2.2 Flowmeters

2.2.1 Flowmeters for Differential Pressure Measurement

In Chapter 1.2.5 the relationship between the pressure drop $\Delta p$ 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 their remains some permanent, unrecovered pressure drop $p_{bl}$.

\[
p_{1} \quad \text{Pressure before orifice restriction} \\
p_{2} \quad \text{Pressure in orifice opening} \\
p_{2,} \quad \text{Lowest static pressure} \\
p_{bl} \quad \text{Permanent pressure drop}
\]
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:

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

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

- \(C\) Flow coefficient
- \(\beta\) Diameter ratio
- \(\varepsilon\) Expansion factor (for compressible media, only)
- \(d\) Inside diameter of the orifice plate
- \(\Delta p\) Differential pressure
- \(\rho_1\) 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 \(\beta\), 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 \(\varepsilon\) 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 \(\varepsilon\).
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.
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. 2-51:** Classical Venturi Tube and Venturi Nozzle

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

**Table 2-3: Application Limits for Primary Flow Differential Pressure Products**

<table>
<thead>
<tr>
<th></th>
<th>Orifices</th>
<th>Nozzles</th>
<th>Venturis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corner Pressure Taps</td>
<td>Flanged Pressure Taps</td>
<td>D and D/2-Pressure Taps</td>
</tr>
<tr>
<td></td>
<td>ISA 1932</td>
<td>Long Radius</td>
<td>Venturi Tube</td>
</tr>
<tr>
<td></td>
<td>ISA 1932</td>
<td>Long Radius</td>
<td>Venturi Nozzle</td>
</tr>
<tr>
<td><strong>d</strong>&lt;sub&gt;min&lt;/sub&gt; [mm]</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>D</strong>&lt;sub&gt;min&lt;/sub&gt; [mm]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>D</strong>&lt;sub&gt;max&lt;/sub&gt; [mm]</td>
<td>1000</td>
<td>760</td>
<td>760</td>
</tr>
<tr>
<td><strong>β</strong>&lt;sub&gt;min&lt;/sub&gt;</td>
<td>0.23</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>β</strong>&lt;sub&gt;max&lt;/sub&gt;</td>
<td>0.80</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Re</strong>&lt;sub&gt;D, min&lt;/sub&gt;</td>
<td>5 · 10&lt;sup&gt;3&lt;/sup&gt; ... 20 · 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>2.5 · 10&lt;sup&gt;3&lt;/sup&gt; ... 540 · 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>2.5 · 10&lt;sup&gt;3&lt;/sup&gt; ... 540 · 10&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Re</strong>&lt;sub&gt;D, max&lt;/sub&gt;</td>
<td>10&lt;sup&gt;8&lt;/sup&gt;</td>
<td>10&lt;sup&gt;8&lt;/sup&gt;</td>
<td>10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Orifices, Nozzles, Venturi Nozzles</th>
<th>Classical Venturi Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter Ratio $\beta$</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Single 90° elbow or tee</td>
<td>10</td>
</tr>
<tr>
<td>Two or more 90° elbows in different planes</td>
<td>(34)</td>
</tr>
<tr>
<td>Diffuser from 0.5 D to D with a length of 1...2 D</td>
<td>16</td>
</tr>
<tr>
<td>Diffuser from 0.75 D to D with a length of 1 D</td>
<td></td>
</tr>
<tr>
<td>Fully opened gate</td>
<td>12</td>
</tr>
<tr>
<td>Outlet side</td>
<td>4</td>
</tr>
</tbody>
</table>

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

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

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 transmitter 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](image)

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.).

![Flow Coefficients of Different Flow Elements](image_url)

**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%.

![Pressure Loss as a Function of H/D Ratio](image)

**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 x D to 10 x D and outlet sections of 3 x D to 5 x 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
- CO₂ 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.

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

- \(Q\) = Volume flow rate
- \(k\) = Constant
- \(A\) = Cross-section of the pipe/duct
- \(h\) = Generated differential pressure
- \(\rho\) = 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.

![Operating Principle of the Variable Area Flowmeter](image)

**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
- $\rho_s$: Density of the float
- $\rho_m$: 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:

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

\( \alpha \) is a function of the geometric shape of the meter tube and the float and above all, of the diameter ratio. \( \alpha \) 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:

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

Mass flow rate:

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

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.

![Rotating Float](image)

**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.

![Float Guides with 3 Ribs or 3 Flats](image)

**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.

![Flow rate vs. Viscosity](image)

**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 $\alpha$ 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:

$$q_{v_{water}} = \frac{q_{v1}}{\sqrt{\frac{(\rho_s - 1) \cdot \rho_1}{(\rho_{s1} - \rho_1) \cdot 1}} }$$  \hspace{1cm} (2.16)

$q_{v1}$ = Volume flow rate of the measuring medium
$q_{m1}$ = Mass flow rate of the measuring medium
$\rho_s$ = Float density, usually 8.02 g/cm$^3$ for stainless steel
$\rho_{s1}$ = Density of the float material actually used
$\rho_{s1}$ = Only for special cases
$\rho_n$ = Density of the measuring medium
$\rho_1$ = Density of water, here = 1 g/cm$^3$

$$q_{v_{water}} = \frac{q_{m1}}{\sqrt{\frac{\rho_s - 1}{\rho_1 / (\rho_{s1} - \rho_1)}} }$$  \hspace{1cm} (2.17)

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

<table>
<thead>
<tr>
<th>Measuring medium</th>
<th>Ammonia, liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate qm</td>
<td>1500 kg/h</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>0.68 kg/l</td>
</tr>
<tr>
<td>Dyn. viscosity $\eta$</td>
<td>0.23 mPas</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>15 bar</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20 °C</td>
</tr>
</tbody>
</table>

From equation (2.17):

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

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

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 $\rho_B$ relative to air before converting to equivalent table values for air:

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

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

$\rho_n$ = Density of gas at normal conditions

$T_n$ = 273.15 K

$T$ = [°C]

$p_n$ = 1.013 bar

$p$ = [bar]

$\rho_1$ = Density of gas at operating conditions

Equation 2.16 can be simplified for gases ($\rho_s << \rho_w; \rho_{s1} << \rho_1$) 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 $\rho_s$ for the air table values:

$$(q_v)_{n\text{Air}} = q_{v1} \left[ \frac{\rho_s \cdot \rho_B}{\rho_{s1}} \right]^{\sqrt{\frac{\rho_B}{\rho_{s1} \cdot \rho_B}}} \quad (2.20)$$

or for the mass flow rate $q_m$:

$$(q_v)_{n\text{Air}} = \frac{q_{m1}}{1.293} \cdot \sqrt[3]{\frac{\rho_s}{\rho_{s1} \cdot \rho_B}} \quad (2.21)$$

**Example:**

<table>
<thead>
<tr>
<th>Measuring medium</th>
<th>Ammonia, gaseous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate $q_m$</td>
<td>1500 kg/l</td>
</tr>
<tr>
<td>Density $\rho_n$</td>
<td>0.7714 kg/m³</td>
</tr>
<tr>
<td>Pressure $p$</td>
<td>5 bar</td>
</tr>
<tr>
<td>Temperature $T$</td>
<td>100 °C</td>
</tr>
</tbody>
</table>

from equations (2.18) and (2.19):

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

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

**Viscosity Effects**

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

$$\text{VUZ} = \eta \sqrt[3]{\frac{\rho_s - \rho_w}{(\rho_{s1} - \rho_1) \rho_1 \cdot \rho_w}} = \eta \sqrt[3]{\frac{1}{(\rho_{s1} - \rho_1) \rho_1}} \quad (2.22)$$

$\eta = \text{Current viscosity value of the measuring medium.}$
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:

<table>
<thead>
<tr>
<th>Measuring medium</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyn. viscosity $\eta$</td>
<td>0.23 m · Pas</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>0.68 kg/l</td>
</tr>
<tr>
<td>Float density $\rho_s = \rho_{s1}$</td>
<td>8.02 (stainless steel)</td>
</tr>
</tbody>
</table>

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

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:

<table>
<thead>
<tr>
<th>Metal tube</th>
<th>Glass tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High pressure and temperature conditions</td>
<td>• Low-cost solution</td>
</tr>
<tr>
<td>• Opaque measuring media</td>
<td>• Visual check of measuring medium</td>
</tr>
<tr>
<td>• Steam applications</td>
<td>• Extremely low pressure conditions</td>
</tr>
<tr>
<td>• High flow rate</td>
<td>• Clear, transparent measuring medium</td>
</tr>
<tr>
<td>• Current and contact outputs</td>
<td>• HART communication</td>
</tr>
<tr>
<td>• Digital display</td>
<td>• Digital display</td>
</tr>
</tbody>
</table>

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](image)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Meter tube holder</td>
<td>1.4401 brass</td>
</tr>
<tr>
<td>Meter tube</td>
<td>Borosilicate glass, Trogamid</td>
</tr>
<tr>
<td>Float</td>
<td>Glass, sapphire, tantalum, 1.4401, Carboloy</td>
</tr>
<tr>
<td>O-rings</td>
<td>Buna N, Viton A, ethylene-propylene</td>
</tr>
<tr>
<td>Protection cap</td>
<td>Polycarbonate</td>
</tr>
</tbody>
</table>
Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Scale Length (mm)</th>
<th>Housing Length (mm)</th>
<th>Meas. Range for Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>10A6134/44</td>
<td>38</td>
<td>120</td>
<td>3...48 cm³/h to 3...132 l/h</td>
</tr>
<tr>
<td>10A6131/41</td>
<td>70</td>
<td>151</td>
<td>24...264 cm³/h to 10...105 l/h</td>
</tr>
<tr>
<td>10A6132/42</td>
<td>130</td>
<td>264</td>
<td>2.6...32 cm³/h to 11.2...140 l/h</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Materials</th>
<th>Borosilicate glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter tube</td>
<td>Glass, sapphire, tantalum, 1.4301, 1.4571, PVDF and others</td>
</tr>
<tr>
<td>Float</td>
<td>PVC, PVDF and others</td>
</tr>
<tr>
<td>Fittings</td>
<td>Buna N, Viton A, ethylene-propylene</td>
</tr>
<tr>
<td>O-rings</td>
<td>Stainl. steel 1.4301</td>
</tr>
<tr>
<td>Housing</td>
<td>FAG1190-97: Female thread</td>
</tr>
<tr>
<td>Connections</td>
<td>FAG1190-98: Flanged connections</td>
</tr>
<tr>
<td></td>
<td>FAG1190-87: Threaded pipe connection</td>
</tr>
</tbody>
</table>
### Specifications:

<table>
<thead>
<tr>
<th>Housing Size</th>
<th>Meter Tube Size</th>
<th>Scale Length</th>
<th>Upper Range Value (Water) [l/h]</th>
<th>Upper Range Value (Air) [m³/h]</th>
<th>Max. Perm. Pressure [bar]</th>
<th>Accuracy Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>1/16</td>
<td>100</td>
<td>0.03...1.1</td>
<td>0.003...0.04</td>
<td>38</td>
<td>6</td>
</tr>
<tr>
<td>1/4</td>
<td>1/18</td>
<td>130</td>
<td>0.37...10</td>
<td>0.022...0.33</td>
<td>33</td>
<td>1.6</td>
</tr>
<tr>
<td>1/4</td>
<td>1/4</td>
<td>130</td>
<td>4.7...132</td>
<td>0.223...4.03</td>
<td>30</td>
<td>1.6</td>
</tr>
<tr>
<td>1/2</td>
<td>1/2</td>
<td>250</td>
<td>43...418</td>
<td>1.3...12.3</td>
<td>21</td>
<td>1.6</td>
</tr>
<tr>
<td>3/4</td>
<td>3/4</td>
<td>250</td>
<td>144...1300</td>
<td>4.3...38.7</td>
<td>17</td>
<td>1.6</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>250</td>
<td>310...2800</td>
<td>9.2...83.0</td>
<td>14</td>
<td>1.6</td>
</tr>
<tr>
<td>1 1/2</td>
<td>1 1/2</td>
<td>250</td>
<td>560...4800</td>
<td>17.3...142.5</td>
<td>9</td>
<td>1.6</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>250</td>
<td>1420...17000</td>
<td>42.6...510</td>
<td>7</td>
<td>1.6</td>
</tr>
</tbody>
</table>
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. 2-73: 55AX1000 Alarm Signalling Unit

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. 2-74: 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.

<table>
<thead>
<tr>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter tube</td>
</tr>
<tr>
<td>Float</td>
</tr>
<tr>
<td>Flanges</td>
</tr>
<tr>
<td>Indicator housing</td>
</tr>
</tbody>
</table>

### Measuring Ranges

<table>
<thead>
<tr>
<th>Nominal Diameter</th>
<th>Length [mm]</th>
<th>Upper Range Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>Water [m³/h]</td>
<td>Air [m³/h]</td>
</tr>
<tr>
<td>15</td>
<td>250</td>
<td>0.03...0.85</td>
</tr>
<tr>
<td>25</td>
<td>250</td>
<td>0.28...6.1</td>
</tr>
<tr>
<td>50</td>
<td>250</td>
<td>4.2...24</td>
</tr>
<tr>
<td>80</td>
<td>250</td>
<td>7...54</td>
</tr>
<tr>
<td>100</td>
<td>250</td>
<td>25...120</td>
</tr>
</tbody>
</table>

### Specifications

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

![Fig. 2-75: Metal Tube VA Flowmeter Series FAM540](image)

<table>
<thead>
<tr>
<th>FAM541</th>
<th>FAM544</th>
<th>FAM545</th>
<th>FAM546</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard design</td>
<td>Hygienic design</td>
<td>PTFE-lined</td>
<td>Heat jacket design</td>
</tr>
<tr>
<td>For universal application</td>
<td>For food and beverage/pharmaceutical applications</td>
<td>For aggressive media</td>
<td>For temperature-sensitive processes</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Materials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-wetted parts</td>
<td>1.4571, PVDF</td>
</tr>
<tr>
<td>O-rings</td>
<td>Viton A, Buna N</td>
</tr>
<tr>
<td>Indicator housing</td>
<td>Aluminium, stainless steel</td>
</tr>
<tr>
<td>Cap</td>
<td>Polycarbonate, Trogamid, stainless steel with glass window</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. meas. range</td>
<td>0.1...1.0 l/h water</td>
</tr>
<tr>
<td>Max. meas. range</td>
<td>0.008...0.048 m³/h air</td>
</tr>
<tr>
<td>Scale length</td>
<td>300...3000 l/h water</td>
</tr>
<tr>
<td>Max. perm. pressure</td>
<td>8...90 m³/h air</td>
</tr>
<tr>
<td>Max. perm. temperature</td>
<td>100 bar</td>
</tr>
<tr>
<td>Accuracy class</td>
<td>150 °C</td>
</tr>
<tr>
<td>Analog output</td>
<td>6</td>
</tr>
<tr>
<td>Contact output</td>
<td>4...20 mA</td>
</tr>
<tr>
<td></td>
<td>1 or 2 limit values using proximity switches</td>
</tr>
</tbody>
</table>

Fig. 2-76: Design Types

Fig. 2-76: 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:

\[ U_o \sim B \cdot v \cdot D \quad (2.23) \]

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:

\[ U_o \sim q_v \]
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 $0.05 \, \mu \text{S/cm}$ 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](image-url)
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](image-url)
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 $U_{\text{noise}}$. During the measurement interval $M_1$ the following applies:

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

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 $U_{\text{noise}}$ does not reverse so that during the measurement interval $M_2$ the following applies:

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

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

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

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 $\mu$S/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 $\Phi$ lags to the excitation current $I$ by almost 90°.

The measuring voltage $U$ is in phase with $\Phi$, 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 $\mu$S/cm. This conductivity limit can be reduced to 0.5 $\mu$S/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 μS/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 aluminium or stainless steel.
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 $U_{\text{Ref}}$ 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 $U_{\text{Ref}}$ occurs which is proportional to the excitation current $I$ and therefore the magnetic inductance $B$. The voltage $U_0$ is also proportional to the induction $B$. When the ratio of these two variables $U_0/U_{\text{Ref}}$ 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 $U_{\text{Ref}}$:

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

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 and 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 ± 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 ± 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:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Status Signal</th>
<th>Examples for Detail Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>❌</td>
<td>Failure</td>
<td>Device-related failure cause</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process-related failure cause</td>
</tr>
<tr>
<td>🔨</td>
<td>Function check</td>
<td>Configuration change</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specify substitute value</td>
</tr>
<tr>
<td>🚨</td>
<td>Out of specification</td>
<td>Device is operated out of specified range.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unsecure through ambient or process effects</td>
</tr>
<tr>
<td>🕵️‍♂️</td>
<td>Maintenance required</td>
<td>Maintenance now required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance soon required</td>
</tr>
</tbody>
</table>

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: ScanMaster 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 (½” 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.

![FXL5000 (Miniflow)](image)

**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 \( \geq 500 \text{ ms} \) 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.
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 preset 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.

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.
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.

![Flowmeter FXF2000 (COPA-XF)](image1)

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 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°.

![Flanged reducer](image)

**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 $\Delta p$ can be read at the intersection between these two values.

**Fig. 2-99:** Pressure Drop with Pipe Restriction
## Specifications

<table>
<thead>
<tr>
<th>Signal Measurement</th>
<th>Galvanic</th>
<th>With Pulsed DC Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magn. Field Excit.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>ProcessMaster FEP300/500</td>
<td>FXF2000 (COPA-XF)</td>
</tr>
<tr>
<td></td>
<td>HygienicMaster FEH300/500</td>
<td></td>
</tr>
<tr>
<td>Liner material</td>
<td>DN 15...2000 PN 10...100</td>
<td>DN 3...200</td>
</tr>
<tr>
<td></td>
<td>Cl150...Cl600</td>
<td>Cl150...Cl600</td>
</tr>
<tr>
<td></td>
<td>Hard rubber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soft rubber</td>
<td></td>
</tr>
<tr>
<td>Ceramic carbide</td>
<td>DN 25...1000 PN 10...100</td>
<td>DN 25...1000</td>
</tr>
<tr>
<td></td>
<td>Cl150/Cl300</td>
<td>Cl150/Cl300</td>
</tr>
<tr>
<td>PTFE</td>
<td>DN 10...600 PN 10...40</td>
<td>DN 10...600</td>
</tr>
<tr>
<td></td>
<td>Cl150/Cl400</td>
<td>Cl150/Cl400</td>
</tr>
<tr>
<td>ETFE</td>
<td>DN 25...1000 PN 10...40</td>
<td>DN 25...1000</td>
</tr>
<tr>
<td></td>
<td>Cl150/Cl300</td>
<td>Cl150/Cl300</td>
</tr>
<tr>
<td>PFA</td>
<td>DN 3...200 PN 10...40</td>
<td>DN 3...200</td>
</tr>
<tr>
<td></td>
<td>Cl150/Cl300</td>
<td>Cl150/Cl300</td>
</tr>
<tr>
<td>Peek</td>
<td>1...2</td>
<td>1...2</td>
</tr>
<tr>
<td>Electrode material</td>
<td>Stainless steel 1.4571 or 1.4539, Hastelloy C4 or B2, titanium, tantalum, platinum-iridium</td>
<td></td>
</tr>
<tr>
<td>Excitation frequency</td>
<td>6 1/4 Hz, 12 1/2 Hz or 25 Hz</td>
<td>12.5/25 Hz</td>
</tr>
<tr>
<td>Min. conductivity</td>
<td>5 μS/cm</td>
<td>5 μS/cm</td>
</tr>
<tr>
<td>Max. poss. pressure rating</td>
<td>PN 100/Cl600 and higher</td>
<td>PN 40/Cl300</td>
</tr>
<tr>
<td>Max. poss. temperature</td>
<td>180 °C</td>
<td>130 °C (150 °C)</td>
</tr>
<tr>
<td>Electrode design</td>
<td>Standard electrode, pointed electrode</td>
<td></td>
</tr>
<tr>
<td>Process connection</td>
<td>Flange DN 3...2000</td>
<td>Wafer Des. DN 3...100</td>
</tr>
<tr>
<td></td>
<td>Welded spud DN 3...100</td>
<td>Weld st. DN 3...100</td>
</tr>
<tr>
<td></td>
<td>Threaded pipe conn. DN 3...100</td>
<td>Thr. pipe conn. DN 3...100</td>
</tr>
<tr>
<td></td>
<td>Tri-Clamp DN 3...100</td>
<td>Tri-Clamp DN 3...100</td>
</tr>
<tr>
<td></td>
<td>Male thread DN 3...25</td>
<td>Fixed clamp DN 10...40</td>
</tr>
<tr>
<td></td>
<td>1/8&quot; sanitary conn. DN 1...2</td>
<td>Male thread DN 3...25</td>
</tr>
<tr>
<td>Upper range value</td>
<td>0.5...20 m/s</td>
<td>0.5...10 m/s</td>
</tr>
<tr>
<td>Max. meas. error</td>
<td>FEP300/FEH300: 0.4 % of rate</td>
<td>0.5...10 m/s</td>
</tr>
<tr>
<td></td>
<td>opt. 0.2 % of rate</td>
<td>0.5 % of rate</td>
</tr>
<tr>
<td></td>
<td>FEP500/FEH500: 0.3 % of rate</td>
<td>Reproducibility</td>
</tr>
<tr>
<td></td>
<td>opt. 0.2 % of rate</td>
<td>≤ 0.2 % of rate</td>
</tr>
<tr>
<td>Current output</td>
<td>4...20 mA, 4...12...20 mA selectable</td>
<td>0...5 mA, 0/2...10 mA, 0/4...20 mA, 0/10...20 mA, 4...12...20 mA selectable</td>
</tr>
<tr>
<td>Load</td>
<td>0...600 Ω</td>
<td>0...600 Ω</td>
</tr>
<tr>
<td>Pulse output</td>
<td>Passive, active</td>
<td>Passive, active</td>
</tr>
<tr>
<td>Pulse width</td>
<td>Selectable from 0.1 ms...2000 ms</td>
<td>Selectable from 0.1 ms...2000 ms</td>
</tr>
<tr>
<td>Supply power</td>
<td>Switch-mode power supply 85...253 V AC, 16.8...26.4 V AC, 16.8...31.2 V DC</td>
<td>16.8...31.2 V DC</td>
</tr>
</tbody>
</table>

**Tab. 2-5:** Overview of Flowmeter Sensor and Transmitter Designs
<table>
<thead>
<tr>
<th>Signal Measurement</th>
<th>Galvanic</th>
<th>Magn. Field Excit.</th>
<th>With Pulsed DC Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td>ProcessMaster FEP300/500</td>
<td>FXF2000 (COPA-XF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HygienicMaster FEH300/500</td>
<td></td>
</tr>
<tr>
<td>Autom. empty pipe detection</td>
<td>yes</td>
<td>≥ DN 10 (TFE ≥ DN 25)</td>
<td>yes ≥ DN 10</td>
</tr>
<tr>
<td>Max./min. alarm</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 meas. ranges</td>
<td>yes</td>
<td>(FEP500/FEH500)</td>
<td></td>
</tr>
<tr>
<td>Presetting totalizer</td>
<td>yes</td>
<td>(FEP500/FEH500)</td>
<td></td>
</tr>
<tr>
<td>Expanded diagnostic functions</td>
<td>yes</td>
<td>(FEP500/FEH500)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Electrode deposit detection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Gas bubble detection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Conductivity monitoring</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Sensor temperature monitoring</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Trend analysis</td>
<td></td>
</tr>
</tbody>
</table>

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

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

**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 ½“ 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:

$$t = \frac{1}{c}$$

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](image)

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

$$t_1 = \frac{1}{c + v} \quad (2.29a)$$

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

$$t_2 = \frac{1}{c - v} \quad (2.29b)$$

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

$$c = \frac{1}{t_1} - v \quad c = \frac{1}{t_2} + v$$
the flow velocity in the measuring medium can be extracted using

\[ v = \frac{1}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \]  

(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

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

**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 $\Delta f$ 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 axissymmetric 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 ± 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 ± 2.0 % of rate. If an on-site calibration can be conducted then accuracies up to ± 0.5 % of rate are possible.

**Specifications**

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

**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.
A mass $m$ is located at point $A$ at an average distance $r$ from the center on a rotating disk with an angular velocity $\omega$ 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 $\omega$. The inertia force which opposes the change is the Coriolis force $F_c$:

$$ F_c = -2 \ m \ (\omega \times \dot{v}) \quad (2.35) $$

$v$ 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.
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 ± 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 decoupling 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.
**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 in 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.

\[ f_R = f(\rho_m) \]

\[ f_R = \frac{1}{2\pi} \cdot \sqrt[4]{\frac{C}{m_{\text{m}} + m_t}} \]

\[ m_{\text{m}} = V \cdot \rho_{\text{m}} \]

\[ f_R = \text{Resonant frequency} \]

\[ m_t = \text{Mass of the meter tube} \]

\[ m_{\text{m}} = \text{Mass of the measuring medium} \]

\[ \rho_{\text{m}} = \text{Density of the measuring medium} \]

\[ C = \text{Constant} \]

**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:

<table>
<thead>
<tr>
<th>% 1</th>
<th>Temp. Concentration</th>
<th>Temp1</th>
<th>Temp2</th>
<th>Temp3</th>
<th>...</th>
<th>Temp 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>% 2</td>
<td>C1</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
</tr>
<tr>
<td>% 3</td>
<td>C2</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
</tr>
<tr>
<td>...</td>
<td>:</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
</tr>
<tr>
<td>% 10</td>
<td>C10</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
<td>Density</td>
</tr>
</tbody>
</table>

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

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

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 Nm\(^3\)/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](image)

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 \(K_1...3\) this relationship can be represented by King's equation:

\[
P = \Delta T \cdot K_1 + K_2 \cdot (q_m)^{K_3}
\]  

(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**

<table>
<thead>
<tr>
<th>Specification</th>
<th>FMT400-VTS</th>
<th>FMT500-IG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>From DN 25, also for non-round cross sections</td>
<td></td>
</tr>
<tr>
<td>Span</td>
<td>up to 1:150</td>
<td></td>
</tr>
<tr>
<td>Oper. temp. of the meas. medium</td>
<td>-25...300 °C</td>
<td></td>
</tr>
<tr>
<td>Pressure range</td>
<td>0.5...40 bar absolute</td>
<td></td>
</tr>
<tr>
<td>Measuring uncertainty</td>
<td>≤ 1 % of rate</td>
<td></td>
</tr>
<tr>
<td>Typical pressure drop</td>
<td>1 mbar</td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td>0.5 s</td>
<td></td>
</tr>
<tr>
<td>Output signal</td>
<td>0/4...20 mA; pulse; frequency; binary</td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>HART, PROFIBUS DPV1</td>
<td></td>
</tr>
<tr>
<td>Supply power</td>
<td>230; 110; 24 V AC; 24 V DC</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>Stainl. steel; Hastelloy; Ceramic</td>
<td></td>
</tr>
<tr>
<td>Explosion protection</td>
<td>Zone 0</td>
<td></td>
</tr>
</tbody>
</table>
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](image)

### Specifications for Sensyflow FMT700-P

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>DN 25…DN 200</td>
</tr>
<tr>
<td>Span</td>
<td>1:40</td>
</tr>
<tr>
<td>Oper. temp. of the meas. medium</td>
<td>-25…80 °C</td>
</tr>
<tr>
<td>Pressure range</td>
<td>2.5 bar absolute</td>
</tr>
<tr>
<td>Measuring uncertainty</td>
<td>≤ 1% of rate</td>
</tr>
<tr>
<td>Typical pressure drop</td>
<td>10 mbar</td>
</tr>
<tr>
<td>Response time</td>
<td>$T_{63} \sim 12$ ms</td>
</tr>
<tr>
<td>Output signal</td>
<td>0/4…20 mA; 0…10 V; RS 232, ASAM-GDI</td>
</tr>
<tr>
<td>Supply power</td>
<td>230/115 V AC</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>to DN 25</td>
</tr>
<tr>
<td>Connections</td>
<td>Small flange, G 3/8&quot;...1&quot;, Legris, Transair</td>
</tr>
<tr>
<td>Span</td>
<td>1:100</td>
</tr>
<tr>
<td>Oper. temp. of the meas. medium</td>
<td>0...50 °C</td>
</tr>
<tr>
<td>Pressure range</td>
<td>10 (16) bar absolute</td>
</tr>
<tr>
<td>Measuring uncertainty</td>
<td>≤ 3 % of rate</td>
</tr>
<tr>
<td>Typical pressure drop</td>
<td>10 mbar</td>
</tr>
<tr>
<td>Response time</td>
<td>T₆₃ ~ 25 ms</td>
</tr>
<tr>
<td>Output signal</td>
<td>0/4...20 mA; 0...5/10 V; pulse, digital, frequency, RS 232</td>
</tr>
<tr>
<td>Supply power</td>
<td>24 V DC</td>
</tr>
</tbody>
</table>
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 $P$.

![Heating Method, Operating Principle](image)

$q_m$: Mass flow rate  
$P$: Constant electrical heating power  
$L$: Thermal power dissipation

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

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

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>to DN 25</td>
</tr>
<tr>
<td>Span</td>
<td>1...50</td>
</tr>
<tr>
<td>Max. operating temp.</td>
<td>70 °C</td>
</tr>
<tr>
<td>Meas. medium</td>
<td>100 bar</td>
</tr>
<tr>
<td>Max. permissible</td>
<td>&lt; 1 % of rate</td>
</tr>
<tr>
<td>pressure</td>
<td>1...5 s</td>
</tr>
<tr>
<td>Measured error</td>
<td>0/4...20; 0...10 V; digital</td>
</tr>
<tr>
<td>Response time</td>
<td>24 V DC</td>
</tr>
<tr>
<td>Output signal</td>
<td>Aluminium, stainless steel, plastic</td>
</tr>
</tbody>
</table>
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.

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.

![Thomson V-Notch Weir](image)

**Fig. 2-119:** Thomson V-Notch Weir

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

\[
q_v = \frac{8}{15} \cdot \mu \cdot \tan \frac{\alpha}{2} \cdot \sqrt{g \cdot h} \cdot h^{5/2} \tag{2.37}
\]

The discharge coefficient \( \mu \) 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 \( \mu \) values in curve form.

![Discharge Coefficient \( \mu \) for a V-Notch Weir](image)

**Fig. 2-120:** Discharge Coefficient \( \mu \) 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](image)

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 $\mu$ 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: \[0.075 \leq h \leq 0.6 \text{ m} \quad b \leq 2 \cdot h_{\text{max}} \leq 0.3 \text{ m}\]

The span of the rectangular weir is 1:20. The measurement of the height \(h\) is made approximately 4 \(x\) \(h\) 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.

\[\begin{align*}
\text{Flow rate indicator} \\
\text{Float} \\
\text{Hydraulic jump} \\
\text{Elevated floor section} \\
\text{Horizontal floor}
\end{align*}\]

**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.

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

![Diagram of Hydrostatic Pressure Measurement](image)

The reference point $A$ must lie below the minimum water level.

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.

![Pressure Transmitter Type 266MDT for Level Measurement](image)

**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**

![Bubbler Method](image)

**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](image)
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.

![Design of the Flowmeter Sensor](image)

**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 $U_{rec}/U_{inj}$.

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.
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.

**Sizing**

The nominal diameter of the transmitter is determined using the adjoining nomograph based on the maximum flow rate under a full meter tube condition utilizing the current flow velocity.

**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:

\[
v = \sqrt{\frac{h_v}{l}} \cdot \frac{2g \cdot d}{\lambda} \tag{2.42}
\]

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:

\[
\lambda = \frac{1}{\left(2 \log \frac{d}{k} + 1.14\right)^2} \tag{2.41}
\]

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 x D and outlet sections of 2 x D should be installed.
### Electrode Materials

<table>
<thead>
<tr>
<th>Liner Material</th>
<th>Electrode Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rubber, soft rubber</td>
<td>Stainl. steel 1.4571</td>
</tr>
<tr>
<td></td>
<td>Hastelloy C or B</td>
</tr>
<tr>
<td>PTFE, PFA</td>
<td>Hastelloy C</td>
</tr>
<tr>
<td></td>
<td>Hastelloy B, Ti, Ta, Pt-Ir</td>
</tr>
</tbody>
</table>

### Nominal Diameters and Pressures

<table>
<thead>
<tr>
<th>Liner Material</th>
<th>DN</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rubber</td>
<td>150...1400</td>
<td>6...40</td>
</tr>
<tr>
<td>Soft rubber</td>
<td>150...1400</td>
<td>6...40</td>
</tr>
<tr>
<td>PTFE</td>
<td>150...600</td>
<td>10...40</td>
</tr>
</tbody>
</table>

### Specifications

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