Measuring technology
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<td>81</td>
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1 Basics of Measuring Technology

1.1. General

Metrology and instrumentation denotes the sum of the procedures and devices used for empirical determination (measurement) of scientific and technical quantities that can be expressed numerically. Further tasks of metrology and instrumentation are the verification of compliance with dimensional tolerances, consumption metering, production monitoring as well as, in general terms, the control of technical processes to measured values (within the scope of instrumentation and control).

In the age of building control and facility management (management, operation and maintenance of buildings), precise measurement of physical quantities is of great importance. Decisions on changes or statements on energy consumption figures and building maintenance costs depend on the accuracy of measured values. In the control loop, precise measurements are highly important for the accuracy and stability of the control-action result. The selection of the correct measuring apparatus is decisive for a correct measurement result, and a correct (i.e. reliable) measurement result is important for a meaningful evaluation.

The basic concepts of measurement are defined in the standards DIN 1319 and VDI/VDE 26000 Sheet 2.

Measuring Instruments

The purpose of measuring instruments is to enable physical quantities such as pressure, temperature, humidity or consumption, e.g. energy, fuels, flow volumes etc., to be measured and monitored or to enable faults or losses to be detected. They are an important tool for economical operations management.

Sensor

The term sensor arose with the development of modern technologies, especially microelectronics. The sensor is the part of the measuring or recording equipment that is directly exposed to the quantity to be measured; it also denotes a device that reacts to electromagnetic radiation (e.g. IR sensor) or touch (e.g. sensor button).

The sensor contains at least the sensing element and the hardware required to fulfill the measuring task. It supplies a standardized electrical measuring signal, e.g. 0 (4) ... 20 mA or 0 ... 10 V, or it changes its electrical resistance as a function of the measured value. This change of resistance can also be standardized, e.g. as per DIN. In relatively large systems, there are usually numerous different measured values. The measured values are summarized on instrument or control panels or on a digital device (e.g. computer, automatisation station, analyzer,...).
Important terms
The processes in metrology can be divided into five areas which should not be confused:

- Measuring
- Testing
- Calibration testing
- Calibration
- Adjustment

Measuring
- Measuring means determining the value $x$ of a physical quantity, the measured variable, by comparing it with a similar standard quantity.
- Determining how many times a similar, previously defined unit of measure is contained in a physical quantity to be measured.

![Fig. 1-1 Principle of measuring (Source: pixabay.com)](image)

1 Measured variable (physical quantity in m)
2 Measuring apparatus (ruler)
3 Measured value (distance in cm)

Testing
Testing means to determine whether an object to be tested complies with predefined conditions. Limits of error and tolerances are evaluated, and a distinction is made between objective and subjective testing.

Example, room temperature:
Subjective testing (based on personal perception): You are too hot, so you open the window.
Objective testing (maintaining a measured value): You measure the temperature and determine that it is 26 °C.

The processes of testing and measuring are closely related.

Calibration testing
Calibration testing is an official activity (Measurement Instruments Directive "MID", European Directive 2014/32/EU). This European directive was adopted as domestic German law in 2006 and replaced all previous calibration testing directives.

In the process of calibration testing, it is determined whether the test candidate (e.g. temperature measuring device) complies with a given calibration specification. Deviations are defined in the calibration certificate and officially recorded. Calibration testing is a special case of calibration. Calibration testing has to be performed for all measurement devices whose accuracy are of public interest, e.g. flow measurement devices in gas stations or scales in the supermarket.
Calibration
Calibration determines the relationship between the reading (output variable) and the measured value (input variable). Calibration happens under precisely defined reference conditions, whereby no technical intervention is necessary on the measuring device. Example: in the case of a known scale, the display error of a given measuring device is determined by calibration (application of a known input variable).

Adjustment (balancing)
A measuring device is set such that the reading deviates as little as possible from the measured value considered to be correct, or it remains within given limits of error. If the calibration results in a reading that deviates too much, the measuring device is adjusted. Adjustment requires intervention that permanently changes the measuring device.

Zero adjustment
Verification of the zero adjustment is an important task in the use of measuring devices. High-quality indicating devices often provide a zero checking facility. **Caution!** Potential source of error if zero is set incorrectly.
1.2. Measured variable

The measured variable is normally a physical quantity whose value is to be determined by measuring. Example for the measured variable of time.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>t</td>
<td>year, month, week, day, hour, minute, second</td>
</tr>
</tbody>
</table>

The more accurate the measurement the greater the metrological effort will be. Measuring is a complex process. Reliable and accurate measuring is the prerequisite of a good control-action result.

We receive a measurement result by comparing the measured value with a known "comparison value".

Comparison value

The basic prerequisites for any measuring process are as follows:

1. A clear definition of the quantity \( x \) to be measured (measured variable)
2. A convention (legal stipulation) for the comparison value (e.g. international prototype kilogram)

These prerequisites are not always given:

The temperature of a body or the pressure of a gas are, for example, simple measured variables for which international conventions have been defined.

In the case of temperature, the freezing and boiling points of water at a pressure of 1013 mbar (at sea level) are available as reference points. Intermediate values are defined by convention via interpolation with standard platinum resistance thermometers.

Other variables, such as "comfort" or "air quality" are very difficult to quantify. Often there are no appropriate comparison values, or they are not generally known or recognized.

Basic units

The International System of Units SI (Système International d'Unité) as we know it today has created a simple order for units of measurement.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>kelvin</td>
<td>K</td>
</tr>
<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
</tr>
<tr>
<td>Time</td>
<td>sekunde</td>
<td>s</td>
</tr>
<tr>
<td>Electric current</td>
<td>ampère</td>
<td>A</td>
</tr>
<tr>
<td>Mass</td>
<td>kilogramm</td>
<td>kg</td>
</tr>
<tr>
<td>Luminous</td>
<td>candela</td>
<td>cd</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mol</td>
<td>mol</td>
</tr>
</tbody>
</table>

Table 1.1 The seven base units of the SI system
1.3. Measured value (measurement result)
A measured value is the value that is determined and indicated at the output (indicator scale) as the representation of a measured variable. It is indicated as the product of a numerical value and the unit of the measured variable.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Measured value (numerical value)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>3</td>
<td>h</td>
</tr>
</tbody>
</table>

1.4. Principle of measurement
Specific principles of measurement are applied in order to determine measured variables.

The principle of measurement is the characteristic physical phenomenon that is used for measuring. The following principles of measurement can be used, for example, for measuring temperature:

- Linear expansion
- Radiation
- Thermoelectric effect
- Variation of electrical resistance

The practical application of a principle of measurement gives rise to a method of measurement.

A distinction is made between direct and indirect methods of measurement.

1.5. Method of measurement

Direct
In the case of direct methods of measurement, also referred to as comparative or relative methods of measurement, the desired value of the measured variable is determined by comparison with a reference value of the same measured variable. Measurements where the measured value is received directly, without supplementary calculations and usually from the reading of a single measuring device, can also be classified as direct methods of measurement. Example: Resistance thermometer, the resistance corresponds to the perceived temperature.

Indirect
In the case of indirect measurements, the desired value of a measured variable is derived from different physical variables. The measured value is determined from these variables using the given physical relationship (equation between quantities).

A further distinction is made between analog and digital methods of measurement.

Analog
A method of measurement and a measuring apparatus are said to be analog if the measured variable is assigned by the method or device to an output variable which is an unambiguous, continuous representation of the measured variable. The measured value normally appears within the measuring range as a continuous, variable position of a pointer against a scale.

Fig. 1-4 Analog multimeter scale
Advantages:
Analog measurement is used where trend measurement and rapid visual acquisition and evaluation of a measured value (pointer deflection, significance) is required.

**Digital**
A method of measurement and a measuring apparatus are said to be **digital** if the measured variable is acquired time-discretely and assigned to an output variable via a conversion process (device) in which the measured variable is displayed numerically in very small, fixed steps (quantization of the measured variable). The measured value is indicated as the sum of the quantization units or of impulses.

![Digital display](Fig. 1-5 Digital display)

Advantages:
The measured values can be printed, stored, electronically transmitted and processed. Convenient reading is possible, because only a digit or series of digits has to be read.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Principle of measurement</th>
<th>Method of measurement</th>
<th>Measuring apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>variation of length</td>
<td>direct, analog</td>
<td>bimetallic element</td>
</tr>
<tr>
<td></td>
<td>variation of volume</td>
<td>direct, analog</td>
<td>thermometer</td>
</tr>
<tr>
<td></td>
<td>variation of electrical</td>
<td>direct, analog</td>
<td>measuring bridge,</td>
</tr>
<tr>
<td></td>
<td>resistance</td>
<td></td>
<td>resistance thermometer</td>
</tr>
<tr>
<td>Humidity</td>
<td>variation of length</td>
<td>indirect, analog</td>
<td>hygrometer</td>
</tr>
<tr>
<td></td>
<td>temperature comparison</td>
<td>indirect, analog</td>
<td>thermometer</td>
</tr>
<tr>
<td></td>
<td>capacitance</td>
<td>direct, analog</td>
<td>diffusion</td>
</tr>
<tr>
<td>Pressure</td>
<td>elastic deformation</td>
<td>direct, analog</td>
<td>barometric cell</td>
</tr>
<tr>
<td></td>
<td>bulging of a diaphragm</td>
<td>direct, analog</td>
<td>diaphragm</td>
</tr>
<tr>
<td>Flow volume</td>
<td>differential pressure</td>
<td>indirect, analog</td>
<td>measuring orifice,</td>
</tr>
<tr>
<td></td>
<td>(orifice)</td>
<td></td>
<td>manometer</td>
</tr>
<tr>
<td></td>
<td>static and dynamic</td>
<td>indirect, analog</td>
<td>pitot tube</td>
</tr>
<tr>
<td></td>
<td>pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ultrasound, delay time</td>
<td>indirect, digital</td>
<td>ultrasound counter</td>
</tr>
<tr>
<td></td>
<td>difference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed of</td>
<td>pulse counting</td>
<td>indirect, digital</td>
<td>photocell,</td>
</tr>
<tr>
<td>rotation</td>
<td></td>
<td></td>
<td>impulse counter</td>
</tr>
</tbody>
</table>

Table 1.2 Examples of measuring methods and equipment
1.6. Measuring by counting

In association with digital methods of measurement, counting is used increasingly in metrology as a method of determining a measured value.

Counting

Counting is the determining of a number of elements or events that are in some respect similar, such as: objects, pulses, revolutions, elementary particles.

Counting is performed by sensory perception or primarily using counting equipment, e.g. person-counting equipment in a department store for ventilation system operation.

Measured values in the form of counts can be converted to other measured variables by data processing.

Example, speed measurement:

- Counting of wheel revolutions per unit time
- Conversion to speed (= wheel circumference * wheel revolutions / time)

1.7. Analog-to-digital and digital-to-analog converters

A/D converter

In most cases, the sensors used in building services and HVAC systems technology supply an analog current, voltage, resistance or pressure signal as the measured value. This signal can be used directly with conventional analog equipment.

In digital systems, an analog input signal (e.g. measured value) must be converted to a digital input value that can be understood by microcomputers.

This is accomplished using an analog-to-digital converter, or A/D converter for short. The reverse process, i.e. conversion of a digital output value into an analog output signal, is also frequently required (e.g. output of an analog actuating signal). The component used for digital-to-analog conversion is called a D/A converter.

Accuracy (resolution)

The accuracy (resolution) of an A/D or D/A converter depends on the number of steps with which the analog signal can be represented. A 10 bit A/D converter can divide an analog signal into $2^{10} = 1024$ steps, for example.

Fig. 1-6 illustrates the process using a 3 bit A/D converter which only permits $2^3 = 8$ steps (very low resolution). $x_1$ is the analog input variable for the A/D converter. The corresponding output variable $x_2$ is shown in the table to the right. The first bit from the right represents the value 1, the middle bit represents the value 2, and the left bit represents the value 4.

If $x_2$ is taken as the input variable of a D/A converter, the resultant output variable is the analog signal $x_3$. 
Although the sequential connection of an A/D converter and a D/A converter makes no practical sense, the example clearly shows the error from digitization, the so-called quantizing error (Fig. 1-6 , right diagram (1)), and the error due to time-discrete measurement (Fig. 1-6 , right diagram (2)). The resolution (high bit count) is decisive for the accuracy of the digital measurement result.

1.8. Measured section/measuring apparatus

Where does the measured section end and the measuring apparatus begin?

**Measured section**

Measured sections are systems or components in which the value to be measured is influenced. They are not sections in the geometrical sense. The measured section cannot be defined until the function of the system and the purpose of the measurement are known. The more precisely they are known the more precisely the measured section can be defined.

The measured section also includes interference variables that affect the value to be measured from the outside.

**Measuring apparatus**

The measuring apparatus contains all of the functions required for the output (display) of the measured value. The term "measuring instrument" is generally used for the measuring apparatus, and it is considered a single device.
In Fig. 1-7, the measured section (1) and measuring apparatus (6) constitute the measuring system (10).

![Diagram of water temperature measurement using an immersion sleeve and a thermometer](image)

**Transfer medium**

The transfer medium (contact medium, e.g. oil or heat transfer paste) makes the connection between the measured section and the measuring apparatus. It can have a considerable effect on the quality of a measuring apparatus.

As Fig. 1-7 clearly shows, the water temperature not is being directly measured but the temperature of the transfer medium (oil) which forms the interface between the measured section and the measuring apparatus.

The water, pipe, immersion sleeve and oil are all parts of the measured section in this case. From physics we know that all of these materials have a different thermal response.

The bulb at the bottom of the thermometer is the sensing element, the capillary tube provides the transfer, and the top of the measuring fluid with the scale provides the temperature indication. They are all parts of the measuring apparatus.

It should now be clear that the measurement result is influenced by a variety of factors (see Fig. 1-8).
Measuring signal amplification
Since a change in the measured variable frequently only gives rise to a small change in the measuring element, the measuring signal must be amplified. For this reason, an amplifier is usually located after the transducer or immediately after the sensor. Amplification is accomplished by multiplying the measuring signal by a constant factor. Instead of an amplifier, a processing system can be used which performs specific mathematical operations on the measuring signal.

Remote transmission
If the components of the measuring apparatus are some distance apart, remote transmission of the signals is necessary. The transmission can take place via electrical wires, pressure lines or by wireless means.

In any transmission of measured values, information can be lost or (especially in the case of analog signals) falsified. This information loss gives rise to false indications and incorrect results, which is a major problem for the measuring apparatus.

Indication
If the measured value is to be read out by human beings, the indication must be perceivable to a sensory organ, e.g. the eye. The most commonly used indications are as follows:

- Position of a pointer on a scale (analog)
- Direct numerical display (digital)
- Plotted indication on paper

Measured value processing
If a large number of measured values are present and need to be used for some purpose at a later date, the values are stored and evaluated by a processing system.
### Table 1.3 Examples of measuring apparatuses

<table>
<thead>
<tr>
<th>Name</th>
<th>thermocouple</th>
<th>resistance thermometer</th>
<th>bimetallic thermometer</th>
<th>liquid-in-glass thermometer</th>
<th>cable sensor</th>
<th>duct sensor (for humidity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor or filling material</td>
<td>Fe constantan, PtRh-Pt, Cu constantan, NiCr-Ni</td>
<td>Platinum, nickel, Cu, semiconductor ceramic</td>
<td>Fe alloys</td>
<td>Mercury, alcohol</td>
<td>Cu, Ms bright nickel plated</td>
<td>printed circuit board with electronics: capacitance = f (humidity)</td>
</tr>
<tr>
<td>Measuring range</td>
<td>-20..2000 °C</td>
<td>-200..700 °C</td>
<td>-20..250 °C</td>
<td>-200..500 °C</td>
<td>-10..100 °C</td>
<td>10..90 %rH</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>30...60 µV</td>
<td>0.4...0.8 °C/K semiconductor: 3 %/K</td>
<td>0.15 % / 100 K</td>
<td>up to 10 mm/K</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Achievable accuracy</td>
<td>0.5 K</td>
<td>0.1 K semiconductor: 0.5 K</td>
<td>1.5 % of range</td>
<td>0.02 K</td>
<td>± 5 %</td>
<td></td>
</tr>
<tr>
<td>Response time of sensor in water</td>
<td>1 s</td>
<td>1..10 s</td>
<td>1..20 s</td>
<td>5..20 s</td>
<td>62.5 s</td>
<td>-</td>
</tr>
<tr>
<td>Scale graduation</td>
<td>linear</td>
<td>linear</td>
<td>linear</td>
<td>linear</td>
<td>linear</td>
<td>linear</td>
</tr>
<tr>
<td>Special application</td>
<td>for high temperatures, for temperature differences (very accurate: 0.01 K)</td>
<td>for low temperatures, telemetry (self-heating error)</td>
<td>cheap air thermometer (with switch, if applicable)</td>
<td>laboratory and check measurements</td>
<td>for difficult space conditions</td>
<td>for measuring relative humidity in ducts</td>
</tr>
</tbody>
</table>

### 1.9. Equipment terms

**Classification of measurement devices**

Measuring devices can be classified according to the following criteria:

1. According to the quantity to be measured:
   - measuring devices for temperature, pressure, humidity, speed, energy etc.

2. According to design:
   - indicating device as an operating aid
   - recording device as an aid for operation monitoring and subsequent tracking of operational processes

3. According to function:
   - Counting device (meter) for determining room occupancy and consumption figures as well as for billing
   - ...

**Basic components of an indicating instrument**

The basic components of an indicating instrument are as follows:

- measuring element, sensor or pickup, e.g. the hair bundle in a hygrometer
- measuring or processing system
- indicating system (pointer, scale, display)

**Measuring apparatus**

Every measuring apparatus can be shown as a "black box" whose input signal is the measured variable and whose output signal is a measured value as a representation of the measured variable.
The measuring apparatus includes all auxiliary devices for sensing a measured variable, conditioning and reproducing a measuring signal and displaying a measured value.

**Measuring instrument**
A measuring instrument can consist of a single device (e.g. a liquid-in-glass thermometer). Generally, however, measuring instruments are only parts of measuring apparatuses (e.g. resistance thermometer, measuring orifice etc.).

**Auxiliary devices**
The parts of a measuring apparatus that are not so decisive for its metrological characteristics are referred to as auxiliary devices.

**Auxiliary power**
The auxiliary power is the energy that must be intermittently or permanently supplied to the measuring instrument to maintain its function and which is not derived from the respective input signal.

**Input and output signals**
A distinction is made between these two signal types in all measuring instruments. The input signal can be the measured variable itself, in which case the term pickup is used. The output signal can be a pointer position, in which case the device is referred to as an indicator (e.g. thermometer).

Measuring instruments can also have more then one input or output signal.

**Measuring range**
The measuring range is the portion of the indicating range within which the indicating error remains within given limits. The measuring range and indicating range can be identical. Some measuring instruments have multiple measuring ranges with different error limits, e.g. multimeter for current, voltage and resistance.

The measuring range is characterized by the measuring range lower limit and the measuring range upper limit (Fig. 1-10, measuring range 20 to 140 °C). The measuring span is the difference between the lower and upper limit of the measuring range (120 Kelvin in this example).
Indication and accuracy

In the case of indicating and recording instruments, a distinction can be made between the measuring range (range of the measured variable) and the signal range (range of the measuring signal). An indicating instrument for connection to an NTC element has, for example, a measuring range of 0 to +30 °C, which corresponds to a signal range of 0-10 V.

Absolute and relative error

The difference between the measured value and actual value is referred to as the error and is expressed as an absolute error in units of the measured variable or as a relative error in percent of the measuring range upper limit (see chapter 3, "Tolerance and measuring error").

The measurement accuracy indicates the maximum permissible positive and negative deviation of the indicated value as a function of the full scale value, e.g. ±1.5 V from the full scale value 150 V.

The quality class or accuracy class indicates the plus/minus relative error as a percentage of the full scale value that is permissible for a measuring instrument, e.g. quality class 0.5 = maximum permissible error of ±0.5% of the full scale value (see Fig. 1-11).

In order for the measuring error to remain within the limits indicated on the measuring instrument, the specified application must be observed. The symbols for the application of measuring apparatuses are specified in the standards and indicated on the measuring instruments (see Fig. 1-12).
**Signal conductors**

These transfer the measuring signals from the measuring element to the measuring mechanism and connect measuring devices in a manner corresponding to the physical nature of the measuring signal (e.g. resistance thermometer leads). Interference can enter the measuring apparatus via the signal conductors, causing falsification of the measurement result. Line resistance must be compensated for, if appropriate.

**Measuring errors, sources of error**

The value of a measured variable indicated by a measuring instrument is never totally error free. The error limits in practical metrology are the agreed or guaranteed maximum upward or downward deviations from the specified indication of an otherwise defined value.

Every measurement result is falsified by the imperfections of the measured object, measuring instruments and methods of measurement. Measurement results are also falsified by the influence of ambient conditions and of the observer. Falsifying ambient conditions are, for example, temperature, air pressure, humidity, external electrical and magnetic fields. Falsifying personal influences depend on the characteristics and skills of the observer, e.g.:

- Attention
- Practice
- Visual acuity
- Ability to estimate
- Stamina

This topic is covered in detail in chapter *Error! Reference source not found.* "Tolerance and measuring error".

Fig. 1-12  Symbols and notes on measuring instruments

**Signal conductors**

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- Attention
- Practice
- Visual acuity
- Ability to estimate
- Stamina

This topic is covered in detail in chapter *Error! Reference source not found.* "Tolerance and measuring error".
1.10. Operating rules for measuring instruments

In order to prevent errors due to incorrect use and inappropriate application of measuring instruments, it is important to observe the following points:

1. Observe the operating instructions
2. Select the appropriate measuring instrument
3. Select the appropriate accessory equipment
4. Check (adjust) the zero position
5. Observe the operating limits: position, temperature etc.
6. Avoid overloading
7. Start with the largest measuring range
8. Select the appropriate measuring range
9. Use the arresting device if appropriate
10. Handle measuring instruments with care
11. When storing multimeters, set the highest alternating current value
2 Transfer characteristic (response)

2.1. General

Jedes Messsystem, die Messstrecke oder Messeinrichtung - oder Teile davon - übertragen
Every measuring system, the measured section or measuring apparatus, or parts thereof, respond to
physical quantities. The term "respond" refers to the description of a reaction. The response
describes, for example, how the output value (resistance) of a temperature sensor behaves in
relation to the input signal (temperature).
A distinction is made between the steady-state response and the dynamic response.

2.1.1. Steady-state response

Steady-state condition
The steady-state response indicates the relationship between the input variable and the output
variable in the steady-state condition.

Fig. 2-1 Statische Kennlinie eines PTC-Temperaturfühlers

Figure 2-1 shows that the sensor's resistance is 1000 Ω at a temperature of 0 °C, and
approximately 1100 Ω at 20 °C, for example. Therefore, a temperature change of 20 K gives rise to a
100 Ω change in the resistance of this sensor. From these two differences, the transfer coefficient $K_P$
can be calculated using the following formula:

$$K_P = \frac{\Delta a}{\Delta e} = \frac{\Delta R}{\Delta \theta} = \frac{100 \, \Omega}{20 \, K} = 5 \, \Omega/K$$

2.2. Dynamic response

The dynamic response refers to the relationship between the change in the input variable $\Delta x_e$ and
the change in the output variable $\Delta x_a$ as a function of time $\Delta t$.

Step response
The dynamic response of the system to be investigated can be evaluated via a sudden change of the
input signal (step function). The result is referred to as the step response.
What happens to the output variable $x_a$ in Fig. 2-2 if the input variable $x_e$ suddenly changes by a random value $\Delta x_e$?

Fig. 2-2  Recording of the transient response via the "step function"
1 Input, measured variable, action, step function
2 Measuring apparatus or measured section or measuring system
3 Output, measured value, reaction, step response

In metrology, the step response provides information on why and how a measurement result changes. It gives us a look into the type of transmission and transfer of variables and helps us to assess and evaluate reactions.

Therefore, the criterion for these examinations is always the time factor, i.e. the size of the delay until the steady-state condition is reached. These delays can be caused by so-called storage elements (mass, time delay).

For practical use in HVAC, however, it is sufficient to describe the following four typical responses:
1. Without time delay (PT₀ system)
2. With dead-time response (PT₀-TT system)
3. With delay due to one storage element (PT₁ system)
4. With delay due to multiple storage elements (PTₙ system)

### 2.2.1. Without time delay

If the control valve in Fig. 2-3 is suddenly opened through a given stroke (step function) a simultaneous change occurs in the measured variable at the "flow volume" sensor. Start with 10% aperture.
2.2.2. With time delay

If the position of the control valve in suddenly changed through a given stroke, the mixed water temperature at the valve changes without delay. However, there is a certain distance between the control valve and the "temperature" sensor. The mixed water must first cover this distance before the sensor can detect the change. This travel time is referred to as the dead time $T_d$.

![Diagram showing time delay](image)

Fig. 2-4  Response with dead time ($T_d$), e.g. mixed water temperature

2.2.3. With delay due to one storage element

If the heating element in Fig. 2-5 is switched to the next higher level, the water temperature in the container rises according to an exponential function.

![Diagram showing exponential response](image)

Due to the initially large temperature difference between the heat-emitting and heat-absorbing media, the initial temperature rise is relatively steep (the initial slope $T_s$ of the transfer step depends in this case on mass and heat output). However, due to the continued heating of the medium, the temperature difference becomes increasing small, causing the rate of rise to decrease continuously. Plotting a tangent at the steepest section of the curve and extending it up to the maximum achievable value of the water temperature gives the time constant $T_s$ ($\tau = \tau$).

**Time constant $T_s$ (often also $T$ or $\tau$)**

The time constant $T_s$ is the time that the output variable $x_a$ would require for 100 % change if the initial rate of change were to remain constant.

Or in simplified terms: 1 $T_s$ is the time that elapses until the measured variable $x$ reaches a value of 63.2 % of the total change $\Delta x$. 

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The subsequent changes after $T_s$ behave in the same manner, i.e. each occurs with the same time interval and the same percentage of the remaining amount, until after 5 time constants 99.8 % of the final value is reached. This must be considered in all measurements.

### 2.2.4. With delay due to multiple storage elements

A sudden change of the position of the control valve in Fig. 2-6 by the amount $\Delta y$ initially only produces a gentle rise with a small rate of change at the sensor (room air temperature). In the area of the inflectional tangent, the rate of rise of the room air temperature is greater. It then decreases again until the final value is reached.

![Fig. 2-6 Response characteristic with two or more storage elements, e.g. heating of a room](image)

The first time segment is referred to as the delay time $T_u$, the second as the balancing time $T_g$. The greater the number of storage elements the more gentle the rise of the temperature change will be. If the examples shown in Fig. 2-4 and Fig. 2-5 also contained dead-time elements, these would, of course, also have to be taken into consideration.

Knowledge of the response of the individual components of the measuring apparatus and of the measured section makes it possible to assess why measurement results do not change in the same way as the input variable and especially what the decisive causes are.

### 2.3. Time constants for temperature sensors

Sensors with immersion sleeves often are built into pipes to measure and acquire temperatures of fluids.

![Fig. 2-7 Measuring sensor in immersion sleeve](image)

The immersion sleeves are the first delay element, the air between immersion sleeve and sensing element the second, and the sensor's time constant the third delay element. The delay caused by the air is the largest of the three, as air is a poor heat conductor. This type of poor transfer characteristic can be improved greatly by oil or glycerin (Fig. 2-7 (3)).
Values for characteristic values of temperature sensor:

Thermal element:
\[ T_u = 1 \text{ to } 5 \text{s} \]
\[ T_g = 5 \text{ to } 25 \text{s} \]

Resistance thermometer:
\[ T_u = 2 \text{ to } 5 \text{s} \]
\[ T_g = 40 \text{ to } 100 \text{s} \]

Fig. 2-8  Transfer characteristic of temperature sensor

Fig. 2-9  Sensor in water without immersion sleeve

Fig. 2-10 Sensor in immersion sleeve filled with oil

Fig. 2-11 Sensor in immersion sleeve without oil
3 Tolerance and measuring errors

3.1. Tolerance

Tolerance is not an error but a limit for the permissible deviation of a measurement from the specified
value. If the deviation is above or below the tolerance limits, it is classified as an error.

Tolerances can be defined as absolute values (°C, bar etc.) or as relative values (percentage of the
measuring range); they can be defined asymmetrically as a plus tolerance (+) and a minus tolerance
(-) or symmetrically as a plus-minus tolerance (±). Example: with a specified value of +20 °C and a
tolerance of ±1 K, the permissible measured value is between 19 °C and 21 °C, so it has a
tolerance band of 2 K.

In instrumentation and control, a distinction is made between two different types of tolerance: steady-
state tolerance and dynamic tolerance.

3.1.1. Steady-state tolerance

Steady-state tolerance is the deviation from the given value (setpoint) in the steady-state condition of
a control system (stable state).

![Steady-state tolerance](image)

Fig. 3-1 Steady-state tolerance
1 Desired value
2 Continuously measured value
3 Tolerance (±)
4 Error

3.1.2. Dynamic tolerance

Dynamic tolerance is the deviation quantity arising from dynamic processes. Therefore, only the
deviceation during the unstable state of the control system, i.e. during the transient recovery process, is
considered.

Steady-state and dynamic tolerance

A tolerance specification can also contain both types of permissible deviation. Example: the
permissible steady-state deviation from the setpoint is ±1 K, and the permissible dynamic deviation
is ±0.5 K. Such tolerance specifications are common in the case of highly sensitive thermodynamic
processes or procedures, e.g. in test rooms or test sections.
3.2. Measuring error

An unexpected measurement result or a divergence from a control check is usually interpreted as a measuring error. However, an incorrect measurement result is not necessarily a measuring error.

A distinction is made between systematic errors and random errors:

- Systematic errors have a specific amount and a specific sign, e.g. + 0.5 °C or 0.1 bar. Therefore, detectable systematic errors can be compensated by corrections.
- Random errors vary unequally in terms of amount and sign; they are usually not detectable, and they make the result unreliable.

What is a measuring error?

The measuring error is the difference between the actual measured value of a measured variable (measured value) and the true value of the measured variable, where the origin of the difference is to be found in the measuring apparatus.

Error = measured value minus true value = absolute error quantity.

Incorrect measurement results whose origin is in the measured section or in the interpretation (reading, evaluation) are not measuring errors but:

- measuring concept errors, planning errors, installation errors, system faults
- behavioral errors (human), interpretation errors, evaluation errors

Measuring errors cannot always be identified and corrected in advance according to a plan. In many cases, they occur irregularly. However, they can be reduced by careful planning.

A measurement can never be performed ideally, i.e. without measuring error and duration. Measuring mainly deviates from the ideal in two points, which are explained in the following.

3.2.1. Steady-state errors

It is not possible to build a totally accurate measuring apparatus at reasonable cost. It will exhibit steady-state errors according to the principle of measurement and hardware design. Additionally, the relationship between the measured variable and the output signal is frequently non-linear, i.e. the transfer coefficient is not constant. Changes can also occur over time, e.g. due to ageing.

The steady-state error is a deviation outside of the permissible tolerance (deviation from the true value) in the steady-state condition (stable state - constant deviation).

Recommendations

- The accuracy of the measuring apparatus must be appropriate for the given control task.
- In order to prevent falsification of the measurement results due to outside influences (e.g. at the immersion sleeve or at the tube of the duct sensor), the manufacturer's installation instructions must be observed.
- Observe the notes on sensor positioning (representative location, see chapter Error! Reference source not found.).
3.2.2. Dynamic errors

As with all other elements of the control loop, the measuring apparatus also has a certain dynamic response which is expressed in the form of a dead time and time constant or a delay time and balancing time. Fig. 3-2 shows a basic characteristic. Reference values for the characteristics of commonly used temperature sensors are indicated in the table below.

![Transfer function of a temperature sensor](image)

<table>
<thead>
<tr>
<th>Standard values for sensor characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Type</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>$T_u$</td>
</tr>
<tr>
<td>$T_g$</td>
</tr>
</tbody>
</table>

Of course, the actual values do not depend only on the measuring element used, but also to a great degree on the design and installation of the sensor. Sensors with a high mass are, for example, slow. The same applies to equipment that is thermally heavily coupled to the measuring location (e.g. immersion sleeve in a pipe).

The dynamic error is a deviation outside of the permissible tolerance (deviation from the true value) while the measured variable is changing. Only the deviation during the transient state is considered. The dynamic error indicates the deviation within a certain time period.

During the change of the measured variable, the result with comparison between input and output can be falsified in two different ways:

1. Pure time lag
2. Time lag with modification of the output variable

**Time lag**

If a sinusoidal input variable $x_e$ is applied to a system with dead time but without storage elements, the resultant output variable $x_a$ will have the same frequency as the input oscillation but with a phase shift (time lag), assuming the time characteristic of the system is linear.

![Dynamic error in a system without storage elements but with dead time](image)

This phenomenon is only possible in a $pT_0$, $T_1$ system (system with dead time only, see chapter “Response”).

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System with storage

If the system has one or more storage (mass) elements, an additional effect occurs (Fig. 3-4): the value of the output \( x_a \) no longer corresponds to the effective value of the input \( x_e \). Not only a phase shift but also a reduction in amplitude (magnitude) occurs.

If the input variable changes by the amount \( \Delta \vartheta = 10 \, \text{K} \), for example, the output variable will change by a smaller amount, e.g. \( \Delta \vartheta = 5 \, \text{K} \).

![Amplitude shift due to a storage element](image)

This phenomenon can occur in \( pT_1 \) systems (first-order systems) and \( pT_n \) systems (higher-order systems) and can also be affected by dead time (see chapter Error! Reference source not found.).

Since the entire measuring system constitutes a chain, the modifications are transferred sequentially through to the result. Each part of the measuring system can be additionally influenced by interference variables which also affect the measurement result. These facts should be taken into consideration in troubleshooting. If such distortions of the measurement result (reading) occur within the measuring apparatus, i.e. on the instrumentation side, there is a measuring error caused by selecting too slow a measuring apparatus.

Errors also occur in measurements where a number of measured variables are required to generate a common result. Even if only one of the measured variables is transmitted to the common processing unit with the wrong value or at the wrong time, the result will be a proportional magnification of the error by the multiplication factor incorporated in the processor.

Recommendations:

- The time constant of the measuring apparatus must correspond to the response of the measured section. Relatively slow-reacting measuring devices can be highly suitable for slow measured sections. However, for measuring rapidly changing processes, the measuring reaction (time constant) must be at least equally fast.
- Observe the manufacturer's installation instructions which aim at making the acquisition of the measured variable as far as possible delay-free.
- Incorrect sensor placement in the sense that the acquired measured variable is not representative for the intended control task. Example: the air flow speed measured at a certain point is not always meaningful with regard to the average speed in the duct.
- Select a distance between the manipulation point and the measuring point that is just large enough to ensure proper mixing of the medium. If the distance between the manipulation and measuring points is too large, the result will be a certain dead time. The greater the distance and the smaller the medium flow speed the greater the dead time will be.
- Work with sensible medium flow speeds (no oversized pipes and ducts).
3.3. Instant of measurement

If measurements are to be taken periodically, the reading intervals must be regular. Irregular readings give rise to uncertainties and distortions with regard to interpretation. Otherwise, as shown in Fig. 3-5, an instantaneously read result may be incorrect under certain circumstances, because the measured variable was not in the steady-state condition at the time of reading. The measured variable reaches a higher or lower measured value at an earlier or later time.

![Fig. 3-5 When is the correct time for reading?](image)

1 Incorrect: time of reading not in steady-state condition
2 Correct: time of reading in steady-state condition

3.4. Troubleshooting

The greater part of correcting an error is locating it. This requires the most time. In addition to solving the technical problem, there is also the orderly sequence of operations to be considered.

The first step is indispensable: determining how an error arises and where its origin is. You must try to logically reconstruct the development process of the error. In this way, you arrive at assumptions about the occurrence of errors. However, the assumptions must still be tested via comparison with the technical documentation (measuring plan - data - plant schematic).

Such assumptions (also known as hypotheses) always start with the initial situation of the error (a hypothesis is an assumption without proof).

**Procedure**

In order to assess a measurement result, all factors of the overall measurement must be taken into consideration. Therefore, the following questions may be helpful for quickly identifying an error:

- What is the purpose of the measurement?
- What are the measurement conditions (permissible deviation, tolerance guarantee)?
- What is the principle of the measured section?
- What is the sequence of functions from the measured section to the measuring apparatus?
- What is the principle of the measuring apparatus?

This initial situation is the most important part of troubleshooting. It provides a basis for all further procedure. You should not proceed any further until the origin of the error is clearly identified. Get a clear concept of the error via the following logical process: observe, make assumptions, test your assumptions, reconstruct the occurrence of the error.

When looking for the cause of an incorrect measurement result, a subdivision of the process into the following three questions suggests itself. Is the cause of the incorrect measurement result to be found in:

- the measuring apparatus?
- the measured section?
- human behavior?
4  Measured variables in HVAC

4.1. General

The most important measured variables in HVAC systems are as follows:

- Temperature of air/water,...
- Relative air humidity
- Air quality
- Pressure
- Speed of flow
- Volume flow

Measuring location

The main purpose of HVAC technology is to provide a defined climate in a room. In order to do so, the variables listed above must be kept within appropriate tolerances so that, for example, the comfort of human occupants is not affected, or so that the room air conditions for a manufacturing process are maintained.

In this connection, four measuring locations with principally different boundary conditions can be distinguished:

1) Outside air with extreme states:
   - cold in winter, with high relative humidity and low absolute humidity
   - hot in summer, generally with medium relative humidity and sometimes high absolute humidity

2) Central building services:
   this is where the plant equipment for treatment of the energy media, i.e. water and air is located

3) Transport paths:
   these include pipes (supply, return) and air ducts (supply air, exhaust air) with appropriate junctions (manifolds)

4) Rooms:
   with various installations, contact surfaces to the outside or to adjacent rooms, with or without windows.

In all of these places or parts of the system, measuring locations for verification or control purposes are defined, i.e. measuring points for the respective measured variable.

The following basic requirement applies to all measuring points: the same measurement results should be received under the same boundary conditions at different measurement times. This requires absolutely accurate measuring devices, and the metrologist must consider which is the correct measuring method, i.e. the correct sensor, and what is the measuring process for each location.

4.2. Temperature

Temperature is a measure of the thermal state of a homogeneous material, or more precisely a measure of the average kinetic energy of its molecules.

The most familiar methods of temperature measurement are based on a range of body or material characteristics that vary with temperature:

- expansion of solids, liquids or gases (liquid-in-glass thermometer)
- change in electrical resistance, e.g. of a nickel or platinum wire (resistance thermometer, temperature sensor)
- thermal e.m.f. (electromotive force), luminous and thermal radiation
4.2.1. Material expansion

Based on the property that, with a change in temperature, a specific, proportional change in length occurs, almost any material could be used for temperature measurement.

In the case of liquid-in-glass thermometers, the expansion of the liquid is used to directly indicate the temperature, as in a clinical thermometer.

If two metal strips with very different coefficients of thermal expansion are permanently joined together (bimetallic element), they curve according to temperature (Fig. 4-1). The difference in elongation can be used for temperature measurement, via an appropriate system of levers, or used as a temperature-dependent switch (thermostat).

![Fig. 4-1 Applications of bimetallic curvature](image)

1 Functioning principle
2 Bimetallic thermometer
3 Bimetallic switch
4 Delayed relay (with heating resistor), e.g. for thermal feedback

4.2.2. Change in resistance

Similar to the change in volume or elongation of materials as a result of a temperature change, the conductivity of electrical conductors is also temperature dependent, i.e. their electrical resistance changes as a function of temperature. Most such materials have a Positive Temperature Coefficient (PTC), which means that their electrical resistance increases with rising temperature. The most common materials of this kind are platinum wire (Pt measuring element) and nickel wire (Ni measuring element).

Pt 100 means: this platinum element has a resistance of 100 ohms at 0 °C.
Pt 1000 means: this platinum element has a resistance of 1000 ohms at 0 °C.

Rated measured resistance Pt 100 (DIN EN 60751). Change of resistance for platinum \( \pm 0.4\%/K \).

The line length thus affects the measuring result; as a consequence, measuring equipment with three or four wires is employed for measurement.

Ni 1000 means: this nickel element has a resistance of 1000 ohms at 0 °C.

Other substances, such as carbon, have a Negative Temperature Coefficient (NTC), which means that their electrical resistance decreases with rising temperature.

These NTC elements consist of pulverized and sintered (iron, nickel and cobalt dioxide) titanium compounds and fillers. They are generated in the form of pearls, sticks and disks. The change in
resistance is about 10 times that of metallic resistance, i.e. ca. 5% K. For temperature changes of 1 K, resistance changes of 1000 ohms are possible. Line length is a negligible factor.

![ resistor](image1.png)  
**Fig. 4-3 Function of a PTC element**  
**Fig. 4-3 Function of an NTC element**

**Wheatstone Bridge**

For temperature sensing and processing, the temperature-dependent resistor is placed in the diagonal branch of a Wheatstone bridge.

![ wheatstone bridge](image2.png)  
**Fig. 4-4 Wheatstone bridge circuit with line compensation resistor Rh**  
T Temperature sensor  
R1 Measuring element  
Rj Compensation resistor  
D Measuring device (measuring apparatus)  
N Voltage source

The bridge is aligned to the measuring element's resistance value at the onset of measuring, resulting in a display = zero at the measuring device.

The current in the diagonal branch of the bridge circuit provides a measure for the resistance of the resistance thermometer or of the setpoint/actual comparator circuit in a temperature controller. A constant voltage source is a prerequisite for exact measurement, because the indication is proportional not only to the current but also to the supply voltage.

**Two-wire circuit**

In some cases the line length must be taken into account (line resistance falsifies the measurement result, and the line resistance is set to a fixed value, e.g. 10 ohms, with Rj).
Three-wire circuit

Three-wire circuits affect temperature deviations on all three wires and result in homogenous change in resistance on all three bridges, thus avoiding changes in the initial voltage. The influence of the ambient temperature on the remote line is compensated for.

![Diagram of a Wheatstone bridge circuit with balancing resistance](image)

Fig. 4-5 Wheatstone bridge circuit, three-wire circuit with line balancing resistance $R_i$

Four-wire circuit

Here, the measuring element is supplied by a constant power source in the measuring device. The power supplied to the sensor is thus maintained constant along the remote line even for changes in resistance due to different line lengths or ambient conditions. A second wire pair is used to measure non-volatile voltage drop on the measuring element. This circuit allows for very accurate measurements without line balancing and without ambient conditions along the remote line.

![Diagram of a four-wire circuit with constant power source](image)

Fig. 4-6 Four-wire circuit with constant power source

4.3. Air humidity

The term humidity refers to the amount of water contained in a substance. In the case of air humidity, the water is homogeneously mixed with the air in a gaseous state.

As with any other substance, air can only absorb a limited amount of water. This limit is referred to as saturation. Below the saturation limit, "humid air" is indistinguishable from "dry air" to the human eye — it is completely colorless and transparent. Above the saturation limit, the excess water precipitates in the form of very fine water droplets as a mist or cloud. The maximum amount of absorbed water at the saturation limit depends on air pressure and temperature. It rises progressively with increasing air temperature. At an altitude of 0 m above sea level and 0 °C it is 3.8 g/kg of air, for example. At 20 °C it is already 14.7 g/kg.

Air humidity can be expressed as a numerical value using the variables of absolute humidity and relative humidity.

Absolute humidity

The term "absolute humidity" refers to the ratio of the weight of water absorbed in the air to the weight of the dry air. The unit is [g/kg].
Relative humidity
The expression "relative humidity" means the following: the quantity of water absorbed in the air in proportion to the maximum possible water quantity (expressed in % relative humidity, % rH).

Example:
Air at a temperature of 20 °C (1) can absorb a maximum of 14.7 g of water per kg of air (14.7 g/kg) (2). Let us assume that the current water content is 7.35 g/kg. Therefore, the relative humidity is 50 % rH (3).
These relationships are visualized on the psychrometric chart, on which the various states can be presented in graphic form.

Fig. 4-7  Psychrometric chart (h,x-Diagram)

4.3.1.  Principles of relative humidity [% rH] measure

Temperature change
In the aspiration psychrometer (Fig. 4-8) the cooling effect of the evaporation of water is used for humidity measurement. The device contains two liquid-in-glass thermometers, one of which is covered with fabric which is dampened immediately before measuring (wet-bulb thermometer). An airflow of approximately 2 m/s is generated by a built-in (clockwork) fan. This causes evaporation cooling at the wet-bulb thermometer, which results in two temperature values: the dry-bulb and the wet-bulb temperature. Depending on the altitude of the location, the resultant temperatures can be used to determine the relative humidity in % with the aid of a psychrometric table or chart (Mollier diagram).
Variation in length
The hair hygrometer (Fig. 4-9) is based on the principle that the length of degreased hair changes by a relatively large amount under the influence of humidity (approx. 1.5 - 2.5 % with a change in relative humidity of 0 - 100 %).

Advantage:
The effect of temperature variations on the change in length is negligible.

Function
A hair bundle (h1) attached at point (a) is connected via a double lever (b) to another hair bundle (h2) in order to increase the effective length. This is connected to a pointer mechanism (w) which transfers the change in length of the hair as a function of relative humidity to a pointer (z) on a scale. It is important that the measuring element is continually exposed to a certain humidity level and that the surrounding air can circulate freely.

This principle is frequently applied in a measuring device with an integrated temperature measuring element, the so-called thermohygrograph (Fig. 4-10).

In recording devices, the measuring element is connected to a fiber or metal-lipped recording pen instead of a pointer. The clockwork motor draws a paper chart past the recording pens over a defined period (e.g. 24 hours or 1 week), and the measured values are plotted on it in the form of a graph.
4.3.2. Principle of capacitive humidity measurement

The measuring element of the sensor (Fig. 4-11) consists of a capacitor with a polymer dielectric and very thin gold electrodes. Humidity enters the dielectric through the electrodes, changing the capacitance of the capacitor. This change in capacitance is electronically processed, amplified and output, e.g. as a 0-10 V signal. The signal corresponds, for example, to a relative humidity of 0 - 100 % (Fig. 4-12).

![Fig. 4-11 Capacitive humidity measuring element](image1)

1. Porous covering electrode
2. Humidity-absorbent polymer
3. Base electrodes
4. Substrate

![Fig. 4-12 Fig. 4-11: Schematic diagram of a capacitive humidity sensor](image2)

4.3.3. Principle of absolute humidity (x) measurement

The measurement of absolute humidity is of interest in all cases where the quantity of water absorbed in air or a gas needs to be known.

**Determine absolute humidity from temperature and relative humidity**

Today, most HVAC plants employ an algorithm in the controller to measure the temperature (1) and relative humidity (2) as measuring variable, absolute humidity x (3).

In HVAC plants with heat recovery RG, this measuring principle is employed, as it acquires the actual energy of air (thermal and water vapor enthalpy). (Example of tx-controlled control).

**Correlation:**
With a temperature of 20 °C and a relative humidity of 50 %, the absolute humidity results in 7.3 g/kg in the psychrometric chart (for 1013 mbar, 0 masl), see Fig. 4-13.
4.4. Air quality

Odors and scents have a significant effect on our comfort in rooms. Unpleasant odors can not only cause psychological discomfort but also physical symptoms such as headaches, nausea and loss of appetite, even without any toxic effect of the odiferous substances.

For this reason, the operation of ventilation and air-conditioning systems is subject to legal requirements which specify a minimum volume of fresh supply air according to the present (or planned) number of occupants in the room.

The technical evaluation of room air quality by sensors is in no way comparable to the human nose. However, they still give astounding results for determining the fresh air demand with indoor air quality control. In this regard, volatile organic compounds (VOC) and carbon dioxide (CO₂) are of special interest.

4.4.1. CO₂ sensor

Carbon dioxide (CO₂) is produced by respiration as well as by all combustion or oxidation processes. CO₂ is an odorless gas which, in small quantities, has no known effects on human beings.

⇒ CO₂ concentration in a space is an indicator of the number of people in the space
⇒ CO₂ also has health implications (our breathing is controlled by CO₂ content) and hence our sense of well-being and ability to concentrate are affected when certain ppm levels are exceeded:
⇒ CO₂ is measured in volume % or ppm (parts per million)

The CO₂ content in normal outdoor air is approximately 0.040 volume % or 400 ppm.
### Table 4.1 CO₂ concentration and limit values

<table>
<thead>
<tr>
<th>Concentration [ppm]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>330...400</td>
<td>Concentration in normal outdoor air</td>
</tr>
<tr>
<td>1'000</td>
<td>Upon entering a room, 20% of people will be dissatisfied with the prevailing air quality</td>
</tr>
<tr>
<td>1'500</td>
<td>Limit value specified in DIN 1946</td>
</tr>
<tr>
<td>2'000</td>
<td>Sensitive persons complain of headaches</td>
</tr>
<tr>
<td>4'000</td>
<td>Maximum value in a classroom at the end of lessons</td>
</tr>
<tr>
<td>5'000</td>
<td>MAC value (Maximum Acceptable Concentration in the workplace)</td>
</tr>
<tr>
<td>100'000</td>
<td>Sufficient to extinguish a candle in the room and cause loss of consciousness</td>
</tr>
</tbody>
</table>

From a concentration of 1000 to 2000 ppm (parts per million = number of cm³ per m³) upwards, the pH of blood moves into the acidic range (reduced oxygen transport). Air quality cannot be determined directly via CO₂. However, it provides valuable guideline information on the air consumption or number of occupants in a room.

The CO₂ content of air can be determined using a CO₂ measuring element as a comparison value.

**Measuring principle**

With the CO₂ measuring principle utilizing the optical infrared-absorption measurement, the change of the wave length of an infrared light source by the CO₂-concentration will be measured (see Error! Reference source not found.).

This infrared light source ages whereby the radiated wave length changes. To maintain a stable and reliable measurement throughout the live time of the sensor, a comparison measurement with a second infrared light source is made sporadically. With that the measurement can be re-calibrated and the aging effect of the infrared light source can be compensated.

**4.4.2. VOC sensor**

Poor-quality air, which causes an unpleasant smell in the nose and is referred to as stale air, is mainly caused by so-called volatile organic compounds (VOC).

VOCs are contained in products containing solvents, such as adhesives, paints and varnishes, thinners as well as cleaning and care products. An effect like alcohol or narcotics is common to all organic solvents. Depending on the compound, tiredness and drowsiness can occur at various concentrations, and even nausea and headaches at higher concentrations. Humans also emit small quantities of VOC components into the room air:
- through respiration
- via sweat and other bodily secretions
- tobacco smoke

Without further signal processing, however, the commercially available VOC sensors are not sufficiently accurate or reliable for use in air conditioning applications, as we need to be able to measure even the smallest concentrations of VOC. However, with an intelligent algorithm, the VOC concentration can be adapted to the current quality of the supply air, and can then measure even very low concentrations of VOC reliably and stably.

**Measuring principle**

VOC levels are detected using a gas sensor based on the Taguchi principle (Fig. 4-15). Essentially, this consists of a sintered ceramic tube containing a filament. Flat-panel thick-film technology sensors have been developed in recent years. The sensor tube is highly porous and thus has a very large surface area. It consists of doped tin dioxide (SnO$_2$). This sensitive material works on the redox principle.

When the sensor tube is heated to 400 °C, free electrons form on the sensor surface. These attract oxygen atoms, which settle on the surface. Ideally, any gases or vapors coming into contact with the sensor surface will be oxidized, giving CO$_2$ and water vapor. In this process, the oxygen required for the oxidation process is removed from the sensor surface. This frees electrons, thereby changing the resistance of the semiconductor. This change in resistance can be measured. The oxygen used in combustion is replaced by oxygen from the air. The mixed gas sensor can thus detect all gases capable of oxidation in proportion to their concentration and redox potential.

The Taguchi principle of measurement has long been used with success for the detection of gas leaks. It has rarely been used for the measurement of air quality in HVAC systems. One reason, certainly, is that the required measuring range is at the lowest sensitivity zone of the Taguchi sensor, where the base value of the sensor signal is relatively widely scattered and subject to drift. Another reason is that, except in relation to CO$_2$, there is no technical literature with quantifiable and binding statements in relation to odor and air quality.

![Fig. 4-15 VOC measurement with gas sensor based on the Taguchi principle](image)

**Combined CO$_2$/VOC measurement**

Today, combined CO$_2$/VOC measurements are seen as the optimum solution for air quality control.
4.4.3. Fine dust

For some time now, more attention has been paid to particulate matter in rooms, which is why it is also measured with special probes in $\mu g/m^3$ for the particle size PM 2.5. If limits are exceeded here, it usually does not help to bring additional outside air into the rooms (which is often the reason for the increased load), but additional filters must be put into operation.

4.4.4. Other indicators

In relation to odor, the terms *olf*, *decipol* and *percentage dissatisfied* (PD) are used, derived from the Fanger’s theories. These variables cannot be measured like $CO_2$, but they do indicate the relationship between odor, the number of air changes and the degree to which occupants of a space find the air quality satisfactory. They cannot be used for control purposes, but are useful e.g. when defining setpoints (cf. Table 4.1, value for 1000 ppm $CO_2$).

*olf*

1 olf is equivalent to the air pollution caused by a “standard person”.

A “standard person” is an adult in a sedentary occupation, with a hygiene standard of 0.7 baths per day. The "olf" unit is used to indicate the pollution load caused by both objects and people. It is not a directly measurable variable: it can only be determined on the basis of the perceived air quality.

*decipol*

1 decipol represents the perceived air quality in a room with a pollution load of 1 olf and a ventilation rate of 10 l/s or 36 $m^3/h$. The decipol is the unit of measurement of perceived air quality.

*PD = Percentage Dissatisfied*

The perceived air quality is defined using data from a number of test persons, whereby the “percentage dissatisfied” is established on the basis of the number who find the air quality unsatisfactory. These values are recorded in relation to the outside air rate, which in turn, is related to the number of people occupying the space.

![Relationship of Percentage Dissatisfied (PD) to the outside air rate per person](image)
4.5. Pressure, volumetric flow and speed

Pressure is the quotient of the uniform force acting on a surface and the surface area on which the force acts: pressure = force/area in [N/m²].

The methods for measuring pressure can be classified as either direct or indirect. The former includes all devices that compare the measured variable with the pressure at the bottom of a column of liquid as well as manometric balances in which the pressure exerted on a piston or dome is compensated with known weights. Indirect pressure measuring devices use indirect-acting measuring elements to convert the measured pressure values to other, analog physical variables, such as travel, electrical voltage or electrical capacitance.

4.5.1. Measurement methods for volume flow

We differentiate between four different methods:

- Differential pressure measurement
- Speed measurement
- Bypass measurement
- Flow measurement

Each of these methods has technical and economic advantages to be weighted for each application. Refer to the table at the end of this chapter.

Below is a definition and brief explanation of each method, followed by a more detailed explanation of each method.

Differential pressure measurement

This method employs the direct relationship between pressure drop at flow resistance and volumetric flow. The basis is Bernoulli's equation supplemented by empirical correction factors, which describes the dependence of the flow's speed (prop. volumetric flow) of pressure.

Speed measurement

Speed is measured in one or several points within a flow cross section, allowing for calculating the volumetric flow.

Bypass measurement

In this measurement, by means of e.g. an orifice produces a pressure drop in the pipe cross-section. The flow measurement does not take place directly via this orifice, but in a smaller pipe, that runs parallel to the main pipe part (bypass). This bypass part is less directly exposed to the changes in the flow in the main part and also less susceptible to contamination.

Flow measurement

In this measurement, mostly based on the revolutions of elements in the flow (e.g., vane anemometer), the flow speed, and therefrom, the flow is measured.
4.5.2. Basics

In the following, a few definitions of different kinds of pressure as well as equations from fluid dynamics are repeated briefly.

4.5.2.1. Pressure

"Pressure" is a collective term for an entire family of different pressure types. This means that the term "pressure" alone does not indicate the type of pressure.

In general terms: "Pressure" $p$ is force $F$ acting perpendicularly on area $A$:

$$p = \frac{F}{A}$$

The following applies to liquid or gas columns of height $h$:

$$p = \rho \cdot g \cdot h$$

Pressure types

In all pressure measurements, the following different types of pressure must be distinguished:

- **Dynamic pressure**
- **Absolute static pressure**
- **Static overpressure**
- **Atmospheric pressure**
- **Total overpressure**
- **Vacuum**
- **Absolute total pressure**

**Static pressure**

Pressure acting on a particle entrained in a fluid flow at the speed of flow. Static pressure is measured perpendicular to the speed vector.

**Absolute static pressure**

Static pressure of a fluid with respect to the absolute vacuum.

**Static overpressure**

Absolute static pressure of a fluid minus atmospheric pressure.

**Dynamic pressure**

Pressure resulting from the kinetic energy of a fluid. Dynamic pressure is zero in a fluid at rest.

**Total pressure**

Static overpressure plus dynamic pressure.
Absolute total pressure
Absolute total pressure characterizes the energy state of a fluid after complete conversion of its flow energy into pressure energy. It represents the sum of the absolute static pressure and dynamic pressure.

Differential pressure
Pressure difference created by a flow resistance, which is used to measure the flow rate or flow speed.

4.5.3. Bernoulli’s equation
Bernoulli’s equation states that, in frictionless, steady-state fluid flows, the sum of the kinetic energy, potential energy and pressure is constant along a flow line. It is as follows for incompressible fluid flows:

\[ \frac{\rho}{2} \cdot v^2 + \rho \cdot g \cdot h + p = \text{const.} \]

<table>
<thead>
<tr>
<th>v</th>
<th>velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>height</td>
</tr>
<tr>
<td>p</td>
<td>absolute pressure</td>
</tr>
<tr>
<td>( \rho )</td>
<td>density</td>
</tr>
<tr>
<td>g</td>
<td>gravity of earth</td>
</tr>
</tbody>
</table>

4.5.3.1. Correction factor \( \varepsilon \)
Bernoulli’s equation assumes frictionless flow, which does not exist in reality. Therefore, the ideal calculation presented here must be modified to reflect the actual conditions using correction factors.

\[ \dot{V} = \alpha \cdot \varepsilon \cdot A_0 \cdot \sqrt{\frac{2}{\rho}} \left( p_1 - p_2 \right) \]

| \( \dot{V} \) | Volumenstrom |
| \( \alpha \) | flow coefficient |
| \( \varepsilon \) | correction factor |
| \( A_0 \) | cross-sectional area |
| \( \rho \) | density |
| \( p_1 \) | pressure before measurement site |
| \( p_2 \) | pressure after measurement site |

4.5.4. Outflow speed and mass flow
Outflow speed

\[ v_2 = v = \sqrt{\frac{2(p_1 - p_2)}{\rho}} = \sqrt{\frac{2 \Delta p}{\rho}} [\text{m/s}] \]

<table>
<thead>
<tr>
<th>v</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>Density</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>pressure before measurement site</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>pressure after measurement site</td>
</tr>
</tbody>
</table>

Mass flow
The mass flow \( \dot{m} \) at cross-section \( A \) is calculated from:

\[ \dot{m} = A \cdot v \cdot \rho = A \cdot \sqrt{2 \Delta p \rho} [\text{kg/s}] \]

<table>
<thead>
<tr>
<th>( \dot{m} )</th>
<th>Mass flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Cross-sectional area [m²]</td>
</tr>
<tr>
<td>( v )</td>
<td>Outflow speed [m/s]</td>
</tr>
<tr>
<td>( \Delta p )</td>
<td>(( p_1 - p_2 )) differential pressure [N/(m²)]</td>
</tr>
</tbody>
</table>
4.5.5. Differential pressure measurement

4.5.5.1. Principle

In flow measurement by the differential pressure method, the cross-sectional area of the pipe is reduced at a single location, which increases the flow speed at the same volume flow rate. The most important basic physical principles of the differential pressure method are provided in the following.

4.5.5.2. Flow resistance

In Fig. 4-21, we used the "pressure and flow progression at an orifice" picture as the most simple illustration for flow resistance. In fact, however, the differential pressure method is not limited to a given type of flow resistance.

Terminology

"Flow resistance" is often used in theoretical considerations. The term "throttling device" is frequently encountered in practice.

In practice...

The following are particularly suitable as flow resistances:

- Orifice
- Nozzle
- Venturi nozzle

We will discuss the properties of these three flow resistances in the following.

Orifice

Most simple type of flow resistance (suitable for differential pressure measurement).

Application

Standard orifices can be used for the following:

- Pipe diameter D in the range 50…1000 mm
- Opening ratios β (d/D) of 0.05 … 0.64

![Fig. 4-21 Pressure and flow progression at an orifice](image-url)
A typical feature of orifices is the contraction of the airflow in the orifice. The amount of contraction, expressed by contraction coefficient $\beta$ (diameter ratio $d/D$), has a decisive influence on the empirically measured flow coefficient $\alpha$, which in turn also depends on the Reynolds number $Re$.

**Average differential pressure measurement ("Annubar measurement")**

The Annubar flow measurement works with a measuring device, which leads across the entire pipe cross-section and makes an average (average) differential pressure measurement. This serves as the basis for the speed measurement resp. derived volume flow measurement.

### 4.5.6. Speed measurement method

**Point measurement**

All speed measurement principles have one thing in common: They measure speed $w$ only at a single point in the pipe or duct cross-section. Annubar flow measurement is an exception.

**Average speed**

As you know from the theory, the speed is not the same everywhere. If the laws of fluid dynamics are observed, i.e. if a sufficiently long inlet and outlet is provided, the average speed can be calculated by the following approach.

\[ v_{avg} = v_{measured} \times (0.8...0.85) \]

**Measuring point selection**

Another approach is the selection of the measuring point in the cross-section. It can be determined as follows. However, the laws of fluid dynamics must also be observed here.

Measuring point $\approx 0.119 \times D$

$D$: Pipe diameter

The measurement expense becomes considerably greater if you want to determine the volume flow rate more precisely, or if there is no fully developed flow.

**Note:**

Precise measurements can only be achieved with grid measurement covering the different speeds over the entire cross-section.
Grid measurements

Speed measurements by the grid method in a defined pipe or duct cross-section can be performed by one of the following procedures. They are applied under the following conditions in particular: Non-uniform speed distribution, and therefore also a shortened inlet section.

Trivial methods

All methods of measurement are referred to as trivial where no particular assumptions can be made about the speed profile. The speed profile is measured point-by-point on any number of measurement lines. The number of measuring points depends on the cross-sectional area and on the expected speed profile.

Fig. 4-23 Division of a rectangular cross-section into equally large measurement areas (o: measuring points)

In rectangular cross-sections, the measurement cross-section can be divided into areas of equal size.

The centroidal axis method (next section) should be applied for circular and annular cross-sections.

Centroidal axis method

The centroidal axis method should be applied for circular and annular cross-sections. With this method, the measuring points are selected such that they are on the centroidal axes covering circular segments of equal area.

The average speed is obtained by calculating the arithmetical mean of the individual measured values.

Fig. 4-24 Division of a circular cross-section into circles of equal area

- A: Circle of area $F_A$
- B, C, D: Concentric annuli of equal area
- $y_n$: Distance from wall

Reason why measurement is performed on the centroidal axes and not at the middle of the annuli:

The measured speed corresponding to the average speed of the respective segment is assigned to each circular segment area.

The diameter of the centroidal axes is greater than the middle of the annulus. If the internal and external surface area are multiplied by the speed, the volume share is equal for both sections.
### 4.5.7. Volumetric flow measurement

In addition to temperature, humidity, and pressure, volumetric flow is an important variable for acquisition in HVAC technology. We differentiate between:

- volumetric flow $\dot{V}$ per time unit with SI unit $\text{m}^3/\text{s}$ and
- mass flow rate $\dot{M}$ per time unit with SI unit $\text{kg/s}$.

#### Equation of continuity

The continuity equation is based on the assumed incompressibility of the flowing medium (unchangeable density $\rho$):

$$\dot{V} = A_1 \cdot v_1 = A_2 \cdot v_2 = \text{const.}$$

| $\dot{V}$ | Volumetric flow | [m$^3$/s] |
| $A$ | Cross-section | [m$^2$] |
| $v$ | Speed | [m/s] |

If pressure $\rho$ changes during the flow, the mass flow rate $\dot{m}$ must be employed for calculation:

$$\dot{m} = A_1 \cdot v_1 \cdot \rho_1 = A_2 \cdot v_2 \cdot \rho_2 = \text{const.}$$

| $\dot{m}$ | Mass flow | [kg/s] |
| $A$ | Cross-section | [m$^2$] |
| $v$ | Speed | [m/s] |
| $\rho$ | Density | [kg/m$^3$] |
4.6. Measurement in gases/air and fluids

4.6.1. Prandtl's pitot tube

The pitot tube measures total pressure and static pressure. The difference between them is the dynamic pressure, from which the speed can be calculated according to the following formula:

$$p_{\text{dyn}} = \frac{\rho \cdot v^2}{2}$$

- \(p_{\text{dyn}}\): Dynamic pressure
- \(\rho\): Density
- \(v\): Speed

Fig. 4-25 Pressure measurement using a pitot tube

Bernoulli’s equation

If there is a change of cross-sectional area in a duct, the static pressure rises or falls. The dynamic pressure changes in the opposite direction, because the speed varies according to the new cross-sectional area. If friction is neglected, Bernoulli’s equation applies along a flow stream:

$$p_{\text{ges}} = p_{\text{stat}} + p_{\text{dyn}} = \text{const.}$$

With the terms \(P_{\text{stat} \ 1}\), \(v_1\) and \(P_{\text{stat} \ 2}\), \(v_2\) the equation is as follows:

$$p_{\text{stat} \ 1} + \frac{\rho \cdot v_1^2}{2} = p_{\text{stat} \ 2} + \frac{\rho \cdot v_2^2}{2}$$

- \(P_{\text{stat}}\): Static pressure
- \(\rho\): Density
- \(v\): Speed

The differential pressure \(\Delta p\) results as:

$$\Delta p = p_{\text{stat} \ 1} - p_{\text{stat} \ 2} = \frac{\rho \cdot v_2^2}{2} - \frac{\rho \cdot v_1^2}{2}$$

- \(\Delta p\): (\(P_{\text{stat} \ 1} - P_{\text{stat} \ 2}\)) differential pressure

From the differential pressure, the speed and mass flow can be calculated with the mass continuity equation (see continuity equation above).
Pressure losses due to friction

In a ventilation system with obstructions, deflections, etc., pressure losses occur due to friction, which the fan must overcome by increasing the static pressure. The following picture shows a typical pressure progression in such a system.

4.6.2. Inclined-tube manometer

As relatively low-cost devices, inclined-tube manometers are used for pressure measurement in HVAC. Their advantages are a compact design, relatively high precision, and reliability.

Principle

Most important values of commercially available inclined-tube manometers:
- Pressure range: 0…750 Pa
- Reading accuracy: 3…10%

The pressure difference is determined by the fluid’s hydrostatic pressure.

\[
P = \rho \cdot h \cdot g
\]

Caution: Note the medium’s density.
4.6.3. U-tube manometer

The U-tube manometer consists of a U-shaped glass tube filled with a colored liquid of known density (Fig. 4-29). To perform the measurement, one or both of the limbs are connected to the respective measuring points. The pressure or pressure difference gives rise to a difference in the height of the liquid in the two limbs of the U-tube.

![U-tube manometer](image)

Practical application of the U-tube manometer: Measuring low pressures or pressure differences (1-1000 Pa, e.g. for filter monitoring).

4.6.4. Closed-ring manometer

The closed-ring manometer shown in Fig. 4-30 (ring balance) is a ring that is half filled with a sealing liquid and mounted on a rotating bearing. The pressure difference acting on the separating wall (3) causes a deflection of the ring until the lifted weight (2) gives rise to a corresponding counter-torque.

![Closed-ring manometer](image)

Practical application of the closed-ring manometer: Measuring low pressures or pressure differences, e.g. for monitoring operating rooms (e.g. 20 Pa).

4.6.5. Elastic pressure meters

Pressure measuring devices contain measuring elements that may deform elastically under density. This movement is transferred to a dial train.

Depending on the application, devices featuring tubes, diaphragm or capsule element gauge systems are better suited.
**Tube spring system**

![Fig. 4-31 Tube spring system, Bourdon tube pressure gauge MAN-R (Source: Kobold)](https://commons.wikimedia.org/wiki/File:Bourdon_tube_pressure_gauge_glass_front.jpg)

The measuring element consists of a flat pipe closed at the end and curved to an arc of a circle of ca. 270°. If the interior is pressurized, the oval cross section puts pressure on the arc, effecting a larger radius of curvature. As the tube spring is finally anchored at the open ending, the changes to the radius of curvature result in a shift of the tube end. This change is indicated via a lever and rotary system.

**Diaphragm pressure system**

![Fig. 4-32 Diaphragm pressure gauge system MAN-P (Source: Kobold)](https://commons.wikimedia.org/wiki/File:Diaphragm_pressure_gauge.jpg)

These measuring devices contain a measuring element made from a springy metal plate attached to the circumference between flanges. If the pressures at both sides of the diaphragm differ, the diaphragm curves to the corresponding side in accordance with the pressure difference.

Fig. 4-32 shows two cross sections with a) vertical and b) horizontal diaphragms and one-sided pressure connection. Adding a pressure connection to the second side and sealing the pressurized space against atmosphere results in a diaphragm pressure difference measuring device. Measuring devices with vertical arrangement offer better transfer possibilities and can also be integrated in panels. For measuring ranges below 1000 Pa, the diaphragm's stroke is insufficient and a capsule element gauge system must be employed.
Capsule element gauge system

Fig. 4-33  Capsule element gauge system Capsule element gauge MAN-K (Source: Kobold)
Measured range: e.g. 0...250 mbar

The measuring devices consists of two interconnected diaphragms as shown in Fig. 4-33. One diaphragm is fixed; as a result, the second diaphragm doubles stroke for pressure changes.

4.6.6. Spring loaded diaphragms and bellows

In this measuring system, the pressure to be measured is converted to a force by a slack diaphragm or metal bellows, whereby the force acts on a helical spring (Fig. 4-34). Suitable materials for slack diaphragms are, for example, rubber, leather and highly flexible plastics.

When pressure \( p \) acts on diaphragm surface \( A \), the spring is compressed until the spring force equals the resultant force of \( p \cdot A \). The stroke of the helical spring is proportional to the pressure or measuring force, i.e. there is a linear relationship between pressure and spring travel. The travel of the spring is transferred to a pointer, recording pen, plunger coil or voltage divider.

With double-sided pressurization of the slack diaphragm, differential pressures can be measured.

Measuring range

Slack diaphragm pressure gauges are generally suitable for measuring positive, negative and differential pressure with measuring ranges between 0...50 Pa and 0...3000 Pa.

The field of application in HVAC is very broad, ranging from filter and drive belt monitoring to measuring apparatuses for pressure control in ventilation systems.
4.6.7. Using electric effects (in gases and liquids)

There are various methods of electrically measuring pressure. For example, the resistance of a wire changes with pressure. The relationship between pressure and resistance is linear and for some materials the resistance is also temperature independent. This measuring technique was earlier used to measure high pressure from 300 to 3000 kPa.

A further method relies on the pressure dependence of the surface resistance of conductors. To increase the conductor surface area (mostly carbon in laminate form) the laminates are molded into a pile. Errors in the region of ±1 – 3% can be reached if very precise production methods are used. Measuring devices which apply this methodology are especially suitable for recording quickly changing pressures because of the high natural frequency.

Piezoresistive system

These method applies the effect that crystals such as quartz, turmaline, Rochelle salt, amongst others have the property that they can be charged with electricity proportional to the pressure on their surface. Quickly changing pressures an pressure oscillations can be easily recorded using these methods. When the charge is very small then the potential difference must be amplified. Further, this method may be used applying various laminates in layers in order to reach a higher charge by using a larger surface area.

- Piezoresistive measuring system
- Output signal DC 0 … 10 V
- Sensor completely encapsulated in a cast synthetic resin
- Unaffected by temperature
- High temperature stability
- No mechanical aging or creepage

![Piezoresistive measuring system](image)

**Application**

These pressure sensors are suitable for the measurement of static and dynamic positive and negative pressures in HVAC applications, particularly in hydraulic and refrigeration systems using liquid or gaseous media. The sensor operates on piezoresistive measuring principles.

The ceramic diaphragm (thick-film hybrid technology) measures the pressure through direct contact with the medium. The measurement is converted electronically into a linear output signal of DC 0 … 10V.
4.6.8. Vane anemometer

In ventilation/air conditioning systems, volumetric flow measurement normally is as described in Fig. 4-25 via dynamic pressure, or via hot wire or vane anemometer. In a vane anemometer, there is ideally the following relationship between peripheral speed \( v_U \) and air speed \( v \):

\[
v_U = v \cdot \tan \alpha
\]

\( \alpha \) Angle of attack between vane and flow direction

Properties

In case of rapid speed variation, vane anemometers measure an excessively high average value. Additionally, correction is required in case of great changes of density. A density change of some 10% gives rise to a speed measurement deviation of approximately 5%.

If a vane anemometer is used in small pipe diameters \( A_k \) where the ratio of the effective anemometer cross-section \( A_g \) to the pipe cross-section is greater than 0.01, correction is required according to the following formula

\[
V_{\text{eff}} = \frac{A_k - A_g}{A_k} V_{\text{displ}}
\]

\( V_{\text{eff}} \) Effective speed
\( A_k \) Pipe cross section
\( A_g \) Effective cross-section
\( V_{\text{displ}} \) displacement speed

Vane anemometers are especially suitable for quick checks on the plant and for measuring speeds in excess of 1 m/s.

Fig. 4-36 Vane anemometer (Source: Schiltknecht)

4.6.9. Hot-wire anemometer

The flow of air past an electrically heated sensor cools it down, so that the sensor's temperature provides a measure of flow speed at constant heating power, or the heating power provides a measure of flow speed at constant temperature.

Properties

Hot-wire anemometers have a short response time, and are especially suitable for low speeds from 0.1 ms\(^{-1}\). Thermal probes have a robust design, so their response time is longer, otherwise the same conditions apply as to hot-wire anemometers. Temperature compensation and dust pollution are a particular problem. Hot-wire anemometers are highly sensitive measuring instruments, and they should be treated as such.
Important

- In the case of low-turbulence flow (e.g. in clean rooms) greater room airflow speeds are permissible than with highly turbulent flow.
- Generally speaking, greater room airflow speeds are permissible at higher room air temperatures than at lower room air temperatures.

4.7. Measurement in fluids

We differentiate between two methods to measure volumetric flow in fluids:

- Still medium
- Flowing medium

Still medium

Fluids in containers can be measured indirectly. To this end, the level and the current fluid volume are determined via the known maximum container volume.

Possible procedures:

- Inspection glass
- Swimmer
- Conducting capacity

Flowing medium

Normally, the time-dependent flowing volume of the flowing medium, i.e. the flow volume, is of interest.

Possible procedures:

- Filling chamber meter
- Displacement meter
- Flow speed measuring equipment
4.7.1. **Filling chamber meter**

In this method, the medium to be measured flows into a measuring chamber. When full, the medium is transported out of the chamber to the next destination and the chamber is refilled.

![Diagram of Drum meter](image)

**Fig. 4-38 Drum meter**

1. Inlet
2. Direction of flow
3. Measuring chamber
4. Outlet

4.7.2. **Displacement meter**

The measuring device features a movable chamber driven solely by the flowing medium, whereby the number of rotations is counted.

![Diagram of Oval wheel meter](image)

**Fig. 4-39 Oval wheel meter (function)**

**Flow speed measuring equipment**

In this method, the flow volume is determined via flow speed and a given flow cross section. When measuring the speeds, applicable influences of laminar or turbulent flow forms must be noted, as the speed profile in these flow pipes differs. Also, pressure losses in the fluid must be accounted for during measuring. There are many ways to determine the throughput rate.

4.7.3. **Oval wheel meter**

The medium flows tangentially onto a vertically positioned wheel whose number of rotations is transferred directly to a dial train (or indirectly via magnetic coupling) by means of a gear train. The result is displayed in volume or speed units.

We differentiate between single or multi-beam meters.
4.8. Heat volume measurement

As energy consumption and saving are also subject to laws, measuring heat volumes is an important function of building automation and control.

Heat volume $\dot{Q}$ is measured (indirect) via the product of flow and temperature difference with the following formula:

$$\dot{Q} = \dot{m} \cdot c \cdot \Delta T$$

| $\dot{Q}$ | J/s = W |
| $\dot{m}$ | kg/s |
| $c$     | J/(kgK) |
| $\Delta T$ | K |

Electronic meters determine the volumetric flow by means of electrical impulse generators such as impeller wheel meters with induction flow meter or ultrasound measuring devices. The flow and return temperatures are acquired via resistance thermometers. An electronic computing system processes the signals to form the product and digitally display the values followed by possible data recording.
Fig. 4-42 Diagram of a district heating relay station
above: with direct feed
below: with indirect feed (without heat exchanger)

A Distribution network connection 1 Heat meter (normally integrated in return)
B Relay station 2 Differential pressure controller
C Internal consumer circuit 3 Secondary flow temperature control
4 Heat transfer

Fig. 4-43 Electronic heat meter (Source: Siemens)
4.9. Solar radiation sensor

Principle
In order to determine solar radiation, the sensor uses two measuring elements which both measure the ambient temperature. One measuring element is exposed to the sun, the other is covered. The difference between the two measured temperature values is directly proportional to the solar radiation. It is amplified by an electronic circuit and output as a DC 0 - 10 V signal which corresponds to a solar radiation of 0 - 1000 W/m². The sensor must be installed at least 3 m above ground at a suitable mounting location.

![Sensor to measure solar radiation](Image)

Application
The solar radiation sensor is used as reference sensor in heating, ventilation and air conditioning plants intended to employ solar radiation compensation. This is required in buildings with large windows or with large areas exposed to direct solar radiation, especially if thermostatic radiator valves cannot be employed.

4.10. Wind sensor

![Wind sensor](Image)

Application
The wind sensor is employed as a reference sensor in heating systems with planned wind reference conduction which is necessary in buildings or for building parts exposed to strong winds that lead to significant impact on room temperature.
5 Placement and installation of sensors

The following section will help you to recognize and avoid the most common mistakes in sensor placement. Firstly, a general overview of fluid flows, pressure ratios and measurement methods will be given. Secondly, recommendations for correct placement and installation of sensors, that measure speed and pressure in pipes, are given.

The purpose of this chapter is to:

- show the professional placement of sensors – mainly with regard to speed and pressure measurement,
- point out the most common sensor placement errors.

High-precision indication for fuzzy data

It has become a matter of course in modern control equipment to indicate the actual values of various physical variables to at least one decimal place (e.g. temperature, humidity, pressure, etc.). With such highly developed equipment, correct measured value acquisition seems to be automatically taken for granted.

The reality of the matter is, in fact, rather different. Sensor placement still remains a critical point of failure in the control loop. In the following, we will attempt to point out common points of failure from practical experience in order to prevent operating faults, poor operating behavior, inefficient functions, elevated energy consumption or incomplete utilization of potential energy savings.

5.1. Flow patterns, speed profile

Liquids and gases basically exhibit two different flow patterns:

Laminar flow

In the case of laminar flow, the flow streams are maintained. The individual layers glide over each other giving rise to a parabolic speed profile.

Fig. 5-1 Speed profile with laminar flow

Turbulent flow

In the case of laminar flow, the flow streams decay and are lost. Lateral and mixing motion occurs. The middle areas supply energy to the outer layers. The slower outer particles migrate inwards, where they have a braking effect. This makes the speed profile more uniform.

Fig. 5-2 Speed profile with turbulent flow

Critical speed

In a given pipe, the transition from laminar flow to turbulent flow occurs at a certain critical speed ("critical Reynolds number"), cf. e.g. "Recknagel - Taschenbuch für Heizung + Klimatechnik 78". Ausgabe 2017/2018".

Laminar flow is relatively rare in the HVAC field. It is desirable in ventilation systems, because it is quiet, but it is undesirable in heat exchangers, because it decreases heat transmission.
Volume flow measurement

The volume flow rate is calculated by multiplying the average speed as determined from the speed profiles by the cross-sectional area. If a speed sensor is intended for volume flow measurement, the respective speed profile must be determined. This is done with the aid of pitot tubes, vane anemometers, thermoelectric anemometers and other devices that are positioned at a series of measuring points over the entire cross-section of the pipe or duct.

This picture shows an excerpt from a measurement sheet for a circular cross-section. At least 10 measuring points are required.

A rectangular or other cross-section is divided into sections of equal surface area.

Measurement is performed at the center of gravity of each section.

Fig. 5-3 Measurement sheet for a circular cross-section (excerpt)

5.2. Time constant of sensors in liquids

For measurements in pipes, sensors are installed in immersion sleeves.

The immersion sleeve constitutes the first time-delay element, and the air between the immersion sleeve and measuring element the second. The third time-delay element is the time constant of the sensor.

Of these three sequential delays, the one caused by the air gap between the immersion sleeve and the sensor is the greatest, because the thermal conductivity of air is poor. This poor response characteristic can be vastly improved by filling the air gap with heat transfer paste.

5.3. Placement of a sensor

For the placement of a sensor, a location must be chosen that meets the following criteria:

- Optimum measuring location in control terms
- Accessible for electrical staff
- Accessible for commissioning
- Accessible for checking and service

The illustrations in Fig. 5-4 to Fig. 5-6 provide installation tips for correct placement of various sensors.
5.4. **External interference**

Sensors must be installed and connected in such a way that the sensor signal is not permanently or intermittently falsified by external interference. This can introduce external interference into the measurement:

- electrically: via the sensor leads, and/or
- physically: via incorrect measured values

**Connections**

Sensor leads must be selected and installed according to the specifications of the control supplier.

**Sealing**

The conduits for the sensor leads (plastic pipe/high-strength conduit) can cause an airflow to the measuring location, which falsifies the measured value (e.g. by cooling the temperature sensor). Therefore, such conduits must be sealed.

**Requirements on control**

The requirements on the control system (stability, tolerance etc.) determine whether point measurement (with the appropriate sensors) is sufficient or whether averaging measurement is required.

**Note:**

Averaging measurement is always necessary if measurements have to be taken in stratified media.

5.5. **Measurement problems**

**Stratifications**

The most common measurement problems are caused by temperature stratification. Temperature stratification occurs in all air treatment processes (heating/cooling, humidification/dehumidification, convergence of two air flows). Stratification also occurs with other physical variables (e.g. humidity, fluid flow, pressure, etc.).

Stratification is only eliminated to a limited degree by the fans, and the ductwork network is also barely able to mix stratified air (e.g. angles/T-pieces with baffles). The results of stratification are as follows:

- Uneven loading of filters (partial icing or soiling of individual filter cells)
- Uneven utilization of heat exchanger surfaces, uneven air outlet temperature
- Poor control response, frost hazard, frost alarm
- In case of radial fans with double-sided intake, temperature stratification in the pressure-side ductwork right up to the air outlets (one side of the room cold, the other warm)
### 5.6. Examples of sensor placement

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td>Each sensor should have a tightly sealable measuring port</td>
</tr>
<tr>
<td><img src="image2" alt="Diagram" /></td>
<td>Connect cable from below to prevent the ingress of water into the sensor housing</td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td>Immerse the entire active length of the sensor in the medium</td>
</tr>
<tr>
<td><img src="image4" alt="Diagram" /></td>
<td>Incorrect installation</td>
</tr>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td>Install against the direction of flow</td>
</tr>
<tr>
<td><img src="image6" alt="Diagram" /></td>
<td>Incorrect installation</td>
</tr>
<tr>
<td><img src="image7" alt="Diagram" /></td>
<td>Note inclination</td>
</tr>
<tr>
<td><img src="image8" alt="Diagram" /></td>
<td>File the contact surface bare, and fill the gap between the sensor and pipe with thermolube in order to improve thermal conduction</td>
</tr>
<tr>
<td><img src="image9" alt="Diagram" /></td>
<td>The entire length of a rod sensor must be exposed to the airflow</td>
</tr>
<tr>
<td><img src="image10" alt="Diagram" /></td>
<td>Do not use rod sensors where stratification can occur (e.g. downstream of mixing dampers, heating coils, coolers or HRUs) – see averaging sensors</td>
</tr>
<tr>
<td><img src="image11" alt="Diagram" /></td>
<td>Each sensor should have an inspection port</td>
</tr>
</tbody>
</table>

Fig. 5-4  **Sensor placement examples**
<table>
<thead>
<tr>
<th>Minimum distance between heat exchanger and sensor: 50 mm</th>
<th>With mean value sensors, the entire sensor length must be installed in the air duct</th>
<th>Distribute the sensor element evenly over the entire cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Install the sensor at a height of approx. 1.5 m in the occupied zone and at least 50 cm from the next wall</td>
<td>Not where the sensor can be exposed to direct sunlight!</td>
<td>In case of solid walls (steel, concrete, etc.) a heat-insulating backing is mandatory</td>
</tr>
<tr>
<td>Not in the immediate vicinity of a door!</td>
<td>Not on walls behind which hot water pipes are located!</td>
<td>Seal plastic pipes/high-strength conduits! (draughts occur in these pipes)</td>
</tr>
<tr>
<td>The installation location with regard to aspect is determined by the system concept</td>
<td>Do not expose to direct sunlight!</td>
<td>Do not install on facades with major thermal convection (metal)! Not on facades that are heated up by solar radiation!</td>
</tr>
</tbody>
</table>

**Fig. 5-5** Sensor placement examples

**Fig. 5-6** Sensor placement examples - mixing distance

Maintain a sufficiently large distance between mixing point and sensor downstream of where water flows of different temperature are mixed (because of stratification)
5.7. Temperature measurement in water

Mixing!
The decisive factor for the quality of measuring equipment in flowing media is primarily good mixing at the measuring point. A secondary consideration is the distinction between immersion sensors and clamp-on sensors.

Criteria for determining the measuring point
A few criteria for determining the measuring point are listed below:

- At least 1 m downstream of the mixing point, e.g. globe valve or mixing valve
- Always downstream of the circulation pump (however the turbulence in a circulation pump does not automatically guarantee good mixing)

For immersion sensors
- Immersion depth at least to the middle of the pipe
- Wherever possible, install the immersion sensor in a bend with the direction of flow against the sensor

For clamp-on sensors
- Bare metal pipe surface for optimal heat transmission at the sensing element
- Tight mechanical connection using a clamping band
- Thermo-lubricant only according to the measuring equipment manufacturer's recommendations
- Give preference to a straight section of pipe instead of an elbow
- Where possible, integrated into the pipe insulation or at least directly enclosed

Pitfalls
- Pipe insulation thickness and electrical connection (draught through the conduit)
- Nominal pipe sizes with storage behavior
5.8. Temperature measurement in air

Air is more difficult!

For temperature measurement in air, the same basic requirements apply as for measurement in water. However: these requirements are many times more difficult to meet in air than in water – in ducts because of the much larger dimensions and isothermal flow conditions, and in free-flowing air (outdoor air temperature, room temperature) due to additional flow disturbances.

Summary

Temperature sensors for air can be roughly classified according to technology and mechanical design:

- Rod sensors
- Cartridge sensors with capillary tube – averaging sensors
- Room sensor – outdoor sensors
- Wind influence sensor – solar sensors

Mounting properties

- Unlike sensors for liquid media, the technology of air temperature sensors allows them to be mounted in any position.
- Since the probes of some of the sensors are considerably more extensive because of their intended use, special attention must be paid to the respective criteria.

Criteria for determining the place of installation (overview)

Different types and technologies require different places of installation. Observe the following criteria for the most important air temperature sensors:

<table>
<thead>
<tr>
<th>Typ</th>
<th>Symbol</th>
<th>Bei der Montage beachten</th>
</tr>
</thead>
</table>
| Stabfühler        | ![Symbol] | • Vollständige Umströmung des Fühler-Elementes mit dem zu messenden Medium  
|                   |        | • 1 Kontroll-Messloch je Fühler  
|                   |        | • Keine Stabfühler verwenden bei möglichen Schichtungen (z.B. nach Mischklappen, Lufterhitzern, Kühlern) |
| Kapillarrohrfühler | ![Symbol] | • Gerätekopf stets höher als Fühlerpatrone installieren  
|                   |        | • Fühlerpatrone nach unten neigen  
|                   |        | • Umgebungstemperatur am Apparatekopf muss größer sein als jede der Fühlerpatrone |
| Mittelwertfühler  | ![Symbol] | • Distanz Wärmetauscher – Fühler min. 50 mm  
|                   |        | • Gesamte Fühlerlänge muss in den Luftkanal  
|                   |        | • Fühlerenteil gleichmäßig auf den gesamten Querschnitt verteilen! |
| Raumfühler        | ![Symbol] | Raumfühler montieren Sie  
|                   |        | • Auf ~1.5 m Höhe in der Aufenthaltszone  
|                   |        | • Min. 50 cm von der nächsten Wand  
|                   |        | • Nicht der Sonnenbestrahlung ausgesetzt  
|                   |        | • Bei Massivwänden wärmedämmt  
|                   |        | • Nicht an Außenwände, Nischen oder Gestelle  
|                   |        | • In der Nähe von Zuleitungsrohren (z.B. Elektroleitungen) nur montieren, wenn diese vollständig abgedichtet sind. |
Table 5.1 Air sensors

<table>
<thead>
<tr>
<th>Außenfühler</th>
<th>Anlegefühler</th>
</tr>
</thead>
<tbody>
<tr>
<td>· Nie direkter Sonnenbestrahlung aussetzen</td>
<td>· Montage-Oberfläche muss blank sein</td>
</tr>
<tr>
<td>· Nie auf Fassaden mit großer Auftriebswärme montieren</td>
<td>· Fühler muss fest anliegen</td>
</tr>
<tr>
<td>· Nicht über Lüftungs-Austrittsöffnungen montieren</td>
<td>· Immer Wärmeleitpaste zwischen Fühler und Montage-Oberfläche verwenden</td>
</tr>
</tbody>
</table>

5.9. Measuring the outdoor air temperature or weather

The good old days…
The statement "always install the outdoor sensor on the north side", which used to be generally applicable in the heating industry is certainly no longer valid as such today, but must be considered in a more differentiated light. Observe the following criteria:

Criteria for a favorable place of installation
- Representative for the interior of the building or for the application within the building (e.g. zoning – south zone – or base load method)
- For individual room control or zone control without a clear zone assignment: N-E (basic supply)
- Up to 3 floors: 2/3 building height
- More than 3 floors between 2nd and 3rd floor
- Observe the manufacturer's instructions for wall mounting (e.g. on the wall, against the wall, in the wall).
- Avoid all obstacles to the airflow (e.g. projecting walls, balconies, etc.)
- Watch out for internal heat influence from windows and exhaust air outlets.
- Not in the outdoor air duct (behind outdoor air dampers) or
- Take start-up response into account.

Pitfalls
Dynamic effects of shadows, warm flows or incorrect flows.
5.10. Temperature measurement in air ducts

Mixing!
The basic requirement of good mixing as already mentioned in the context of water temperature sensors applies equally to duct temperature sensors.

Inversion
Depending on the operating mode and season, different isothermal conditions can be encountered, especially in the case of central air treatment. The main causes are the mixing chamber and any heat exchanger: although the stratification caused by the mixing chamber can dissipate downstream, the temperature conditions of a heating coil or cooler can produce new layers. Depending on the magnitude of the temperature spread, the rotary action of the fan is often not sufficient to eliminate it. In meteorology, this phenomenon is referred to as "inversion", which can give rise to very stable conditions. If the conditions are unclear, determine the measuring point via multiple temperature measurements over one or more duct cross-sections using a mobile probe.
Pitfalls

- Unfavorable mixing chamber configuration
- Rod sensor length

Nicht-isotherme Strömung


Fühler in der Nähe lufttechnischer Aggregate


Temperaturverteilung

Die Temperaturverteilung nach einem Lufterhitzer wird im Wesentlichen durch die wasserteitige Temperaturspreizung bestimmt. Entsprechende Rohrschaltungen innerhalb des Wärmetauschers und einer Mischtururregelung verringern die Gefahr einer Schichtung.

Stolpersteine

- Durchschnittsfühler bei Schichtungen.
- Fühler in der Nähe lufttechnischer Aggregate.

Montageort eines Kanaltemperaturfühlers:

- Gerader Luftkanal, ohne Temperaturschichtung bzw. Strahlungseinflüssen
- Nach Luftwäsichern Mindestabstand 1 m bei guten Tropfenabscheidern, sonst entsprechend länger.
- Nach Dampfbefeuchtung Abstand abhängig von Befeuchtungsgrad und Luftgeschwindigkeit (Herstellerangaben berücksichtigen).

Fig. 5-12 Mixing of outdoor air and recirculated air
### Siemess devices from practice: QAM22

![QAM22 sensor](image)

**Fig. 5-14 QAM22 duct sensor (Source: Siemens)**

### Placement

- **For supply air temperature control**
  - If a fan is installed downstream of the last air treatment element: downstream of the fan
  - If no fan is present, or it is not situated downstream of the last air treatment element: downstream of the last air treatment element at a distance of at least 0.5 m!

- **For extract air temperature control**, always upstream of the extract air fan
- As a limit sensor for supply air, as close as possible air inlet into the room
- For dew point control, directly downstream of the air washer's drip screen

### Note:

- Manually bend the sensor rod such that it runs diagonally through the duct, or
- Draw the sensor rod in equidistant loops across the entire duct cross-section.
- The sensor rod must not touch the duct wall.
5.11. Room temperature measurement

Occupied zone
Room temperature control normally pertains to the occupied zone of a room. The occupied zone is difficult to reach in many cases, because a sensor can only rarely be placed in the center of the room.

Place of installation
Therefore, the following applies to the place of installation:
- Install at the edge of the occupied zone.
- Avoid unfavorable locations, such as heat sources (radiator, secondary heat sources, electrical equipment, etc.).
- Air circulation must be guaranteed, so do not install sensors in alcoves.
- Avoid direct sunlight.
- Do not place on surfaces with greatly varying temperatures (flue walls, exterior walls).
- Do not install in direct draughts.

Pitfalls
- Flow changes depending on plant operating state (fan coil units).
- Moving solar irradiance.
- Ingress of lower-temperature air through wiring conduits
- Thermostatic valves
- Wall influence

Places of installation

![Fig. 5-15 a: Room sensor installation](image1)

![Fig. 5-15 b: Room sensor installation (NOT like this!)](image2)

![Fig. 5-16: Room sensor without and with display (Source: Siemens)](image3)
5.12. Speed measurement

5.12.1. Speed measurement devices

Vane anemometers
In the case of vane anemometers, there is a choice of several manufacturers. Devices made by Schiltknecht are frequently used. They are very practical and user-friendly.

+ The advantage over the pitot tube is the direct speed read-off.

Average speed value
Additionally, devices that enable the average speed value to be determined are also available commercially.

+ Another practical feature is the measuring range switchover, which enables speeds in the lower range, i.e. < 1 m/s, to still be read off properly.

Thermoelectric anemometer
The thermoelectric anemometer is especially suitable for low speeds below 5 m/s.

+ Even values down to a few cm/s can be measured.
+ This device is mainly suitable as a complement to measuring devices for higher speeds.

Digital indication and instantaneous values
Devices with digital indication of instantaneous values are mainly suitable for constant speeds. In the case of varying speeds, however, it is not easy to read off the values. Conventional devices with dial gages generally permit better estimation of the average value than the rapidly changing numbers on a digital display.

Wind tunnel measurements
The following flow pattern shows the speed profiles in the ideal duct/pipe downstream of a 90° deflection with turbulent flow at the start. It shows that a highly distorted speed profile occurs directly after the elbow, so that even partial backflows can be observed. The rule-of-thumb formula for minimum duct/pipe length until the initial profile is achieved again is also indicated.

![Fig. 5-17  Speed profiles in an ideal (frictionless) pipe](image-url)
5.12.2. Speed sensors

Settling distances

Sufficient settling distances are a major requirement for the measurement of flow speeds. Otherwise the same requirements apply as for pressure measurement.

The picture before shows that clear speed measurements are only possible if sufficient settling distances are present

- upstream or downstream of elbows and junctions,
- downstream of single-element dampers and fans, or
- changes of cross-section.

Changes of cross-section are usually indicated in multiples of the pipe diameter. In the case of rectangular ducts of sides \(a\) and \(b\), the equivalent diameter \(D_{gl}\) is calculated using the following formula:

\[
D_{gl} = \frac{2 \cdot a \cdot b}{a + b}
\]

The images shown in the picture below point out possible placement errors (left), and indicate the necessary settling distances (right).

Important

The sensors must be installed in such a way that they obstruct only a negligible part of the total cross-section.

- Speed is readily measurable downstream of resistances such as heating coils, coolers and filters, because the flow profile exhibits quite uniform development in such locations.
- Downstream of heat exchangers, however, a certain distance is required for the flow to settle.
Placement examples
Unfavorable or incorrect placements are shown on the left, favorable/correct placements are shown on the right.

Preferably not like this…

…but this is good!

Distance from obstruction

Sensor in the middle of the duct

Placement downstream of filters and flow straighteners is good because there is no swirl there

Place sensors upstream of diffusers and confusers

Filters settle the flow

Fig. 5-19 Placement of speed sensors

Fig. 5-20 Speed sensor QVM 62.1 (WERKBLICK Siemens)
5.12.3. Pressure sensor placement

Important
Knowledge of the flow conditions in the duct are important for exact installation of a pressure sensor. In case of direction changes (e.g. after bends) or after changes of cross-sectional area, air speed \( w \) rises and, with it, dynamic pressure \( p_{dyn} \) increases quadratically. Therefore, the measurement results also vary of course. All disturbances of the airflow must be avoided, especially for static pressure measurement.

Take care!
- Minimum distance downstream of a change in flow approx. \( 6 \, D_{GL} \)
- Since, according to Bernoulli, the total pressure remains constant, the static pressure in the duct decreases. It can even fall below the ambient pressure. Then air is drawn in through the vent.
- Arrange sensors side by side
  (When measuring static pressure, the probe must not detect any part of the dynamic pressure. This is always the case to a certain degree in turbulent flows. Therefore, the sensor's installation must avoid any disturbance of the airflow by other sensors or by intrinsic disturbance).
- The probe should be mounted on a duct wall that is parallel to the airflow.
- The air tubes between the measuring point and the sensor must be tightly sealed and dry.
- In the case of differential pressure measurement, also ensure that similar, comparable flow conditions are present on both sides.
- Exact, burr-free drilling of duct wall openings
- Use the same tube.

Differential pressure measurement
In the case of differential pressure measurement, ensure that the two measuring points exhibit similar, comparable interior flows at all expected air speeds, otherwise the pressure difference will be influenced, and the measurement will be undermined.

If the static pressure in a duct is measured without a probe but simply with an opening in the duct wall, measuring errors can occur depending on the quality of the hole.

![Fig. 5-21 Wall drilling for static pressure measurement](image1)

![Fig. 5-22 Differential pressure sensor installation](image2)
Limitation

The placement of two devices in the way shown above only applies to diaphragm sensors (static sensors).

This differential pressure sensor is suitable for direct mounting on air ducts, walls and ceilings, as well as in control panels. Please note:

- The sensor should be mounted vertically.
- Wherever possible, the pressure connections should be at the bottom and situated higher than the connected probes in the air duct.
- Horizontal mounting (with the hinged cover at the top or bottom) is not recommended, because this gives rise to certain measured value deviations.
- If the pressure connections point upwards or are lower than the probes, condensate can gather in the sensor and destroy it.

The normal place of installation is directly on the air duct. The device can be attached to a DIN mounting rail or mounted directly on a vertical or horizontal surface.

- The "+" connection must be connected to the higher-pressure side
- The "−" connection must be connected to the lower-pressure side
- Course impurities can be intercepted by making a twist in the air supply tube.
Duct pressure control

Fig. 5-25  Positioning of the pressure sensor for fan control, pressure progression in ductwork

A 100% volume flow, volume flow controller (VFC) fully open
B Throttling of flow by volume flow controller (VFC)
C Reduction of the fan speed
D as C, pressure measuring at $p_0$

Curve A
Curve A shows the pressure progression in the ductwork with the volume flow controller fully open and at the maximum volume flow rate. Negative pressure with respect to the environment builds up in the inlet duct towards the fan. The fan provides the necessary pressure rise for the ductwork; the positive pressure downstream of the fan dissipates towards the room according to ductwork design.

Curve B
In the absence of open-loop fan control or closed-loop pressure control, *approximately* the pressure progression shown by curve B results from setting a smaller volume flow rate (via the volume flow controller).

Note:
*Approximately* because in reality the fan will produce a different pressure difference according to its pressure-volume flow rate characteristic, which is not reflected in the picture.

Curve C
Without throttling via the volume flow controller but with a reduced volume flow rate (by reducing the fan speed), the pressure progression as per curve C is produced. In more complex systems, direct fan speed control with the volume flow rate as the setpoint can only be achieved with considerable control effort, because the sum of all partial volume flow rates must be determined as the reference variable.

Compromise...
A compromise is pressure control in the ductwork, provided the pressure sensor is meaningfully placed. If the pressure sensor is installed immediately upstream ($p_c$) of the volume flow controller, the ideal pressure progression in the ductwork as per curve C is also achieved.

Curve D
If the pressure sensor is unsuitably installed, e.g. if the sensor is moved to point $p_0$, the result is the pressure progression as per curve D. This automatically gives rise to higher fan drive energy consumption.
6 Measuring Concept/Measuring Planning

6.1. Measuring concept

The term "concept" denotes an outline plan.

A measuring concept contains only the basic conditions. Detailed conditions belong in the domain of measuring planning.

If a measuring task is set, it must be considered as soon as the targets are defined whether a measuring concept is necessary. It will hardly be necessary in case of simple measuring tasks. A measuring concept becomes indispensable, however, if the target definition requires measuring on a larger scale with simultaneous measuring of various measured variables over an extended period of time.

A well-devised concept provides an overview of the costs to be expected, of how many measuring devices of what kinds must be deployed and of who should organize, supervise, check and evaluate the measurements.

The significance of all measurement results and the question of how they can be interpreted must be clearly outlined in advance in the concept.

Before commencing the development of the measuring concept, up to and including the final report, the applicable form of contract for the measurements (service contract or job order) must first be defined.

Concept types

Different boundary conditions apply for consulting engineers, contractors, operators and experts. This gives rise to different concepts for each of these specialist fields:

![Measuring Concept Diagram]

Fig. 6-1 Measuring concept

6.2. Measuring planning

Measuring planning can commence if and when a proper measuring concept is present. The measuring plan includes the following in the order indicated:

- Organization
- Execution
- Evaluation
- Final report
In order to develop a measuring plan, all necessary information must be obtained. This includes operating specifications, schematics and function charts as well as system data. In case of existing systems, a survey on site will provide useful information for planning.

6.2.1. Organizational planning

Organizational planning determines how the execution of the measuring tasks should be handled. This part of the planning provides the basis for cost-effective handling of the measuring job.

In detail, organizational planning includes the following points:
- Who is responsible for the execution of the job?
- Within what timeframe are the measurements to be performed (date, season etc.)?
- Measurement time: at what time and how long is which variable measured?
- Clarification of needs: are instruments, installation means, building-side prerequisites present?

6.2.2. Technical planning

Technical situation

Eine Zusammenstellung der technischen Gegebenheiten kann sowohl bestehende Unterlagen wie auch neu zu erstellende Dokumentationen umfassen.

Plan of measuring points

The measuring points are marked in the facility plans (plans and elevations). This will demonstrate what scope of measuring installations and which building-side prerequisites are necessary.

Measuring schematic

The creation of a separate measuring schematic is recommended. A simple, clear, synoptic presentation gives the best possible overview of the relationships. It must provide information on all principle functional processes (control). The measuring points are indicated with the applicable symbols and connected with the respective measuring instruments via function lines.

Coding (item number):

An item number is assigned to each measuring point. This is indispensable for the setup (wiring) of the measuring equipment. The item number applies to the entire measurement, all the way through to the final report.

![Measuring item symbol and coding](image)

Measuring item

A measuring item includes:
1. Address: designation of the plant, rooms, branch etc.
2. Measuring item number: this is a freely assigned sensor number
3. Measuring point: only required for recording instruments with multiple channels

Measuring apparatus
A major part of the technical planning is the selection of the appropriate measuring equipment:

- Quality class of the measuring apparatus
- Tolerance and resolution of the measured variables
- Reasonable relationships between scale graduations (measuring ranges) in case of simultaneous use of multiple devices
- Selection of measuring apparatus according to deployment: ambient temperature, humidity, vibrations etc.
- Record of scale significance in case of plotting paper
- Start time - end time (time pattern)
- Identify units of measurement

Installation
The effort involved in installing the measuring instruments and the necessary connecting cables is often underestimated. There is, for example, a considerable difference in the effort required to install a built-in temperature sensor or a strap-on sensor.

Additionally, the respective national regulations must be observed for the installation of electrically powered instruments and cables.

The routing of measuring cables must ensure that no external interference can affect the transmission of measurements, e.g. induced voltage (mains frequency oscillations in the measuring cable induced by power cables located in the vicinity), temperature differences and telecommunications signals.

6.2.3. Evaluation of measurements
When all measurement results are present, they must be processed by the responsible specialist.

The first step is to sort the results:

- for comparable time parameters (time axis t)
- for optically comparable measuring ranges
- Sort out unimportant auxiliary measured variables and results with measuring errors.

After sorting, the results are presented in graphic form on the common time axis so that initial relationships can be identified and so that an assessment is possible, e.g. to determine whether a system fault is present or whether the control functions are incorrect. With correct measurements, the evaluation shows where the error is located so that appropriate action can be taken to improve the system.

If the measurement results are required for calculations, whether for performance auditing or for the modernization of building services systems, mainly maxima and minima are required instead of functional processes (dynamic method of measurement). The interpretation of these values provides the basis for calculation.

6.2.4. Final reports
In the final report, the knowledge gained from the measurements must be summarized, and a concluding assessment must be made. Therefore, it includes information on:

- The system state
- Identified errors
- Corrective action implemented
- Work to be done
6.2.5. Checklists

A checklist is the presentation of the logical sequence of actions or facts. The measuring checklist is a tool for the setup of a measurement both during the concept phase and in the planning and implementation phase. It contains only briefly formulated memory aids and provides the guidelines for the entire measuring process. It shows the correct sequence of operations.

Fig. 6-3 Checklist for planning and implementation of measurements
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