmeter for partially full pipings because this meter measures the combined dynamic effects of velocity and the utilized cross sectional area. This means that at zero flow no metering signal exists. The FXP4000 can measure flow in both directions. This means, it can also measure the backflow.

The velocity distribution within the flow cross sectional area in the FXP4000 should be approximately uniform. Therefore subcritical flow is preferred so that the irregularities that might exist in the vicinity of a hydraulic jump can be avoided. Below are shown some practical piping installations:

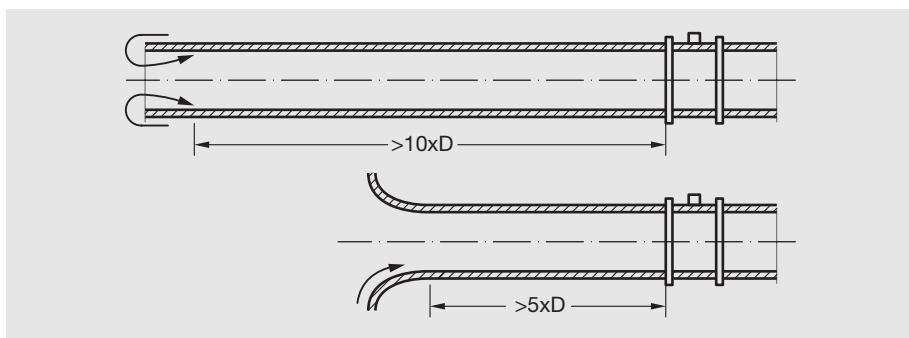


Fig. 4-1: Pipe Inlet

When the flow into the pipe occurs at a blunt entry as shown in Fig. 4-1, evidences of separation at the wall near the inlet appear, coupled with vortex formation. Dependent on the pipe roughness, inlet sections $15 \times D$ (pipeline size) or longer are required so that the flow is uniform in the measuring section. A more effective flow stream entry with a trumpet shape can be used to reduce the length of the inlet section.

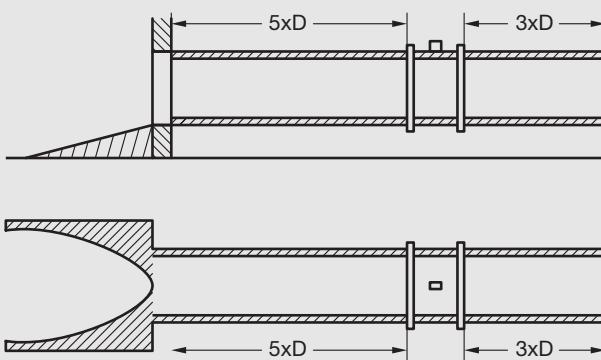


Fig. 4-2: Transition from Rectangular to Circular Cross Section

The FXP4000 reduces construction expenditures and can therefore be installed in many locations. The transition to a circular cross section is very important because waves and vortices can occur at these locations. An example of a transition from a rectangular to a circular cross section is shown in Fig. 4-2. Smooth transitions are preferred with an important consideration that the bottom elevation extends right through the FXP4000. The transitions already begin in the basin bottom with a channel.

A constant bottom elevation should also be maintained for installation in rounded channels whenever possible. The more the channel approaches an egg shape the more readily can a FXP4000 be fitted (Fig. 4-3). An effective flow stream transition should also be provided in these situations.

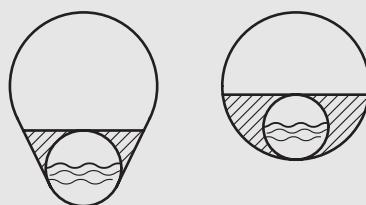


Fig. 4-3: Transition to a Round Cross Section

It is important to consider the conduit conditions far upstream of the measuring point. A perpendicular inflow from the side generates vortices which will persist even after a $15 \times D$ long straight section (Fig. 4-4). An overflow weir in the entry assures a satisfactory flow stream.

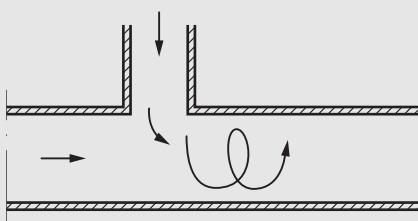


Fig. 4-4: Partially Full Channel with Perpendicular Side Inflow (Top View)

Supercritical inflow must be transformed to subcritical.

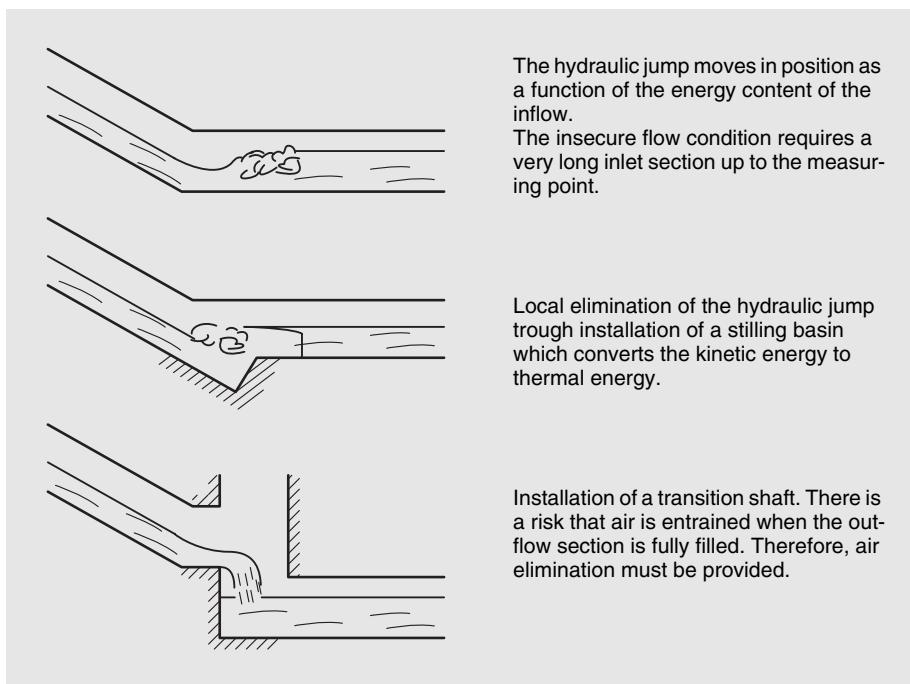


Fig. 4-5: Supercritical Inflow



Fig. 4-6: Flat Gate in Outlet Section

The gate in the piping (Fig. 4-6) generates unsteady flow stream conditions. The hydraulic influences upstream however are small. Therefore the measuring point should be situated 1 to $3 \times D$ ahead of the gate.

The upstream effects of disturbances downstream of the FXP4000 are relatively small so that generally a short outlet section is sufficient. An example is the free fall exit (Fig. 4-7).

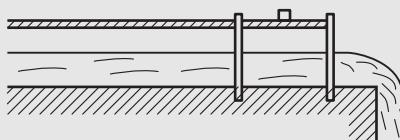


Fig. 4-7: Free Fall Downstream of the Measuring Point

The measuring point must far enough away so that the water surface level drop off curve does not begin inside the meter. Usually, a distance of $3 \times D$ is sufficient.

Occasionally, a measurement must be made after a channel bend which may include a sloped bottom (Fig. 4-8). The centrifugal forces produce a sloped surface with a perpendicular secondary flow. The local conditions determine possible measurement errors.

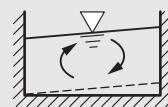


Fig. 4-8: Cross Section Through a Channel Bend

5 Overview of the Outstanding Meter Features

5.1 Oval Gear Meters, Oscillating Piston Meters

Advantages:

- High measuring accuracy
- Suitable for measuring media with high viscosity
- Operates in both flow directions (forward and reverse)
- No flow profile effects, thus no inlet and outlet sections required
- No external power supply
- Approved by the Board of Weights and Measures

Limitations:

- Volume totalizer
- For liquids only
- High pressure drop
- Moving parts, wear
- Accuracy decrease for lower viscosities due to gap losses
- Sensitive to contamination, filter required
- Flow blockage at zero flow through solid impurities
- Sensitive to overloading
- Monitoring and maintenance

5.2 Lobed Impeller Meters

Advantages:

- Excellent measuring accuracy for gas measurements
- No inlet and outlet sections required
- No external power supply
- Approved by the Board of Weights and Measures

Limitations:

- Volume totalizer
- For gases only
- Moving parts, wear
- Flow blockage at zero flow through solid impurities
- Sluggish toward quick changes
- Also affected by quick changes at high differential pressure, danger of over speeding
- Monitoring

5.3 Turbine Meters

Advantages:

- No external power supply for Rotating vane and Woltman meters
- Rotating vane and Woltman meters approved for water by the Board of Weights and Measures
- Turbine flowmeters suitable for cryogenic liquids
- Turbine flowmeters usable at extreme temperatures and pressures
- Turbine flowmeters approved for gas by the Board of Weights and Measures

Limitations:

- Limited choice of materials
- Only for low viscosities
- Moving parts, wear
- Sensitive to contamination
- Axial flow totalizers are flow profile sensitive
- Inlet and outlet sections required (not for rotating vane meters)
- Affected by overloading and quick changes at high differential pressure, danger of over speeding
- Vibration sensitive

5.4 Vortex Flowmeters

Advantages:

- No moving parts
- Rugged construction
- Suitable for liquids, gases and steam
- Easily sterilized
- Unaffected by pressure, temperature and density changes
- Linear relationship between flow rate and measured value

Limitations:

- Inlet and outlet sections required
- Minimum Reynolds number required

5.5 Swirl Flowmeters

Advantages:

- No moving parts
- Short inlet and outlet sections → $3 \times D / 1 \times D$
- Suitable for liquids, gases and steam
- Excellent repeatability
- Unaffected by pressure, temperature and density changes

Limitations:

- Pressure drop
- Minimum Reynolds number required

5.6 Differential Pressure Flowmeters

Advantages:

- Universally suitable for liquids, gases and steam
- Also usable in extreme situations, e.g. viscosity, due to variety of versions
- Calculations possible for unusual situations
- Suitable for extreme temperatures and pressures
- Range changes possible
- Low pressure drop for nozzles

Limitations:

- Square root relationship between flow rate and differential pressure, therefore smaller span
- Affected by pressure and density changes
- Pressure drop for orifice plates
- Edge sharpness for orifice plates must be assured, therefore no solids or contamination
- Very long inlet and outlet sections
- Expensive installation requiring differential pressure lines, fittings and sensors
- Installation and maintenance experience advantageous
- High maintenance requirements

5.7 Variable Area Flowmeters

Advantages:

- Inexpensive
- No external power supply required for local indication
- Suitable for liquids, gases and steam
- No inlet and outlet sections required
- Simple meter design, therefore easy to install and maintain
- Indication also with opaque liquids
- Metal cone meter with transmitter
- Metal cone meter can be sterilized, CIP tested

Limitations:

- Vertical mounting position
- Constant pressure drop
- Affected by density, temperature and viscosity changes
- Solids damage metering edge, otherwise slight contamination allowed
- Affected by pulsation and vibration
- Expensive when exotic materials are required

5.8 Electromagnetic Flowmeters

Advantages:

- Unobstructed flow passage without projecting parts
- No moving parts
- No additional pressure drop
- Essentially flow profile insensitive, only short inlet and outlet sections required
- Unaffected by changes in temperature, density, viscosity, concentration and electrical conductivity
- Favorable choice of materials for chemically aggressive or abrasive measuring media
- Unaffected by contamination and deposits
- Especially suitable for hydraulic solids transport
- Can be sterilized, CIP tested
- Linear relationship between flow rate and measured variable
- Operates in both flow directions (forward and reverse)
- Measuring range setting can be optimized
- Low maintenance, but still easy to maintain
- Approved by the Board of Weights and Measures

Limitations:

- For liquids only
- Lower conductivity limit $0.05 \mu\text{S}/\text{cm}$
- Gas inclusions cause errors

5.9 Ultrasonic Flowmeters

Advantages:

- Unobstructed flow passage
- No moving parts
- No additional pressure drop
- Favorable choice of materials for chemically aggressive liquids
- Linear relationship between flow rate and measured variable
- Low maintenance
- Operates in both flow directions (forward and reverse)
- Transit time meters unaffected by temperature, density and concentration
- Later installation in existing pipe possible with individual elements, but onsite calibration required

Limitations:

- Still problematic for liquid and gas measurements
- Sound beam must traverse a representative cross section, therefore flow profile dependent. Long inlet and outlet sections required
- Errors due to deposits
- Transit time meters require clean liquids
- Doppler meters only for slight contamination or few gas bubbles
- Doppler meters affected by sound velocity changes due to temperature, density and concentration
- Unsuitable for heavily contaminated liquids
- Gas bubbles cause errors

5.10 Coriolis Mass Flowmeters

Advantages:

- True mass flow measurement
- Additional temperature and density measurements
- Very high accuracy for mass flow measurements
- Highly accurate density measurement
- Unaffected by pressure, temperature and viscosity
- No inlet and outlet sections required
- Operates in both flow directions (forward and reverse)
- Can be sterilized, CIP tested, EHEDG certified
- Measuring range settings can be optimized for flow rate and density
- Self-draining

Limitations:

- Affected by gas inclusions
- Vibration sensitive when improperly installed
- Limited choice of materials
- Nominal diameter limited at the top

5.11 Thermal Mass Flowmeters

Advantages:

- Direct gas mass flow measurement
- No pressure and temperature compensation required
- Very low pressure drop
- High measuring accuracy
- Large span
- No moving parts
- Rugged construction
- Short response time
- Easily sterilized

Limitations:

- For gases only
- Inlet and outlet sections required

5.12 Weirs

Advantages:

- Simple design
- Minimum space requirements at the measuring point
- Low construction costs

Limitations:

- Damming, therefore higher space requirements upstream of the measuring point
- Risk of deposit build up upstream of the weir, not suitable for waste water
- Stream separation through ventilation must be assured
- Affected by large floating items

5.13 Venturi Flumes

Advantages:

- No potential energy differences compared to the weir
- Low pressure drop
- Suitable for unclean waste water
- Easy to maintain

Limitations:

- Nonlinear flow characteristic
- Channel constriction resulting in damming of the headwater and risk of deposit build up in the event of velocity decrease
- Risk of plugging through larger floating items
- Measurement impossible when backflow exists in tail water up to Venturi flume
- Quality and reliability of the measurement depending on connected sensor
- Installation costs

5.14 Electromagnetic Flowmeters in Culverts

Advantages:

- All the advantages of the electromagnetic flowmeters listed in Item 5.8
- Smaller nominal diameter as compared to FXP4000, lower price
- Higher accuracy than FXP4000

Limitations:

- Building required, cost intensive
- Higher pressure drop as compared to FXP4000
- Risk of deposit build up in the event of too low flow velocity

5.15 Electromagnetic Flowmeter FXP4000 for Partially Full Pipelines

Advantages:

- All the advantages of the electromagnetic flowmeters listed in Item 5.8
- No culverts required
- No onsite calibration required
- Unobstructed passage, no cables or mechanical parts across the pipe cross section
- No additional pressure drop
- Direct installation in free surface pipes
- Easy cleaning
- Backwater is permissible
- No risk of deposit build up, contrary to culverts
- No constrictions through the measuring system, thus no backwater in free surface pipes
- Short inlet and outlet sections

Limitations:

- Minimum nominal diameter: DN 150

6 Keywords for the Operating Conditions and Requirements on the Measuring Point

When a measuring point is being planned, certain requirements must be satisfied in order for the desired measuring effect to be realized. Shall the meter provide information by itself (for example through local indication) or support another function (for example as an actual value generator for a controller). The planner begins his preparations for the meter selection by considering the operating conditions. He raises questions regarding the measuring medium, the local conditions and the measured value presentation requirements. The following keyword summary is provided as a selection aid:

Properties of the Measuring Medium:

- Gas, steam: dry, wet
- Liquids: gas and solids content, crystallizing component deposits, dust in gas
- Density
- Temperature, temperature variations, time relationships
- Viscosity
- Electrical conductivity, of the deposits
- Chemical aggressiveness, material selection
- Abrasion danger

Operating Conditions:

- Pipe nominal diameter
- Design of a channel, slopes, damming
- Pressure rating
- Flow rate, smallest, largest value: type of flow changes (step changes)
- Flow conditions: linear, turbulent flow
velocity distribution, swirl, pulsation
- Bidirectional (forward and reverse)
- Static pressure, pressure shock, pressure drop permissible

Ambient Conditions:

- Ambient temperature
- Humidity effects, degree of protection
- Dust entry, degree of protection
- Vibration
- Pipeline construction upstream and downstream of the measuring point
- Explosion protection
- Power supply, cabling
- Electromagnetic and radio frequency interference
- Mounting options

Measured Value Presentation:

- Measuring accuracy
- Fixed, adjustable, internal, external measuring range
- Internal, external monitoring capabilities
- Local indication
- Totalization, integration
- Alarm signalling unit
- Standardized analog output, what value?
- Pulse output for remote totalization
- Communication, which type?
 - PROFIBUS, FOUNDATION Fieldbus
 - HART Protocol
- Explosion protection
- Calibratability

7 Standards and Regulations

DIN 1319	Grundbegriffe der Messtechnik <i>Fundamentals of metrology</i>
DIN ISO 6817	Durchflussmessung von leitfähigen Flüssigkeiten <i>Measurement of conductive liquid flow in closed conduits</i>
DIN ISO 9104	Durchflussmessung von Fluiden <i>Measurement of fluid flow in closed conduits</i>
DIN 1952	Durchflussmessung mit Blenden, Düsen, Venturi-Rohren <i>Measurement of fluid flow by means of orifices, nozzles and Venturi tubes</i>
DIN 19559	Durchflussmessung von Abwasser in offenen Gerinnen und Freispiegelleitungen <i>Measurement of flow of waste water in open channels and gravity conduits</i>
VDE/VDI 3512	Durchflussmessungen mit Drosselgeräten, Messanordnungen <i>Measurement of fluid flow with primary devices, measurement setup</i>
VDE/VDI 2040	Berechnungsgrundlagen für die Durchflussmessung mit Drosselgeräten <i>Measurement of fluid flow with primary devices, calculation bases</i>
EN 60529	IP-Schutzarten <i>Specification for degrees of protection provided by enclosures (IP code)</i>
EN 29104	Verfahren zur Beurteilung des Betriebsverhaltens von magnetisch-induktiven Durchflussmessgeräten <i>Methods of evaluating the performance of electro-magnetic flow-meters for liquids</i>
DIN VDE 0170/017	Bestimmung für explosionsgeschützte elektrische Betriebsmittel <i>Requirements for electrical apparatus for potentially explosive atmospheres</i>
DIN VDE 0165	Errichten elektrischer Anlagen in explosionsgefährdeten Bereichen <i>Explosive atmospheres - Electrical installations design, selection and erection</i>

DIN EN 50014 to 50020 and 50028	Elektrische Betriebsmittel für explosionsgefährdete Bereiche <i>Electrical apparatus for potentially explosive atmosphere</i>
NAMUR NE 21	NAMUR-Empfehlung Elektro-magnetische Verträglichkeit <i>NAMUR Recommendation</i> <i>Electromagnetic Compatibility (EMC)</i>

8 Materials, Corrosion Resistance Tables

Included among the criteria for meter selection are the materials to be utilized. Of primary interest are those materials which come in contact with the measuring medium. Also the ambient conditions must not be neglected where it is most important that humidity be considered.

Generally the user knows his measuring media so well that he can readily indicate suitable materials. The following tables are provided for assistance. The listed information is taken from manufacturers' publications. However, a guarantee for the completeness and correctness cannot be given.

The following list includes the available materials for the process-wetted parts in the individual measuring devices.

Vortex Flowmeters:

Meter tube:	Stainless steel 1.4571, Hastelloy C
Sensor:	Stainless steel 1.4571, Hastelloy C
Shedder:	Stainless steel 1.4571, Hastelloy C
Gasket:	Graphite, PTFE, Viton A, Kalrez

Swirl Flowmeters:

Meter tube:	Stainless steel 1.4571, Hastelloy C
Sensor:	Stainless steel 1.4571, Hastelloy C
Shedder:	Stainless steel 1.4571, Hastelloy C
Gasket:	Graphite, PTFE, Viton A, Kalrez

Electromagnetic Flowmeters:

Liner	Hard rubber, soft rubber, PFA, PTFE, Torlon, Peek, PVDF, Ceramic Carbide
Electrodes	Stainless steel 1.4571, Hastelloy B, Hastelloy C, stainless steel 1.4539, Titanium, Tantalum, Platinum Iridium

Coriolis Mass Flowmeters:

Meter tube	Stainless steel 1.4571, 1.4435, Hastelloy C
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Thermal Mass Flowmeters

Meter tube	Stainless steel 1.4571, Hastelloy
Sensor	Stainless steel 1.4571, Hastelloy,
Gasket	Ceramic Al ₂ O ₃ Viton, Kalrez

Variable Area Flowmeters:

Meter tube	Glass, Hastelloy C, PTFE, stainless steel 1.4404
Float	Glass, stainl. steel 1.4571, Hastelloy C, PVDF, PTFE
Fittings	Stainl. steel 1.4301, PVC, Hastelloy C
O-rings	Buna N, Viton A, Ethylene/ Propylene = EPDM

The following symbols are used in the resistance tables:

- + indicates usable material
- indicates unsuitable material
- open fields indicate unknown resistance

Even though the tables may indicate that a metal is satisfactory, electromagnetic flowmeters may nevertheless show malfunctions, due to electrochemical reactions in the flowmeter.

Liability Note:

The following resistance table for ABB flowmeters has been compiled from reference literature and own experience. It is intended to allow for a pre-selection of potentially suited materials for a special application, or for excluding unsuitable materials a priori.

However, these specifications are only recommendations for which no liability can be assumed since the corrosion behavior under actual operating conditions may deviate from results obtained in the laboratory with clean measuring media. Reliable specifications require operational corrosion tests or must be based on the user's operational experience.

The specifications in the tables refer to laminar corrosion attack. The risk of local corrosion attack (pitting corrosion, stress corrosion cracking) has not been taken into account.

	Gaseous/Liquid	Electrical Conductivity	Concentration (%)	Metals							Non-Metals							Titanium		Tantalum		Platinum		Hard Rubber		Soft Rubber		PFA		PTFE		EPDM		Buna N		Viton A		PVDF		PVC		Glass		Al ₂ O ₃	
				40	80	100	-	-	-	-	Stainl. steel 1.4301	Stainl. steel 1.4539	Stainl. steel 1.4541	Stainl. steel 1.4571	Hastelloy B	Hastelloy C	Titanium	Tantalum	Platinum	Hard Rubber	Soft Rubber	PFA	PTFE	EPDM	Buna N	Viton A	PVDF	PVC	Glass	Al ₂ O ₃															
				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
Acetic acid	F	-	100	40	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-	+	+												
Acetic acid	F	+	50	80	+	+	+	+	+	+	+	+	+	+	+	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	+	+												
Acetic anhydride	F	+	100	20	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Acetylene	G	-	100	20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+												
Alum. chloride solution	F	+	30	70	-	-	-	-	+	-	-	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Alum. chloride solution	F	+	80	70	-	-	-	-	+	-	-	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Alum. sulfate solution	F	+	20	50	-	-	-	-	+	-	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Alum. sulfate solution	F	+	50	50	-	-	-	-	+	-	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Ammonia	G	-	100	50	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Ammonia solution	F	+	25	50	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Aniline	F	-	100	25	+	+	+	+	-	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+												
Argon	G	-	100	100	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+												
Beer	F	+		10	+	+	+	+	+	+	+	+	+	+	+																			+	+										
Benzene	F	-	100	50	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+											
Blood	F	+			+	+	+	+	+	+	+	+	+	+	+																			+	+										
Brine	F	+		20	-	-	-	-	+	-	+	-	+	+	+																		+	+											
Bromine	F	-	100	20	-	-	-	-	+	-	+	-	+	+	+																			+	+										
Butane	G	-	100	50	+	+	+	+	+	+	+	+	+	+	+																			+	+										
Butyl acetate	F		100	50	+	+	+	+	+	+	+	+	+	+	+																		+	+											
Butyl alcohol	F	-	100	20	+	+	+	+	+	+	+	+	+	+	+																		+	+											
Butylene	G	-	100	20	+	+	+	+	+	+	+	+	+	+	+																		+	+											
Calcium chloride solution	F	+	100	20	+																														+	+									
Calcium hydroxide sol.	F	+	50	50	+	+	+	+	+	+	+	+	+	+	+																			+	+										
Calcium hypochlor. sol.	F	+	20	50	-	-	-	-	+	+	+	+	+	+	+																			+	+										
Caprolactam	F	-	50	50					+	+	+																									+	+								
Carbolic acid	F	-	90	50	-	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+											
Carbon dioxide	G	-	100	50	+	+	+	+																												+	+								
Carbon tetrachloride	F	-	100	50	+	+	+	+	+	+	+	+	+	+	+																				+	+									
Carbonic acid	F	+		50	+	+	+	+	+	+	+	+	+	+	+																			+	+										
Carboxylic acid, diluted	F	-		50					+	+	+	+	+	+	+																				+	+									
Chlorinated water	F	+	100	20	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
Chlorine dioxide, dry	G	-	100	20	+				+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-										

	Gaseous/Liquid	Electrical Conductivity	Concentration (%)	Temperature (°C)	Metals				Non-Metals															
					Stainl. steel 1.4301	Stainl. steel 1.4539	Stainl. steel 1.4541	Stainl. steel 1.4571	Hastelloy B	Hastelloy C	Titanium	Tantalum	Platinum	Hard Rubber	Soft Rubber	PFA	PTFE	EPDM	Buna N	Viton A	PVDF	PVC	Glass	Al ₂ O ₃
					+	+	+	-	+	+	+	+	+	-	+	+	+	-	+	+	+	+	+	
Chlorine, dry	G	-	100	20	+	+	+	+	-	+	+	+	+	-	+	+	-	+	+	+	+	+	+	
Chlorine, dry	F	-	100	20	+	+	+	+	-	+	+	+	+	-	-	+	+	-	+	+	-	+	+	
Chlorine, wet	G	-	100	20	-	+	-	-	-	+	+	+	+	-	-	+	+	-	+	+	+	+	+	
Citric acid	F	+	60	50																				
Copper chloride solution	F	+	50	20	-	-	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Copper sulfate solution	F	+	50	80	+	+	+	+	-	+	+	+	+	+	+	-	+	+	+	+	+	-	+	
Copper sulfate solution	F	+	100	80	+	+	+	+	-	+	+	+	+	+	-	+	+	+	+	+	+	-	+	
Deionized water	F	-																						
Diesel fuel	F	-	100	50	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	-	+	+	
Ethane	G	-	100	50	+	+	+	+	+	+	+	+	+	+	+	+	-	+	-	-	-	+	+	
Ethanol	F	-	96	50	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	
Ethyl acetate	F	-	100	50	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	+	-	+	
Ethyl alcohol	F	-	100	78	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	
Ethyl ether	F	-	100	20	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	-	+	+	
Ethylene	G	-	100	50	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	
Ethylene chloride	F	-	100	50	-	+	-	+	+	+	+	+	+	-	-	+	+	-	+	-	-	+	+	
Ethylene glycol	F	+	100	50	+	+	+	+	+	+	+	+	+			+	+	+				-	+	+
Fatty acid	F	-	100	50	+	+	+	+	+	+	+	+	+	-	-	+	+		+		+	+	+	
Ferric chloride solution	F	+	3	20	-	+	-	-	+	+	+	+	+			+	+	+	+	+	+	+	+	
Ferric chloride solution	F	+	10	20	-	-	-	-	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+	
Ferric sulfate solution	F	+	10	20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Fluorine	G	-	100	20	+	+	+	+	-	+						+	-			+	+	-	-	
Formaldehyde solution	F	+	40	50	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	+	+	+	
Formic acid	F	+	100	80	-	+	-	+	-	+	-	+	+	-	-	+	+	-	+	+	-	+	+	
Gasoline	F	-	100	20	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	-	+	+	
Gelantine	F	+		50	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Glycerine	F	-	100	100	+	+	+	+	+	+	+	+	+	+	-	+	+	-	+	-	-	+	+	
Glycol	F	-	100	50												+	+		+	+		+	+	
Heating oil	F	-	100	80	+	+	+	+	+	+						+	+	-	+	+	+	+	+	
Helium	G	-	100	80	+	+	+	+	+	+	+	+	+			+	+	+	+		+	-	+	
Heptane	F	-	100	50	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	+	+	-	+	

	Gaseous/Liquid	Electrical Conductivity	Concentration (%)	Temperature (°C)	Metals				Non-Metals													
					Metals				Non-Metals													
					Stainl. steel 1.4301	Stainl. steel 1.4539	Stainl. steel 1.4541	Stainl. steel 1.4571	Hastelloy B	Hastelloy C	Titanium	Tantalum	Platinum	Hard Rubber	Soft Rubber	PFA	PTFE	EPDM	Buna N	Viton A	PVDF	PVC
Hexane	F -	100	50	+ + + + + + + +												+ + -	+ + -	+ + -	+ + -	+ + -	+ + -	+ + -
Hydrazine solution	F +	25	20	+ - + - - -												+ - - + + + -	+ + + + -	+ + + -	+ + + -	+ + + -	+ + + -	+ + + -
Hydrobromic acid	F +	48	50	- - - - + - -												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrochloric acid	F +	10	50	- - - - + - -												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrochloric acid	F +	37	20	- - - - + + -												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrocyanic acid	F +	100	20	+ + + + + + + +												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrofluoric acid	F +	40	20	- - - - + + -												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrofluoric acid	F +	70	20	- - - - + + -												+ + + + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -	+ + + + -
Hydrogen	G -	100	50	+ + + + + + + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Hydrogen chloride	G -	100	20	- + + + + + + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Hydrogen peroxide sol.	F +	40	20	+ + + + + + + +					+ - + + - - -							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Hydrogen sulfide, dry	G -	100	20	+ + + + + + - + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Kerosine	F -	100	20	+ + + + + + + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Krypton	G -	100	50	+ + + + + + + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Magnesium chloride s.	F +	50	20	- - - - + + + +												+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Magnesium sulfate sol.	F +	20	50	+ + + + + + + +					- + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Malic acid	F +	50	50	+ + + + + + + +					+ + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Methane	G -	100	50	+ + + + + + + +					+ + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Methanol = Methyl alc.	F -	100	50	+ + + + + + + +					+ + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Methylbenzene = Toluol	F -	100	50	+ + + + + + + +					+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Methylene chloride	G -	100	20	+ + + + + + + +					+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Monochloroacetic acid	F +	70	50		+ + + + + + + +				+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Natural gas, dry	G -	100	40	+ + + + + + + +					+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Neon	G -	100	100	+ + + + + + + +					+ + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Nitric acid	F +	20	40	+ + + + + + + +					+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Nitric acid	F +	70	50	- + + + + -	+ + + + + + + +				- + + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Nitrogen	G -	100	50	+ + + + + + + +					+ + + + + + + +							+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +	+ + + + + + + +
Oleum	F +	10	50	- - - - + + + +					- - + - - - -							+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -
Oleum	F +	20	20	- - - - + + + +					- - + - - - -							+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -	+ - - - - -
Olive oil	F -		50	+ + + + + + + +					+ + + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -
Oxalic acid solution	F +	10	50	- + - + + + +	- + + + + + +				- + + + + + +							- - + + - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -	+ + - - - -

	Gaseous/Liquid	Electrical Conductivity	Concentration (%)	Temperature (°C)	Metals					Non-Metals													
					Stainl. steel 1.4301	Stainl. steel 1.4539	Stainl. steel 1.4541	Stainl. steel 1.4571	Hastelloy B	Hastelloy C	Titanium	Tantalum	Platinum	Hard Rubber	Soft Rubber	PFA	PTFE	EPDM	Buna N	Viton A	PVDF	PVC	Glass
Oxygen	G	-	100	50	+	+	+	+	+	+	-	-	-	-	+	+	+	-	-	+	+	-	+
Ozone	G	-	10	20	+	+	+	+	+	+	-	-	-	-	+	+	+	-	-	+	+	+	+
Perchloroethylene	F	-	100	50	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+
Petroleum	F	-	100	20	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	+	+
Phenol	F	-	90	50	-	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	+	-	+
Phosgene	F	-	100	20	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	-	+	-	+
Phosphoric acid	F	+	30	50	-	+	-	+	+	-	+	+	-	-	+	+	+	-	-	+	+	-	+
Phosphoric acid	F	+	80	20	-	+	-	+	+	-	+	+	+	+	+	+	+	-	-	+	+	+	+
Photographic emulsion	F	+		20	+	+	+	+	+	+		+		+	+	+	+						+
Phthalic anhydride	F	-		20	-	-	-	+	+	+	+	+	+	+	-	+	+	-	+	+	+	+	+
Potassium chloride sol.	F	+	30	20	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Potassium hydroxide sol.	F	+	50	20	+	+	+	+	+	+	-	-	+		+	+	+	-	-	+	+	+	+
Potassium permang. sol.	F	+	50	20	+	+	+	+	+	+	+	+	-	-	+	+	+	+	+	+	+	+	-
Potassium sulfate sol.	F	+	20	50	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+
Propane	G	-	100	50	+	+	+	+	+	+				-	-	+	-	-	+	-	-	+	+
Sea water	F	+		50	-	+	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	-	+
Sodium bicarbonate s.	F	+	20	50		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sodium bisulfate solut.	F	+	10	50	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sodium bisulfate solut.	F	+	50	50	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sodium carbonate sol.	F	+	50	50	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Sodium chloride sol.	F	+	10	20	-	+	-	-	-	+	+	+	+	+	-	-	+	+	+	+	+	+	+
Sodium chloride sol.	F	+	20	20	-	-	-	-	-	+	+	+	+	+	-	-	+	+	+	+	+	+	+
Sodium hydroxide sol.	F	+	20	50	+	+	+	+	+	+	+	-	-	+	-	+	+	+	-	-	+	+	-
Sodium hydroxide sol.	F	+	50	50	+	+	+	+	+	+	-	-	+	+	+	+	+	-	-	+	+	-	-
Sodium hypochloride s.	F	+	20	50	-	-	-	-	+	+	-	-	+	-	-	+	+	+	+	+	+	-	+
Sodium nitrate solution	F	+	30	50	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+
Sodium silicate solution	F	+	30	50	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+
Sodium sulfate solution	F	+	20	50	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	-
Sodium vanadate sol.	F	+	10	50	+	+	+	+	+	+							+	+	+	+	+	+	+
Spinning bath	F	+		50			+	+	-	-	+		-	-	+	+	-	+	-	+	-	-	+
Sulfur dioxide, dry	G	-	100	50	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+	-	+
Sulfuric acid	F	+	10	50	-	+	-	-	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+
Sulfuric acid	F	+	50	20	-	+	-	-	+	+	-	+	+	+	+	+	+	-	+	+	-	+	+

	Gaseous/Liquid	Electrical Conductivity	Concentration (%)	Temperature (°C)	Metals				Non-Metals															
					Stainl. steel 1.4301	Stainl. steel 1.4539	Stainl. steel 1.4541	Stainl. steel 1.4571	Hastelloy B	Hastelloy C	Titanium	Tantalum	Platinum	Hard Rubber	Soft Rubber	PFA	PTFE	EPDM	Buna N	Viton A	PVDF	PVC	Glass	Al ₂ O ₃
					-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Sulfuric acid	F	+	96	20	-	+	-	+	+	+	-	+	+	-	-	+	+	-	+	+	-	+	+	
Sulfurous acid	F	+	10	20	+	+	-	+	-	+	+	+	+	-	+	+	+	+	+	+	+	+	+	
Tannic acid	F	+	50	50			+	+	+					+	+	+	+	-		-		+	+	
Tartaric acid	F	+	20	50	-	-	-	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	
Toluene	F	-	100	50	+	+	+	+	+	+				-	-	+	+	-	-	+	+	-	+	
Trichlorethylene	F	-	100	50	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	+	-	+	+	
Tricresylphosphate	F		100	50	+	+	+	+	+	+				-	-	+	+	+	-	-	-	+	+	
Urea	F	+	30	50			+		+					+	+	+	+	+	+	+	+	-	+	+
Vinyl acetate	F		100	20	+			+	-	+				-	-	+	+	+	-	+	+	+	+	
Vinyl chloride	F		100	20	+		+	+	+		+	+	-	-	+	+		-	+		-	+		
Wort	F	+		5	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	
Xylene	F	-	100	50	+	+	+	+	+	+				-	-	+	+	-	-	+	-	+	+	
Yeast	F	+		20	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	

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Danfoss
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Dechema-Werkstofftabelle: Dechema Frankfurt/Main
[*Materials table*]

The features and characteristics of the most important methods of measuring the flowrate and quantities of flowing fluids are described and compared.

Numerous practical details provide the user with valuable information about flow metering in industrial applications.