



HUMIDITY



FLOW



TEMPERATURE

# Basic Theory

## Humidity measuring technology

The physical quantities of temperature and atmospheric humidity are of prime importance to the physiological wellbeing of humans. A temperature between 22 °C and 26 °C and an atmospheric humidity between 30 % RH and 65 % RH is generally found to be agreeable. The German industrial standard DIN 1946 recommends these ranges for rooms where people are present. When these limits are observed, air-conditioned rooms are generally believed to provide an environment for better work performance and a better quality of work.

In many industrial processes, atmospheric humidity is an important factor determining quality. Above all, in industrial premises where natural materials such as wood, paper, wool fibres, tobacco, coffee, noodles, cheese etc. are processed, the atmospheric humidity must be measured and controlled in order to improve product quality. Likewise, in facilities where such products undergo further processing, refining or finishing, in print shops, spinning mills etc., specific values of humidity are absolutely essential for maintaining reproducible quality.

In agriculture and horticulture, including greenhouses, maintaining particular humidity values is essential for maximizing the crop.

Storage of artwork in museums, galleries, churches, libraries etc. requires constant atmospheric humidity within a narrow range to prevent damage by crack formation or bacterial decomposition. Attempts are made to preserve all kinds of cultural heritage for future generations by keeping such objects at constant climatic conditions.

Controlled dehumidification of indoor swimming pools, waterworks and power generation facilities, with optimum use of energy, can prevent damage to buildings and equipment.

There is a variety of other fields of application where measuring or controlling atmospheric humidity is important. Just as humidity has a bearing on physical, chemical and biological processes, controlling naturally occurring levels of humidity can also be important and beneficial to industrial processes.

There are several methods for determining relative atmospheric humidity, with these methods achieving various degrees of accuracy. While it is not possible to measure the water content of the air directly, secondary physical effects can be measured. These include changes in the length of hygroscopic (humidity-attracting) fibres, electrical resistance of salts, dew formation as the temperature changes, cold due to evaporation, change in electrical capacitance, etc.



INNOVATIVE SENSOR TECHNOLOGY





# Selected climate-related terms

## Air

Air is a mixture of various gases comprising the following components:

Component	Vol.%	Wt.%
Nitrogen N <sub>2</sub>	78.03	75.47
Oxygen O <sub>2</sub>	20.99	23.20
Argon Ar	0.93	1.28
Carbon dioxide CO <sub>2</sub>	0.03	0.04
Remaining components H <sub>2</sub> , neon, helium, krypton	0.02	0.01

At room temperature and atmospheric pressure, these principal components behave as perfect (ideal) gases. In other words, Dalton's law applies. -> The total pressure of a mixture of gases is equal to the sum of the partial pressures of the individual component gases.

## Pressure

Water vapour is a further component essential to life on earth. The surrounding atmosphere only contains a small amount of water vapour, with the mass fraction being approx. 0.1 % to 2 %. In spite of this small quantity of water present in the air, our wellbeing and many technical processes nevertheless depend on the humidity content. This water vapour, called partial water vapour, forms part of the total air pressure.

Apart from water vapour, below the critical pressure of 380 bar and above the critical temperature of -141 °C the remaining components of air behave as a perfect (ideal) gas. Thus in the context of environmental conditions, Dalton's law applies both to individual components of air and to the mixture as a whole.

Total pressure = partial pressure N <sub>2</sub> + partial pressure O <sub>2</sub> + ....	
<b>p<sub>ges</sub> = p<sub>a</sub> + p<sub>b</sub> + p<sub>c</sub> + p<sub>d</sub> + ...</b>	p      total pressure
	p <sub>a</sub> partial pressure component a
	p <sub>b</sub> partial pressure component b
	p <sub>c</sub> partial pressure component c
	p <sub>d</sub> partial pressure component d

Since all the components occupy the available space evenly, the following applies:

Partial pressure = volume fraction * total pressure	
<b>p<sub>i</sub> = r<sub>i</sub> * p</b>	p <sub>i</sub> partial pressure
	r <sub>i</sub> volume fraction
	p      total pressure



INNOVATIVE SENSOR TECHNOLOGY





At a barometric pressure of 1013 mbar the partial pressure of nitrogen with a 78 % volume fraction is for example 790 mbar. At atmospheric pressure, water vapour below the saturation limit can also be considered a perfect (ideal) gas. If the remaining components of the gas mixture "air" are taken together, the following applies:

Total pressure = partial pressure of the dry air + partial pressure of the water vapour		
	$p$	total pressure
	$p_l$	partial pressure of the dry air
	$p_d$	partial pressure of the water vapour
$p = p_l + p_d$		

### Air pressure

The term air pressure  $p$  refers to the total pressure which a vertical column of air which extends to the limit of the earth's atmosphere, exerts on its base area at any place on earth. Air pressure also refers to the total pressure in closed off spaces which due to physical processes differs from the surrounding air pressure of the earth's atmosphere.

### Saturation pressure

Water vapour cannot occur at any quantity in the air. The air can only absorb a particular maximum quantity of water. There is a temperature-dependent limiting value which cannot be exceeded. This maximum limiting value is known as saturation humidity. Saturation humidity depends on the temperature. In summer at high temperatures the air can absorb more water vapour than in winter at low temperatures. The saturated water vapour pressure is thus the partial pressure of the water vapour present in the atmosphere at saturation, at the respective temperature, above a surface of water or a surface of ice.

Thus, saturation pressure only indicates the maximum possible partial pressure of water vapour which can occur at a certain temperature. The correlation between the temperature and the saturated water vapour pressure constitutes a natural characteristic curve. A great number of researchers have been involved in calculating this correlation, with the Magnus equation nowadays being the most commonly applied. Other correlations are stated in the Goff-Gratch equation. More information on these correlations is provided in the German industry standard DIN 50 010 Part 2, available from Beuth Verlag, Berlin.

In the above-mentioned German industry standard, the saturated water vapour pressure is respectively designated  $e_w$  (above water) or  $e_i$  (above ice).



INNOVATIVE SENSOR TECHNOLOGY





Magnus has published the following equation for the temperature-dependent saturated water vapour pressures  $e_w$  and  $e_i$ :

$$e_w \text{ or. } e_i = C_1 \times \exp(C_2 \times t / C_3 + t)$$

in mbar, with

Phase	t °C	C <sub>1</sub> mbar	C <sub>2</sub> -	C <sub>3</sub> °C
Ice	-50.9 to 0.0	6.10714	22.44294	272.440
Water	-50.9 to 0.0	6.10780	17.84362	245.425
Water	0.0 to 100	6.10780	17.08085	234.175

Please refer to DIN 4108 for other approximated equations and possible calculations.

#### Humidity content (mixture ratio)

The humidity content of air is a dimensionless quantity which states the ratio of the mass of water present in the air to the mass of dry air.

The above is in contrast to the water vapour content which represents the ratio of the mass of water vapour to the mass of humid air which contains the mass of water vapour.

In tables and diagrams, the humidity content is however frequently indicated in g water / kg air so as to obtain more manageable values. The mixture ratio is often used in process technology as a measured variable, because many technological processes depend on the absolute water quantity present.

The humidity value at 100 % RH corresponds to the saturation humidity content. The latter denotes the maximum amount of humidity which can be in the air in a gaseous state at a particular temperature and at a particular air pressure. Even at very low temperatures, air can absorb a certain, albeit small, amount of humidity. As the temperature rises, the water absorption capacitance of air rises exponentially. Excess moisture can only be present either as mist (liquid aggregate state in the "moist mist area" of the saturation curve above 0.01 °C) or as ice mist (solid aggregate state in the "ice mist area" of the saturation curve below 0.01 °C).



INNOVATIVE SENSOR TECHNOLOGY





T °C	1000 mbar		2000 mbar	
	50 % RH g/kg	100 % RH g/kg	50 % RH g/kg	100 % RH g/kg
-10	0.807	1.62	0.403	0.87
0	1.91	3.82	0.952	1.91
10	3.84	7.73	1.91	3.84
20	7.35	14.8	3.64	7.35
30	13.48	27.55	6.67	13.48
40	23.81	49.52	11.68	23.81

The table shows that the humidity content of the air, i.e. the quantity of water present in the air, depends on the temperature, the relative humidity, and the air pressure. As the air pressure increases, the air can absorb less humidity. This is the reason for humidity arising in compressed air systems, in the form of condensate.

The following mathematical correlation applies:

$$X = \frac{m_d}{m_l} \left[ \frac{kg(H_2O)}{kg(dry - air)} \right]$$

X      humidity content  
 $m_d$     mass of the water vapour  
 $m_l$     mass of the dry air

If the general gas equation is applied and the gas constants for air and water vapour are inserted, the following results:

$$X = 0,622 * \frac{p_d}{p_l}$$

$p_d$     Partial pressure of the water vapour  
 $p_l$     Partial pressure of the dry air

$$X = 0,622 * \left( \frac{\phi * p_s}{p - \phi * p_s} \right)$$

$p_s$     Saturation pressure at the respective humidity

$$X_s = 0,622 * \frac{p_s}{(p - p_s)}$$

$X_s$     Humidity content at saturation



INNOVATIVE SENSOR TECHNOLOGY





The ratio of the effective humidity content  $X$  of the air to the maximum humidity content  $X_s$  is called the degree of saturation. In the context of meteorological and climatic calculations, the degree of saturation corresponds approximately to the relative humidity.

$F_1 = \frac{X}{X_s}$	$F_1$ Degree of saturation
-----------------------	----------------------------

### Relative humidity

In practical applications, relative humidity is the most often used quantity to describe the amount of humidity present in air.

Relative humidity is the partial pressure ratio of the prevailing water vapour pressure to the saturated water vapour pressure in relation to water or ice at the same total pressure and temperature. Relative humidity is a dimensionless quantity. As a proportional number it is expressed in per cent.

Many processes in nature are based on a particular state of equilibrium. For example absorption or release of humidity by hygroscopic materials depends on the relative humidity of the surrounding atmosphere.

For example if wood is moved to a dry atmosphere (drying oven), then after some time the wood reaches a moisture level which depends on the relative humidity of the surroundings. In diagrams, this state of equilibrium is shown by means of sorption isotherms.

From a mathematical point of view, the following equation applies:

$\varphi = \frac{p_d}{p_s}$	$\varphi$ relative humidity $p_d$ partial water vapour pressure $p_s$ saturated water vapour pressure
<p>The relative humidity can also be calculated from the humidity content:</p>	
$\varphi = \frac{p * X}{p_s * (0,622 + X)}$	$p$ total pressure $X$ humidity content
<p>In practical application the dimensionless proportional number of relative humidity is expressed in %:</p>	
$U_w = \varphi * 100$	$U_w$ relative humidity in %



INNOVATIVE SENSOR TECHNOLOGY





The German industrial standard DIN 50 010 Part 2 provides information concerning the correct way of expressing relative humidity in writing. An international committee for weights and measures concerning the international unitary system (SI) has decided that the correct written expression is e.g. "50 % relative humidity" or "U = 50%". However, since the designation U is already used for various quantities, this decision does not reflect the commonly applied expression "50 % RH". In the 20 or so years since this decision was made, this self-chosen way of writing has not found widespread use and is unlikely to do so in the next few years.

### Absolute humidity

Absolute humidity refers to the quantity of water effectively present in a volume of air, irrespective of the temperature of the gas.

$$a \left[ \text{g} / \text{m}^3 \right] = \frac{m_d}{V}$$

a	absolute humidity
$m_d$	mass of the water vapour
V	volume

In practical application the index of absolute humidity is not very often used because most climate-related correlations and processes can better be represented via the humidity content.

### Dew point

If unsaturated air is cooled, at first the humidity content and the partial pressure of the water remain constant. However, the relative humidity increases since saturated water vapour pressure coming from above more and more approximates the partial water vapour pressure. This is the reason why cold air is able to absorb less humidity than warm air. When the saturation limit is reached at 100 % RH, i.e. when the saturated water vapour pressure equals the partial water vapour pressure, this is called the dew point temperature. If any further cooling occurs, the excessive humidity condenses in the form of mist (fine water droplets). Relative humidity remains at 100 % and the humidity content of the atmosphere decreases.

Thus colloquially, the imaginary temperature where condensation has just not yet occurred, is called the dew point.

The following applies to the dew point:

- The moisture content at dew point is unchanged; no water has yet condensed. The partial water vapour pressure is unchanged; it equals the saturated water vapour pressure.
- The relative atmospheric humidity at dew point is 100 %. The air has reached maximum water vapour saturation.



INNOVATIVE SENSOR TECHNOLOGY





Calculation of the dew point is somewhat elaborate because the value of the saturated water vapour pressure needs to be known. This value is either derived from published steam pressure tables, or it can be calculated using equations. The Magnus equation, mentioned earlier, is an equation which is easily handled.

Inverted to calculate the dew point, the following mathematical correlation results:

$tp = \frac{-\ln \frac{p_d}{C_1} * C_3}{\ln \frac{p_d}{C_1} - C_2}$	tp	dew point
	p <sub>d</sub>	partial water vapour pressure
	C <sub>1</sub>	Magnus coefficient
	C <sub>2</sub>	Magnus coefficient
	C <sub>3</sub>	Magnus coefficient

The dew point is a very important index in meteorology (mist, ground frost) as well as in air conditioning technology. For example, the dew-point temperature of an atmosphere is the critical temperature for control systems in the field of drying technology. If a colder object is present in the same atmosphere, condensation effects occur which will need to be avoided to prevent damage to equipment or the building.



INNOVATIVE SENSOR TECHNOLOGY





### Calculation example for determining the Relative Humidity from temperature and dew point

Given quantities:            t            temperature in °C  
                                      tp            temperature of dew point in °C

Equations:

$$p_s = C_1 * \exp \frac{C_2 * t}{C_3 + t} \quad [ \text{mbar} ]$$

p<sub>s</sub>            saturated water vapour pressure

t            temperature in °C

C<sub>1,2,3</sub>        Magnus coefficients from table

$$p_{s_{tp}} = C_1 * \exp \frac{C_2 * tp}{C_3 + tp} \quad [ \text{mbar} ]$$

p<sub>stp</sub>            saturated water vapour pressure of the temperature of dew point

tp            temperature of dew point

$$U_w = \frac{p_{stp}}{p_s} * 100 \quad [ \% ]$$

U<sub>w</sub>            Relative Humidity in %

Table of Magnus coefficients				
Phase	t °C	C <sub>1</sub> mbar	C <sub>2</sub> -	C <sub>3</sub> °C
Ice	-50.9 to 0.0	6.10714	22.44294	272.440
Water	-50.9 to 0.0	6.10780	17.84362	245.425
Water	0.0 to 100	6.10780	17.08085	234.175



INNOVATIVE SENSOR TECHNOLOGY







HUMIDITY



FLOW



TEMPERATURE

**Calculation example for determining the dew point from temperature and relative atmospheric humidity**

Given quantities:      t      temperature in °C  
                                  U<sub>w</sub>      Relative Humidity in %

Equations:

$\varphi = U_w \div 100\%$	[ ]	$\varphi$	Relative Humidity
		U <sub>w</sub>	Relative Humidity in %
$p_s = C_1 * \exp \frac{C_2 * t}{C_3 + t}$	[ mbar ]	p <sub>s</sub>	saturated water vapour pressure
		t	temperature in °C
$p_d = p_s * \varphi$	[ mbar ]	C <sub>1,2,3</sub>	Magnus coefficient from table
		p <sub>d</sub>	partial water vapour pressure
$tp = \frac{-\ln \frac{p_d}{C_1} * C_3}{\ln \frac{p_d}{C_1} - C_2}$	[ °C ]	tp	dew point temperature

Table of Magnus coefficients				
Phase	t °C	C <sub>1</sub> mbar	C <sub>2</sub> -	C <sub>3</sub> °C
Ice	-50.9 to 0.0	6.10714	22.44294	272.440
Water	-50.9 to 0.0	6.10780	17.84362	245.425
Water	0.0 to 100	6.10780	17.08085	234.175



INNOVATIVE SENSOR TECHNOLOGY







# Saturated saline solutions

Saline solutions can be used to create a constant climate. The ambient climate which forms in the airspace above aqueous saturated solutions, provides a possibility of readjusting or verifying humidity sensors in a simple way.

It is important that the saline solution is made from chemically pure salts with distilled or de-ionised water.

You can prepare a homogenous saline solution by adding salt crystals to boiling water until they no longer dissolve. After this, leave the solution to cool to the desired temperature.

For more information refer to our Calibration Kit which includes ready-made humidity reference cells containing saturated saline solutions.

Temperature in °C	Relative Humidity U in %	
	Magnesium chloride	Sodium chloride
1	33.6 +- 0.3	75.5 +- 0.3
10	33.4 +- 0.3	75.7 +- 0.3
20	33.1 +- 0.2	75.5 +- 0.2
25	32.8 +- 0.2	75.3 +- 0.2
30	32.5 +- 0.2	75.1 +- 0.2
40	31.6 +- 0.2	74.9 +- 0.2
50	30.5 +- 0.2	74.4 +- 0.2
60	29.3 +- 0.2	74.5 +- 0.3



INNOVATIVE SENSOR TECHNOLOGY





HUMIDITY



FLOW



TEMPERATURE

# Constants and characteristic quantities

Molar gas constant  $R = 8314 \text{ J / kmol}\cdot\text{K}$

## The following applies to dry air:

Weight per litre  $D = 1.2928 \text{ g / N}\cdot\text{dm}^3$

Mean molar mass  $M = 28.95 \text{ kg / kmol}$

Gas constant  $R_l = 287.2 \text{ J / kg}\cdot\text{K}$

Mean spec. thermal capacitance  $c_{pl} = 1006 \text{ J / kg}\cdot\text{K}$

## The following applies to water vapour:

Weight per litre  $D = 0.768 \text{ g / N}\cdot\text{dm}^3$

Molar mass  $M = 18.016 \text{ kg / kmol}$

Gas constant  $R_d = 461.5 \text{ J / kg}\cdot\text{K}$

Spec. thermal capacitance  $c_{pd} = 1860 \text{ J / kg}\cdot\text{K}$



INNOVATIVE SENSOR TECHNOLOGY





# Information on capacitive polymeric humidity sensors made by IST

The latest developments and knowledge in the field of polymer technology at the end of the 20th century enable us to produce humidity sensors with outstanding characteristics. This body of knowledge has been rigorously applied and converted to developing sensors which thanks to their excellent resistance to hot water and chemicals were able to be used in fields of application which were hitherto practically impossible.

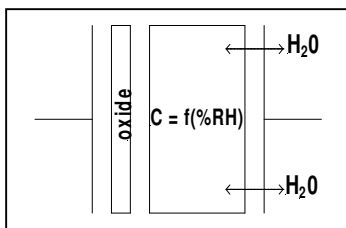
The mechanically robust design even allows these precision instruments to withstand temperature cycling stress or thermal shocks of up to 140 °C/sec without any damage. The generally large temperature-humidity window of our humidity sensors provides ideal solutions to many problems in humidity measuring technology.

## Diagrammatic view of capacitive humidity sensors

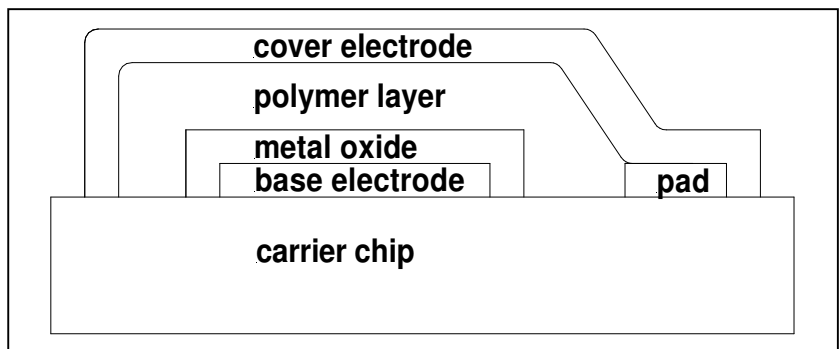
Our humidity sensors are based on proven manufacturing technology for classical thin film capacitors, supplemented with technology to meet the specific application requirements of measuring relative humidity.

The base electrode applied to a stable carrier chip is covered with a special metal oxide film. On the structured polymer layer applied over it, there is a vapour permeable cover electrode.

### Basic circuit diagram



### Diagrammatic view of a planar capacitive polymer humidity sensor



INNOVATIVE SENSOR TECHNOLOGY





HUMIDITY



FLOW



TEMPERATURE

## Function

---

Capacitive humidity sensors can detect water in its vapour phase. In an enlarged sense they are thus gas sensors which react to H<sub>2</sub>O molecules. This occurs by storing water vapour molecules in the polymer layer. As a result of the high dielectric constant of water ( $\epsilon_r = 80.5$ ) when compared to that of plastics ( $\epsilon_r = 2 \dots 4$ ), the capacitive change of the signal is correspondingly large. To ensure that this is the case, in a classic capacitor design, at least one of the opposing area-shaped electrodes has to assume a dual function:

- ⊕ it must act as an electrically conductive electrode;
- ⊕ it must ensure free transport of water molecules, as far as is possible, between the polymer and the surrounding atmosphere.

The exchange of water vapour between the polymer and the surrounding air occurs only as a result of an existing diffusion gradient. If this gradient is zero, the sensor has been adapted and the capacitance corresponds to the partial water vapour pressure of the surrounding air. In other words, allocation of capacitance to relative humidity is now possible, and the measured value can be acquired.



INNOVATIVE SENSOR TECHNOLOGY

