

Part One: Theory

Humidity Academy

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Key



Definition



Law



Tip



Alert

What Is Humidity?

Humidity is defined as some measure of the water vapor content of air (or other gas). The term “humidity” is a general term to quantify the amount of water vapor in the gas.

The term “humidity” is often interchangeable with “relative humidity,” but there’s a significant difference between these two terms in the context of precise measurement. This chapter explains why the difference between these two terms matters for people who are in the business of measuring water vapor in sensitive environments, and it covers the terms and definitions used to quantify the amount of water vapor in the gas.

Water vapor plays a critical role in maintaining quality and efficacy for products that improve our daily lives – products we consumers trust are manufactured to specification. It is essential for manufacturers in a variety of industries to understand how accurate humidity measurements work, and the role your measurement instrument plays.

The Importance of Accuracy

Humidity is measured using a hygrometer, a tool that utilizes various materials and measurements to gauge a room or space’s level of water vapor. While no scientific measurement is absolutely true, reaching humidity measurements that are as accurate as possible is crucial across industries. Since water vapor above certain levels can lead to condensation and eventually corrosion or mold, highly accurate humidity measurements are vital to preventing the degradation of everything from wooden construction materials, food products, pharmaceuticals, fuels, paper, electronic components and many other materials. Humidity measurements help maintain optimal environmental conditions for products and prevent costly damage to valuable goods.

Technical Information

In this section, we’ll uncover the basic laws of physics that govern relative humidity. Within a temperature range of -50 to 150°C and at pressures not in excess of 1000 kPa, water vapor practically behaves like an ideal gas. We’ll use examples to illustrate the influence of temperature and pressure on relative humidity, and how to convert relative humidity into dew point and absolute humidity.

First let’s cover the basics with a review of the general properties of water vapor in a moist gas.

Properties of Water Vapor in a Moist Gas

Evaporation

When a water molecule leaves a surface and takes gas form, it has evaporated. Through the absorption or release of kinetic energy a water molecule transitions from the liquid state to the vapor state. Liquid water that becomes water vapor takes a parcel of heat with it in a process called *evaporative cooling*.



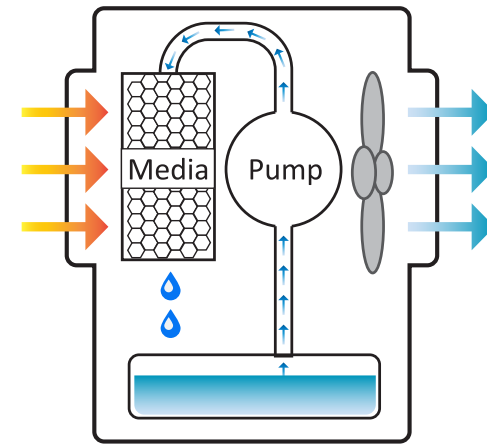
Evaporative cooling is the reduction in air temperature resulting from the evaporation of a liquid, which removes heat from the surface from which evaporation takes place. The energy removed during evaporative cooling is known as "latent heat."

Evaporative cooling is restricted by atmospheric conditions. The evaporation process consumes more heat when the air is very hot and dry, which makes the cooling effect more pronounced compared to evaporative cooling in hot and moist air.

Condensation

The conversion of water vapor to a liquid is called condensation. Water vapor will only condense on a surface when the surface is cooler than the dew point temperature or when the water vapor equilibrium in the air has been exceeded. When water vapor condenses on a surface, a net warming occurs. The water molecule releases heat, and in turn, the temperature of the atmosphere slightly rises.

Evaporative Air Cooling Mechanism



A "Swamp Cooler" conditions air in hot weather through the evaporation of water. They work well in dry climates like Denver or Phoenix, but would not work well in Houston or Boston, where there is more moisture in the air.

Chemical Reactions

Many chemical reactions yield water as a product. If the reactions take place at temperatures higher than the dew point of the surrounding air, the water will be formed as vapor and increase the amount of water vapor in the gas. If they take place at temperatures lower than the dew point, condensation will occur, and water vapor will leave the gas.

Other chemical reactions take place in the presence of water vapor, resulting in new chemicals forming, such as rust on iron or steel.

Relative Humidity, Pressure and Temperature

Reviewing the laws of physics that govern water vapor in a moist gas can help you better understand the properties of what you're measuring. Understanding these properties will help you make a more accurate measurement and do your job more effectively, whether it's protecting a product from corrosion or maintaining a precise environment for storage or manufacturing.

Humidity and Laws of Physics

From pressure to temperature, the following ideal gas laws help us understand how humidity levels shift depending on the environment.

Name	Definition	Law	Notes
Boyle's Law	At constant temperature, the product of the volume and pressure of a given amount of gas is a constant.	$P \times V = \text{constant}$	The value of the constant depends on how much gas is in the volume.



Standard Temperature and Pressure (STP) is set at a temperature of 0° C, 32° F and a pressure of 101.3 kPa at one atmosphere.

Name	Definition	Law	Notes
Charles's Law	At constant pressure, the volume of a given quantity of gas is proportional to absolute temperature (°K). Or at constant volume, the pressure of a given quantity of gas is proportional to absolute temperature.	$V = q \times T$ Or $P = j \times T$	q is a proportionality constant that depends on the quantity of gas. j is a proportionality constant that depends on the particular sample of gas and its volume. To convert temperature in °C into absolute temperature in °K, add the constant 273.15.
Dalton's Law of Partial Pressures	The total pressure of a mixture of gases is equal to the sum of the pressures that each gas would exert if it were present alone.	$P_t = P_1 + P_2 + P_3 + \dots$	P1, P2, etc., are the partial pressures of gases 1, 2, etc.
Avogadro's Hypothesis	Equal volumes of gases at the same temperature and pressure contain equal numbers of molecules.	Example: one liter of any ideal gas at a temp. of 0°C and a pressure of 101.3 kPa, contains 2.688 x 10 ²² molecules.	The temperature of 0°C and pressure of 101.3 kPa is the standard temperature and pressure condition or STP.



It has been experimentally determined that the number of atoms in 12 grams of ^{12}C is 6.022×10^{23} .

This number is called Avogadro's number.



Avogadro

image credit: [Wikipedia](https://en.wikipedia.org/wiki/Avogadro)

Name	Definition	Law	Notes
Volume of a Mole of Gas at Standard Temperature and Pressure (STP)	As one liter of gas at STP contains 2.688×10^{22} molecules (or atoms in the case of a mono atomic gas), it follows that a mole of gas (6.022×10^{23} molecules) occupies a volume of 22.4 l at STP.		See definitions of mole and Avogadro's number below.
Ideal Gas Law	The product of volume and pressure of a given amount of gas is proportional to absolute temperature.	$P \times V = n \times R \times T$	n is the number of moles of gas and R the molar gas constant. The constant R is equal to: 0.08206 atm x liter/K x mole 8.30928 Pa x m ³ /K x mole

Mole Fractions and Partial Pressure

The composition of one mole of a gas mixture can be expressed in terms of the mole fractions of its components. The mole fraction of a particular component is defined as the total number of moles of the component divided by the total number of moles of all the components. From this definition, it follows that the sum of all mole fractions is equal to one.



A mole of any element is defined as the amount of that element that contains the same number of molecules (or atoms in the case of a mono atomic element) as exactly 12g of ^{12}C (Carbon 12).

Example: Dry air near sea level

1. Nitrogen: Mole Fraction: 0.78084
2. Oxygen: Mole Fraction: 0.20948
3. Carbon Dioxide: Mole Fraction: 0.0004

If P_t is the total pressure of a gas mixture and n_1, n_2 , etc. the mole fractions of its components, it follows that:

$$P_t = P_t \times (n_1 + n_2 + \dots) \text{ and}$$

$$P_t = P_t \times n_1 + P_t \times n_2 + \dots$$

where $P_t \times n_1, P_t \times n_2$, etc. are the partial pressures of components 1, 2, etc.



The equation above is another form of Dalton's law.

Water vapor is one of several gases that makes up air. For example if the total pressure of a system such as air at sea level is 1,013 kPa (or 29.9 inches of mercury), and that air is made up of Nitrogen, Oxygen, water vapor and other trace gases, each of those gases contributes to the total pressure of 1,013 kPa. The portion that is water vapor is called the partial pressure of water vapor. The partial pressure of water vapor is a key metric found as a component in the formulas that define all other humidity parameters.

Effect of a Change in Pressure



According to Dalton's law, the total pressure of a gas mixture is equal to the sum of the partial pressures of its components. This means that the partial pressure of a component is equal to the product of the total pressure times the mole fraction of the component.

Therefore, a change in the total pressure of a gas mixture, at constant composition, results in the same change in the partial pressure of each component. For instance, doubling the total pressure of a gas mixture results in doubling the partial pressure of each component. As the total pressure increases, the partial pressure of water vapor increases proportionately. This is an important fact to understand, as you will see when we define relative humidity and dew point temperature. An increase in the pressure of a closed system will increase the relative humidity and raise the dew point temperature until saturation is achieved.

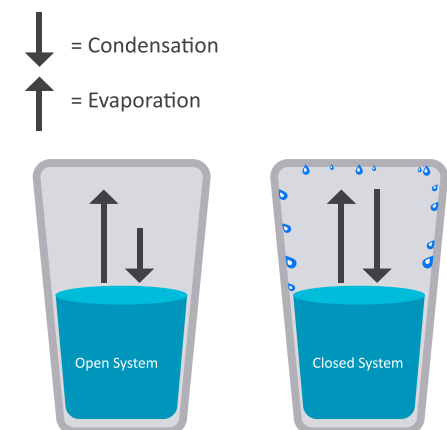
Vapor Pressure Above a Liquid

Because molecules in a liquid are closer to one another than they are in a gas, intermolecular forces are stronger than in a gas. For a liquid to vaporize, the intermolecular forces have to be overcome by the kinetic energy of the molecules.

If a liquid is placed in a closed container, the particles entering the vapor phase cannot escape. In their random motion, particles strike the liquid and are recaptured by intermolecular forces. Thus, two processes occur simultaneously: evaporation and condensation.

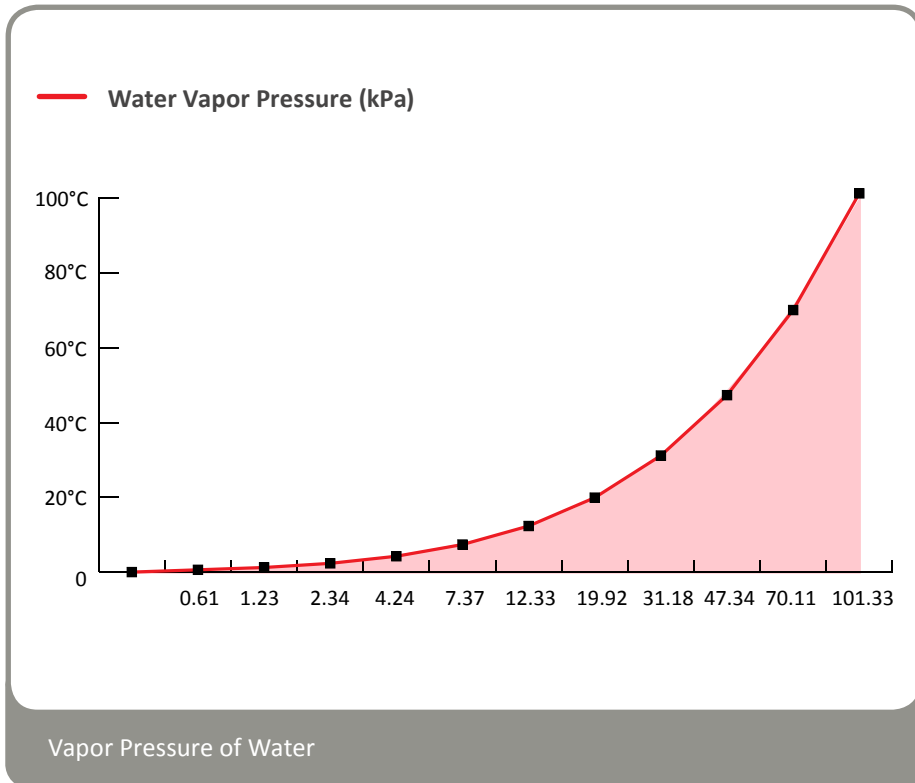
The rate of evaporation increases as temperature increases. This is because an increase in temperature corresponds to an increase in the kinetic energy of molecules. At the same time, the rate of condensation increases as the number of particles in the vapor phase increases: more molecules strike the surface of the liquid. When these two processes become equal, the number of particles and, therefore, the pressure in the vapor phase, becomes stabilized.

The value of the equilibrium vapor pressure depends on the attractive forces between particles of the liquid and on the temperature of the liquid. Vapor pressure above a liquid increases with increasing temperature.



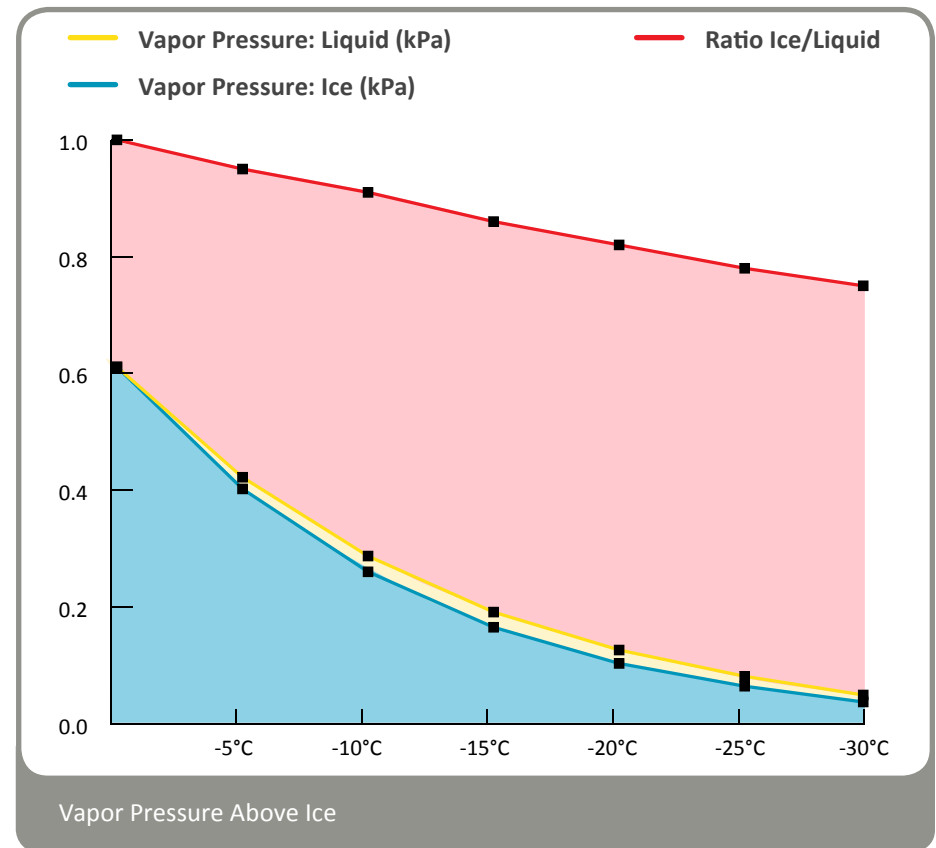
Vapor Pressure of Water

The vapor pressure of water increases strongly with increasing temperature.



Vapor Pressure Above Ice

When water freezes, the molecules assume a structure that permits the maximum number of hydrogen-bonding interactions between molecules. Because this structure has large hexagonal holes, ice is more open and less dense than liquid water. As hydrogen bonding is stronger in ice than in liquid water, the inter-molecular attraction forces are the strongest in ice. That's why vapor pressure above ice is less than the vapor pressure above liquid water.



Definitions of Humidity

Vapor Concentration (Absolute Humidity)

The vapor concentration or absolute humidity of a mixture of water vapor and dry air is defined as the ratio of the mass of water vapor M_w to the volume V occupied by the mixture.

$$D_v = M_w / V \text{ expressed in grams/m}^3 \text{ or in grains/cu ft}$$

The value of D_v can be derived as follows from the equation $PV = nRT$

$$M_w = n_w \times m_w \text{ where}$$

n_w = number of moles of water vapor present in the volume V

m_w = molecular mass of water

$$D_v = M_w / V = n_w \times m_w / V = m_w \times p / RT \text{ where}$$

$$m_w = 18.016 \text{ gram}$$

p = partial pressure of water vapor [Pa]

$$R = 8.31436 \text{ Pa} \times \text{m}^3 / \text{K} \times \text{mole}$$

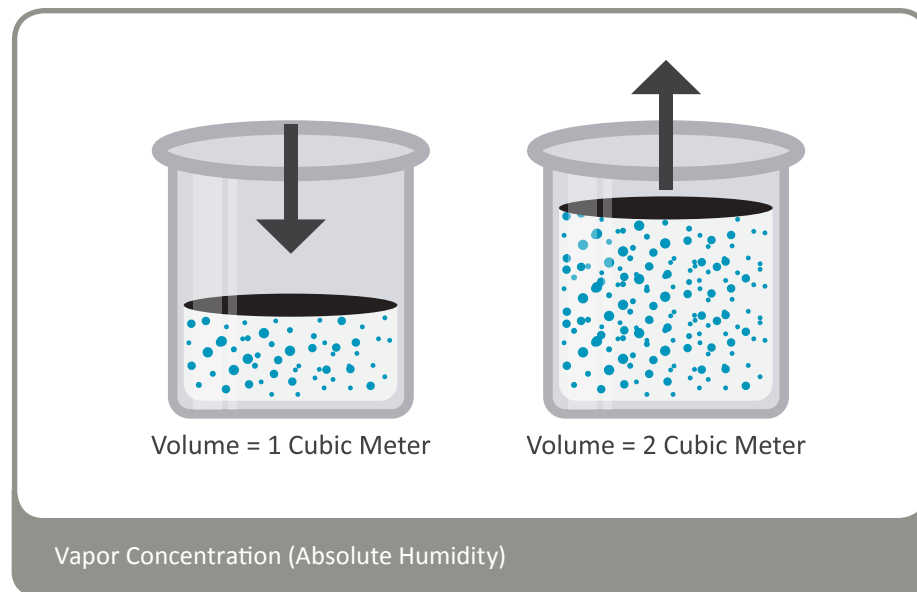
T = temperature of the gas mixture in K

$$D_v = p / 0.4615 \times T \text{ [g / m}^3\text{]}$$

$$1 \text{ gr (grain)} = 0.0648 \text{ g (gram)}$$

$$1 \text{ cu ft} = 0.0283168 \text{ m}^3$$

$$D_v \text{ [gr / cu ft]} = 0.437 \times D_v \text{ [g / m}^3\text{]}$$



Specific Humidity

Specific humidity is the ratio of the mass M_w of water vapor to the mass ($M_w + M_a$) of moist air.

$$Q = M_w / (M_w + M_a)$$

$$Q = p m_w / (p m_w + (P_b - p) m_a)$$

$$Q = 1000 p / (1.6078 P_b - 0.6078 p) \text{ [g / kg]}$$

$$1 \text{ gr (grain)} = 0.0648 \text{ g (gram)}$$

$$1 \text{ lb} = 0.4535923 \text{ kg}$$

$$Q \text{ [gr / lb]} = 7 \times Q \text{ [g / kg]}$$

Mixing Ratio

The mixing ratio r of moist air is the ratio of the mass M_w of water vapor to the mass M_a of dry air with which the water vapor is associated:

$$r = M_w / M_a$$

$$M_w = n_w \times m_w = m_w \times p V / RT$$

$$M_a = n_a \times m_a = m_a \times (P_b - p) V / RT, \text{ where:}$$

n_w = number of moles of water vapor present in the volume V

n_a = number of moles of dry air present in the volume V

m_w = 18.016 gram

m_a = 28.966 gram

p = partial pressure of water vapor [Pa]

p_a = partial pressure of dry air [Pa]

P_b = total or barometric pressure [Pa]

$R = 8.31436 \text{ Pa} \times \text{m}^3 / \text{K} \times \text{mole}$

T = temperature of the gas mixture in K

V = volume occupied by the air – water vapor mixture

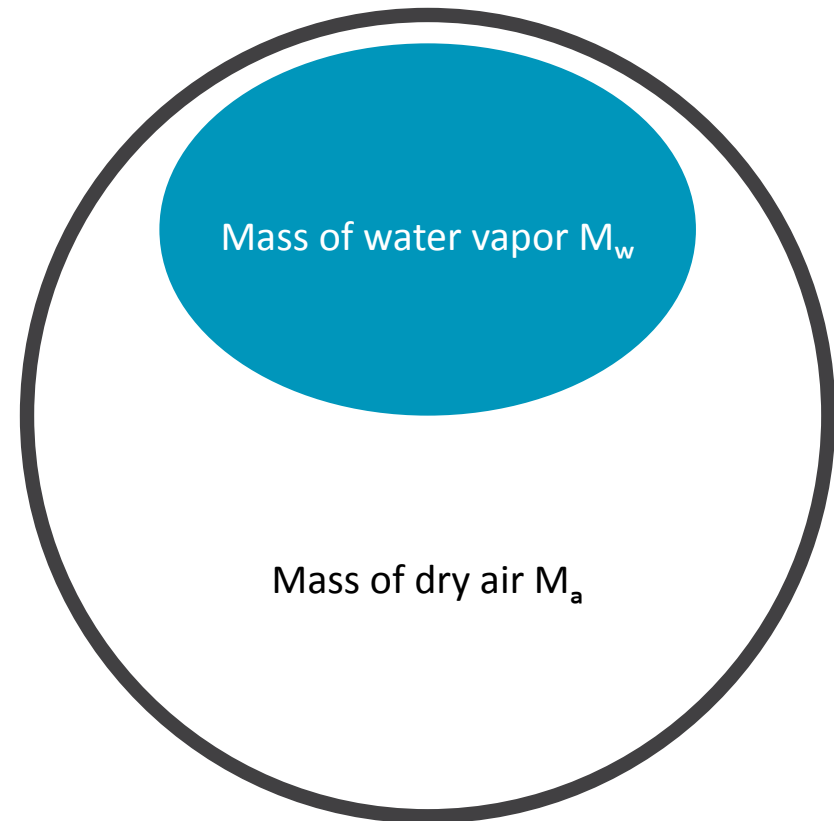
$$r = m_w p / m_a (P_b - p)$$

$$r = 621.97 \times p / (P_b - p) \text{ [g / kg]}$$

1 gr (grain) = 0.0648 g (gram)

1 lb = 0.4535923 kg

$$r \text{ [gr / lb]} = 7 \times r \text{ [g / kg]}$$



$$r = M_w / M_a$$

Volume Mixing Ratio

The volume mixing ratio is the ratio of number of moles of water vapor n_w to the number of moles of dry air n_a with which the water vapor is associated.

This usually expressed in terms of parts per million:

$$PPMv = 10^6 \times n_w / n_a$$

$$n_w = p V / RT$$

$$n_a = p_a V / RT = m_a \times (P_b - p) V / RT, \text{ where:}$$

p = partial pressure of water vapor [Pa]

p_a = partial pressure of dry air [Pa]

P_b = total or barometric pressure [Pa]

$R = 8.31436 \text{ Pa} \times \text{m}^3 / \text{K} \times \text{mole}$

T = temperature of the gas mixture in K

V = volume occupied by the air – water vapor mixture

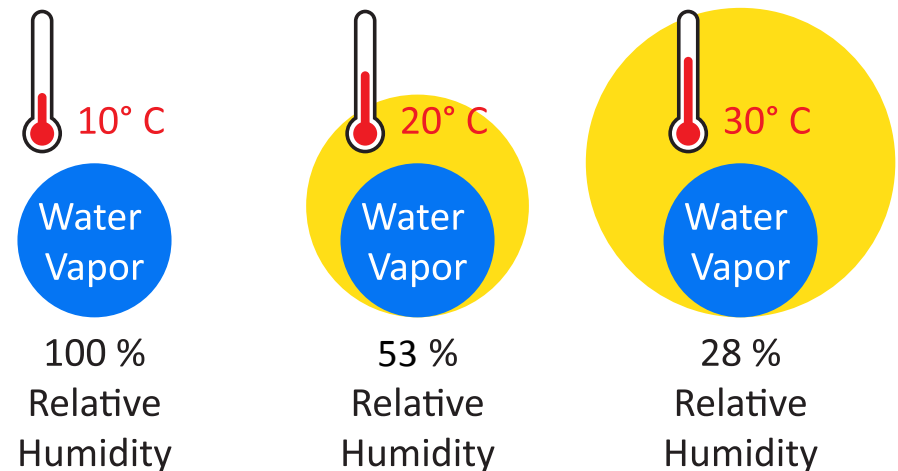
$$PPMv = 10^6 \times p / (P_b - p)$$

Relative Humidity

Relative humidity is the ratio of two pressures:

$\%RH = 100 \times p/p_s$ where p is the actual partial pressure of the water vapor present in the ambient and p_s the saturation pressure of water at the temperature of the ambient.

Relative humidity sensors are usually calibrated at normal room temperature (well above freezing). Consequently, it is generally accepted that this type of sensor indicates relative humidity with respect to water at all temperatures (including below freezing). As already noted, ice produces a lower vapor pressure than liquid water. Therefore, when ice is present, saturation occurs at a relative humidity of less than 100%. For instance, a humidity reading of 75% RH at a temperature of -30°C , corresponds to saturation above ice.



Dew Point and Frost Point Temperature

The dew point temperature of moist air at temperature T , pressure P_b and mixing ratio r is the temperature to which the air must be cooled in order to be saturated with respect to water (liquid).

The frost point temperature of moist air at temperature T , pressure P_b and mixing ratio r is the temperature to which the air must be cooled in order to be saturated with respect to ice.

Wet Bulb Temperature

The wet bulb temperature of moist air at pressure P_b , temperature T and mixing ratio r is the temperature that the air assumes when water is introduced gradually by infinitesimal amounts at the current temperature and evaporated into the air by an adiabatic process at constant pressure until saturation is reached.

Effect of Temperature and Total Pressure on Vapor Pressure

One common mistake in taking humidity measurements is failing to distinguish the effects of temperature and pressure on water vapor. When considering the effect of temperature, pressure and space on the partial pressure of vapor, make sure to differentiate between the following situations:

- saturation (liquid or ice) vs. no saturation (vapor only)
- closed container of fixed volume vs. open space

Saturation

The partial pressure of vapor is equal to the saturation pressure and its value depends only on temperature. There is no difference between the situation in an open environment and that in a closed container.

No Saturation

Water vapor behaves almost like an ideal gas, and the following equation applies regarding the partial pressure of vapor:

$$p \times V = n \times R \times T$$

In an open space, the volume V occupied by vapor is free to expand. Therefore, the partial pressure p is not affected by temperature. The partial pressure p can vary only if n varies (vapor is being added or removed) or if the total pressure varies (Dalton's law of partial pressures). For instance, total pressure drops with increasing altitude, which results in a decrease of the partial pressure of vapor.



Dalton's law

In a closed container of fixed volume, vapor occupies the entire volume of the container and this volume is constant. The partial pressure of water vapor (p) can vary only if there is a change in absolute temperature (degrees K) or a change in the amount of water vapor p . The partial pressure p does not vary with a change in total pressure unless the total pressure change is due to a change in the partial pressure of water vapor p .

Effect of Temperature and Pressure on %RH

Saturation vapor pressure depends only on temperature. There is no effect of total pressure, and there is no difference between the situation in an open space and that in a closed container.

In an open space, at constant moisture level and temperature, %RH is directly proportional to the total pressure. However, the value of %RH is limited to 100% as p cannot be greater than p_s .

In a closed container of fixed volume, %RH decreases as temperature increases, but not quite as strongly as in open space.

Examples

(A) Office building

For practical purposes, an office building can be considered an open environment.



A localized increase in temperature created by a heater or an office machine, for instance, doesn't modify the value of the partial pressure of water vapor, so the local vapor pressure is the same throughout the building. However, the saturation vapor pressure is locally increased. Consequently, relative humidity in the immediate vicinity of the heat source is lowered.

If we assume that elsewhere in the building the temperature is 25°C and relative humidity is 50%, a localized increase of temperature to 30°C lowers relative humidity as follows:

$$p_s \text{ at } 25^\circ\text{C} = 3.17 \text{ kPa}$$

$$p_s \text{ at } 30^\circ\text{C} = 4.24 \text{ kPa}$$

$$p = 0.5 \times 3.17 \text{ kPa} = 1.585 \text{ kPa, corresponding to } 50 \% \text{RH}$$

$$\text{Localized \%RH} = 100 \times 1.585/4.24 = 37.4\%$$

(B) Dew on a chilled mirror

If the temperature of a mirror is lowered to precisely the value that makes dew appear on the surface, the value of the mirror temperature is called dew point. Using the previous example, the dew point corresponding to a condition of 50 %RH and 25°C can be found as follows:

$$p_s \text{ at } 25^\circ\text{C} = 3.17 \text{ kPa}$$

$$p = 0.5 \times 3.17 \text{ kPa} = 1.585 \text{ kPa, corresponding to 50 \%RH}$$

If there is equilibrium between the dew on the mirror and the environment, it follows that p_s at the temperature of the chilled mirror must be equal to the vapor pressure p . Based on a simple interpolation of the values of the saturation vapor tables, we find that a value of p_s of 1.585 kPa corresponds to a temperature of 13.8°C. This temperature is the dew point.

The example above shows that converting relative humidity into dew point and vice versa requires the use of a thermometer and saturation vapor tables.

(C) Compression in a closed chamber

If the total pressure inside a closed chamber is increased from one to one and a half atmospheres and temperature is kept constant, the partial pressure of water vapor is increased 1.5 times. Because temperature is the same, so is the saturation pressure p_s . If we assume that we had a condition of 50% RH and 25°C before the compression, the condition afterwards is 75 %RH and 25°C.

(D) Injection of a dry gas in a closed chamber

If dry nitrogen is injected in a closed chamber where there is already air at a condition of 50 %RH and temperature is kept constant, total pressure in the chamber increases. However, the partial water vapor pressure p remains constant because the mole fraction of water vapor in the chamber decreases by an amount that exactly balances the increase in total pressure (see Dalton's law). Because temperature is maintained constant, the saturation vapor pressure p_s is also unchanged. Therefore, relative humidity stays at 50%, despite the fact that a dry gas was injected in the chamber.



Rules of Thumb for relative humidity in moist air applications

Recall that $\%RH = p/p_s \times 100$

1. As the temperature of a system increases, the relative humidity will decrease because p_s will increase while p stays the same. Likewise, as the temperature of a system decreases, the relative humidity will increase because p_s will decrease while p stays the same. As the temperature is decreased, the system will eventually reach saturation where $p = p_s$ and the air temperature = the dew point temperature.
2. As the total pressure of a system decreases, the relative humidity will decrease because p will decrease but p_s will not change because the temperature has not changed. Likewise, as the total pressure of a system increases, the relative humidity will increase until eventually saturation is reached.

The Capacitive Sensor

The capacitive humidity sensor consists of a hygroscopic dielectric material placed between a pair of electrodes that forms a small capacitor. Most capacitive sensors use a plastic or polymer as the dielectric material, with a typical dielectric constant ranging from 2 to 15. When no moisture is present in the sensor, both this constant and the sensor geometry determine the value of capacitance.

At normal room temperature, the dielectric constant of water vapor has a value of about 80, a value much larger than the constant of the sensor dielectric material. Therefore, absorption of water vapor by the sensor results in an increase in sensor capacitance. At equilibrium conditions, the amount of moisture present in a hygroscopic material depends on both the ambient temperature and the ambient water vapor pressure. This is true for the hygroscopic dielectric material used on the sensor.

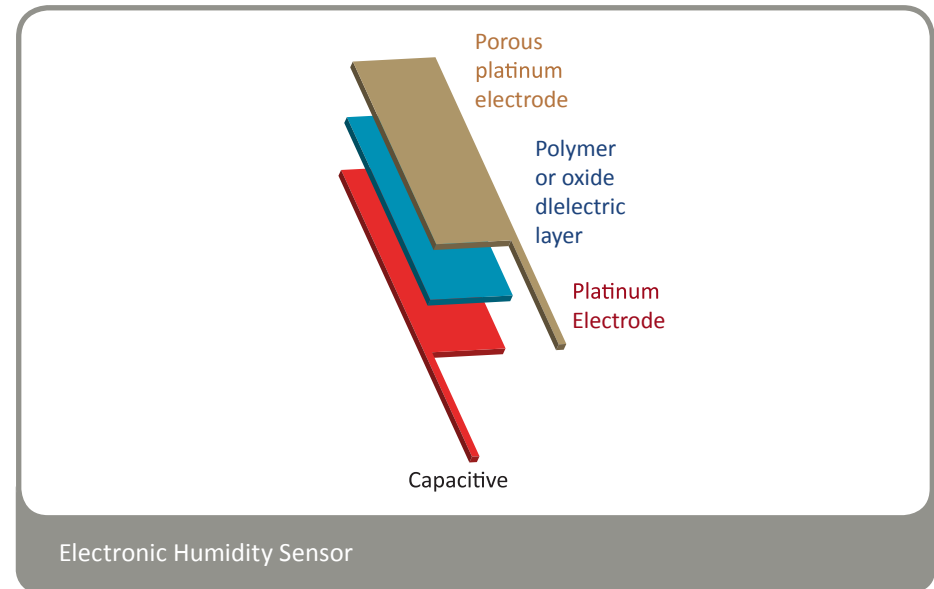


Application Considerations - Capacitive Humidity Sensors

Newer humidity measurement techniques such as the HYGROMER IN-1 capacitive humidity sensor have greater accuracy than that of the wet- and dry-bulb technique and also offer superior control characteristics over a wide range of temperatures and humidity.

By definition, relative humidity is also a function of both the ambient temperature and water vapor pressure. So there is a relationship between relative humidity, the amount of moisture present in the sensor and sensor capacitance. This relationship is the basis of the operation of a capacitive humidity instrument.

In a capacitive instrument, as in practically every other type of instrument, humidity is measured by a chain process and not measured directly. Instrument performance is determined by all of the elements of the chain, not by the sensor alone. Since the sensor and associated electronics cannot be considered separately, any factor that can disturb the chain process of measurement is bound to have an effect on the instrument performance.



Capacitive Humidity Sensors

Pros:

- Wide measurement range
- Wide temperature range
- Excellent stability
- Fast response
- Full recovery from condensation
- Highly resistant to chemicals
- Small
- Low cost
- Requires very little maintenance

Cons:

- Can be limited by distance from sensor to the electronics
- Loss of relative accuracy below 5% RH
- Requires electronics to convert capacitance to relative humidity



Choosing sensor technology that is compatible with your specific application is critical to achieving reliable, repeatable and accurate measurement

Classification of Errors in Capacitive Humidity Sensors



Systematic errors are predictable and repeatable, both in magnitude and sign. Errors resulting from a nonlinearity of the instrument or from temperature effects fall into this profile. Systematic errors are instrument specific.



Random errors are dependent on factors external to the instrument, which means that while systematic errors are predictable and repeatable, random errors are not. For example, errors resulting from sensor hysteresis, which we'll define below, as well as those resulting from the calibration procedure, are random errors. Usually, random errors are estimated on the basis of statistical data, experience and judgment.

Linearity Errors

The typical response of a relative humidity sensor (between 0 and 100% RH) is non-linear. Depending on the effectiveness of the correction made by the electronic circuits, the instrument may have a linearity error. Assuming that both the sensor and associated electronics have reproducible characteristics, the linearity error is a systematic error.



Careless selection of the calibration values can result in a different distribution of the linearity error and can be detrimental to instrument accuracy.

Generally, the values recommended by the instrument manufacturer for calibration were determined with the goal of minimizing the linearity error. Calibrating at those values should produce an even plus and minus distribution of the linearity error.

Temperature Errors

Temperature can have a major effect on several elements of the chain process of measurement described earlier. In the specific case of a capacitive humidity instrument, the following effects can produce a temperature error.

Sensor hygroscopic properties vary with temperature. A relative humidity instrument relies on the assumption that the relationship between the amount of moisture present in the sensor hygroscopic material and relative humidity is constant. However, in most hygroscopic materials, this relationship varies with temperature. In addition, the dielectric properties of the water molecule are affected by temperature. At 20°C, the dielectric of water has a value of about 80. This constant increases by more than 8% at 0°C and decreases by 30% at 100°C.

Sensor dielectric properties also vary with temperature. The dielectric constant of most dielectric materials decreases as temperature increases. Fortunately, the effect of temperature on the dielectric properties of most plastics is usually more limited than in the case of water.

Any length of cable connecting the sensor to the electronic circuits has its own capacitance and resistance. The electronic circuits cannot discriminate between the sensor and its connecting cable. Therefore, since the capacitance of the sensor and the cable can vary with temperature, the humidity values reported by the electronics must be compensated for the effects of temperature. Failure to do so can result in large measurement errors, sometimes up to 8% RH or more.

Hysteresis



Hysteresis is the maximum difference that can be measured between corresponding pairs of data, obtained by running an ascending and a descending sequence of humidity conditions. Hysteresis determines the repeatability of a humidity instrument.

For any given instrument, the value of hysteresis depends on several things:

- the total span of the humidity cycle used to measure hysteresis
- exposure time of the sensor to each humidity condition
- temperature during the measurements
- criteria used to determine sensor equilibrium
- and previous sensor history

Usually, sensor hysteresis increases as the sensor is exposed to high humidity and high temperature over longer periods of time.



Temperature can change the capacitance of the sensor and the cable. Humidity values reported by the electronics must compensate for the impact of temperature on the sensor.

It's only meaningful to state a sensor's hysteresis values while also providing details on how the tests were performed. In actual measurement practice, conditions are extremely diverse and hysteresis may or may not reach its maximum value. Therefore, it is reasonable to consider hysteresis a random value that can be neither fully predicted nor compensated. When the accuracy of an instrument is specified, half the maximum value of hysteresis should be equally distributed as a positive and a negative error. However, instrument repeatability should not be specified at less than the full value of hysteresis.

Calibration Errors



Calibration consists of comparing the output of a measurement instrument against a reference and reporting the results. Adjustment consists of changing the output of an instrument being calibrated to match the output of the reference. In some cases, the service named "calibration" includes both calibration and adjustment.

The reference instruments used to provide known humidity and temperature values for calibration have their own accuracy, repeatability, and hysteresis values, which must be taken into consideration when specifying final instrument uncertainty. In addition, no adjustment made during a calibration service can perfectly replicate the value seen by the reference

instruments. These errors must be considered and treated as random errors in the calculation of instrument uncertainty.

Long-Term Stability

One crucial factor is the instrument's ability to return the same values for RH for a given humidity condition over a long period of time. This value, usually termed repeatability, measures an instrument's ability to maintain its calibration in spite of shifting characteristics of the sensor and its associated electronics over long periods of time. Generally, one can split the problem of repeatability into two areas: the ability of the sensor to maintain its response to a given humidity condition at a given temperature and the stability of the electronics over time.



Long-term stability plays a critical role in the frequency of calibration required for a humidity instrument.



The stability of the instrument significantly affects the value of the measurement data received from the instrument between calibration cycles.

Chemical Resistance

Capacitive polymer humidity sensors are sensitive to the presence of chemicals in the surrounding gas.

The amount of the influence depends on a number of parameters:

- type of chemical
- concentration
- length of the influence
- amount of humidity and temperature
- and presence of other chemicals

Because it's difficult to make predictions about the deviation and the lifetime of the sensor, it's best to test.

Uncritical Chemicals

The following tables refer to the impact of these gases on the Rotronic IN-1 family of sensors:

Argon	Ar
Carbon dioxide	CO ₂
Helium	He
Hydrogen	H ₂
Neon	Ne
Nitrogen	N ₂
Nitrous oxide (Laughing gas)	N ₂ O
Oxygen	O ₂

The following gases have no or little influence on the sensor and the humidity measurement:

Butane	C ₄ H ₁₀
Ethane	C ₂ H ₆
Methane	CH ₄
Natural gas	
Propane	C ₃ H ₈

Critical Chemicals

In the following concentrations, the gases listed in the following table have no or little influence on the sensor or humidity measurement. The shown data are only guide values. The resistance of the sensor depends strongly on the temperature and humidity conditions and the length of the pollutant influence.

Allowed fault caused from the pollutant: +/- 2 %RH

Pollutant	Formula	Maximum Workplace Concentration		Allowed Concentration Continuous Operation	
		ppm	mg/m ³	ppm	mg/m ³
Acetic acid	CH ₃ COOH	10	25	800	2000
Acetone	CH ₃ COCH ₃	1000	2400	3300	8000
Ammonia	NH ₃	25	18	5500	4000
2-Butanone (MEK)	C ₂ H ₅ COCH ₃	200	590	3300	8000
Chlorine	Cl ₂	0.5	1.5	0.7	2
Ethanol	C ₂ H ₅ OH	1000	1900	3500	6000
Ethyl acetate	CH ₃ COOC ₂ H ₅	400	1400	4000	15000
Ethylene glycol	HOCH ₂ CH ₂ OH	100	260	1200	3000
Ethylene oxide	C ₂ H ₄ O	3		3	
Formaldehyde	HCHO	1	1.2	2400	3000
Hydrochloric acid	HCl	5	7	300	500
Hydrogen sulfide	H ₂ S	10	15	350	500
Isopropanol	(CH ₃) ₂ CHOH	400	980	4800	12000
Methanol	CH ₃ OH	200	260	3500	6000
Nitrogen oxides	NO _x	5	9	5	9
Ozone	O ₃	0.1	0.2	0.5	1
Petrol		300	1200		150000
Sulfur dioxide	SO ₂	5	13	5	13
Toluene	C ₆ H ₅ CH ₃	100	380	1300	5000
Xylene	C ₆ H ₅ (CH ₃) ₂	100	440	1300	5000

Application Examples

(A) Humidity Measurement in Sterilisation Chamber (Ethylene oxide)

Customer application:	Sterilisation of medical equipment
Sensor:	C-94
Concentration Ethylene oxide:	15% by volume
Carbon dioxide:	85% by volume
Pressure:	0.2 to 2.5 bar absolute
Temperature:	app. 40°C
Humidity:	app. 80 %RH

Application experience:

The sensors have a lifetime of approximately 3 months. The chamber is in continuous operation.

(B) Humidity Measurement in Ozone Chamber

Sensor:	C-94
Concentration ozone:	app. 500 ppm
Temperature:	app. 23°C
Humidity:	app. 50 %RH

Application experience:

The sensors have a lifetime of approximately 1 month at 500 ppm ozone.

(C) Special Application: Humidity Measurement in Oil

Humidity measurement direct in oil is possible in principle, but the lifetime of the sensors depends strongly on the used oil. Measurements in oil are only possible with a special sensor, and plan for tests.

The Wet Bulb/Dry Bulb Technology (psychrometer)

Introduction

Wet- and dry-bulb temperature measurement is a commonly used and widely accepted technique for controlling relative humidity in environmental chambers. ASTM standard E 337-02 (2007) reviews in great detail the wet- and dry-bulb technique. According to this standard, the accuracy which can generally be expected in the case of a ventilated dry- and wet-bulb device is in the range of 2 to 5 %RH.

The accuracy generally achieved in the case of a ventilated dry- and wet-bulb device is acceptable in the case of environmental chambers where both temperature stability and uniformity are specified to within 1 degree C, because an uncertainty of 1 degree C at 95% confidence $k=2$ on temperature automatically results in an uncertainty of 5 to 6 %RH at 95% confidence $k=2$ at high humidity. However, some chambers that are specified to within 0.3-0.5 degree C permit and require better humidity control.

Dry Bulb



Cloth

Wet Bulb



Water

Pros and Cons of the Technique

While the wet- and dry-bulb measurement technique has a sound theoretical basis, the problem is that it's simple only in appearance, leading many users to forego the caution and precision necessary to achieve accurate results. We'll explore the most common overlooked requirements and other problems below.

Pros:

- Simple and fundamental measurement
- Low price
- Good stability if operated correctly and consistently
- Tolerates condensation without damage

Cons:

- High uncertainty
- Requires training and skill to use and maintain
- Results must be calculated
- Requires a large air sample
- Process adds water vapor to the sample
- Many variables cause increased uncertainty

Disregarding the Basic Requirements of the Technique

In practice, there is a tendency to disregard some of the following requirements of the wet- and dry-bulb technique:

- Psychrometer coefficient: This is used to establish the psychrometric chart that converts wet- and dry-bulb temperature readings into relative humidity. This coefficient has to be determined for each specific design of psychrometer and in particular for each design of the wet-bulb.
- Barometric pressure: Psychrometric charts are usually valid at the “standard” barometric pressure and require a correction at other pressures.
- Matching of the thermometers: The wet-and dry-bulb thermometers should not only be accurate, but they should also be matched so as to minimize the error on the temperature depression readings (or temperature difference).

Interferences During Measurements

In an environmental chamber, errors of measurement can result due to poor choice in the mounting location of the wet- and dry-bulb thermometers. This is the case when the thermometers are installed too closely to a source of moisture (water supply for the wet-bulb, steam injector, etc.). Errors may also occur when the thermometers are too close to the walls of the chamber.



Make sure the thermometers are mounted at a location where conditions are fairly representative of the average conditions inside the chamber.

Poor Handling and Maintenance

Proper handling and frequent maintenance are major requirements of the wet- and dry-bulb technique. Poor measurement is frequently a result of the following:

Dirty Wick

The wick should never be directly touched with fingers. A new wick should be flooded with distilled water so as to wash away any contamination. In an environmental chamber, the wick is continuously ventilated and tends to get dirty after some time. From a maintenance standpoint, this is probably the most concerning aspect of the dry- and wet-bulb technique.

Wick Not Properly Pulled

The wick should sufficiently cover the wet-bulb thermometer so as to minimize errors due to heat conduction along the stem of the thermometer. The wick must also be in close contact with the surface of the thermometer.

Wick Not Really Wet

A wick that is too old or that has been left to dry out may not supply enough water. A properly wetted wick should have a glazed appearance.



Never directly touch a wick. Flood a new wick with distilled water to wash away contamination. If the wick doesn't look glazed, it's too dry.

Typical Accuracy of the Technique

Most of the problems mentioned above have a direct influence on the accuracy of the wet- and dry-bulb technique. Specifically, most errors show up on the wet-bulb temperature and the temperature depression measurement.

Considering just the uncertainties on temperature measurement and psychrometric coefficient, ASTM Standard #E 337-02 (2007) indicates that the range of errors for ventilated wet- and dry-bulb devices goes from 2 to 5 %RH.

An error of 2 %RH corresponds to an error of 0.1C on temperature depression and 0.2C on dry-bulb temperature, while an error of 5 %RH corresponds to an error of 0.3C on temperature depression and 0.6C on dry-bulb temperature. The most important factor is the accuracy of temperature depression measurement.

Taking into account the many other potential sources of error, the effective accuracy of the wet- and dry-bulb devices installed in most environmental chambers is no better than 3 to 6 %RH. The error tends to be the largest at low humidity and low temperatures where readings are usually too high.

Operational Limitations of the Wet- and Dry-Bulb Technique

In addition to limitations regarding accuracy, the wet- and dry-bulb technique has other limitations which may be important in the case of environmental chambers:

- No measurement below the freezing point.
- Adds water to the environment (a problem with chambers operating at low humidity).
- Sluggish response and therefore, poor control characteristics. The wet-bulb temperature reacts slowly to changes in humidity because of the mass of the wet-bulb thermometer and wick. Slow reaction to changes in temperature is due to the time required by the water supply to adapt.
- Requires a water supply and, therefore, can support the growth of micro-organisms.
- Calibration can be difficult.

Summary of Other Technologies

Chilled Mirror Technology

How it Works

A chilled mirror or condensation hygrometer is a technology used to directly measure the dew or frost point of a gas. If the temperature of a mirror is lowered to precisely the value that makes dew appear on the surface, the value of the mirror temperature is called dew point. Using the previous example, the dew point corresponding to a condition of 50 %RH and 25°C can be found as follows:

$$p_s \text{ at } 25^\circ\text{C} = 3.17 \text{ kPa}$$

$$p = 0.5 \times 3.17 \text{ kPa} = 1.585 \text{ kPa, corresponding to 50 \%RH}$$

If there is equilibrium between the dew on the mirror and the environment, it follows that p_s at the temperature of the chilled mirror must be equal to the vapor pressure p . Based on a simple interpolation of the values of the saturation vapor tables, we find that a value of p_s of 1.585 kPa corresponds to a temperature of 13.8°C. This temperature is the dew point. The above example shows that converting relative humidity into dew point and vice versa requires the use of a thermometer and saturation vapor tables. When the mirror is clean and dry, the intensity of the reflected light is at its maximum.



The mirror surface gradually cools until condensation occurs and water or frost forms on the mirror. When the water or frost forms, the light signal changes and the change is noted at the light receiver. As the light signal changes, the precise temperature of the mirror is recorded as the dew or frost point temperature.

If the condensate is known to be in the liquid form, even for temperature below freezing, the measured temperature is taken to be the dew point. If the condensate is known to be ice or frost, the measured temperature is taken as the frost point.

Pros:

- Very low uncertainty (as low as +/- 0.1 C at 95% confidence, k=2)
- Wide measurement range
- Able to measure very low frost point temperatures (as low as -95C)

Cons:

- Much more expensive than other technologies
- Requires training for operation and maintenance
- High level of maintenance
- Requires a clean environment
- Not suitable for inline process measurement

Aluminum Oxide Technology

How it Works

An aluminum oxide sensor is a type of capacitor formed by depositing a layer of porous aluminum oxide on a conductive substrate and then coating the oxide with a thin film of gold.

The capacitance measured between the sensor's aluminum core and the gold film fluctuates as the water vapor content in the air changes. The number of water molecules absorbed determines the electrical impedance of the capacitor, which is proportional to the water vapor pressure.

When the sensor is exposed to moisture, water vapor is rapidly transported through the exposed (positive) electrode layer where the polar water molecules form weak hydrogen bonds at the oxide surfaces. Absorption causes changes in the dielectric constant and resistivity of the oxide layers. Thus, a measure of the sensor conductance is a measure of moisture loading on the aluminum oxide dielectric, and is proportional to the moisture concentration in the sample gas.



Aluminum oxide sensors measure the absolute amount of water vapor in the gas. Capacitive sensors measure the relative humidity in the gas (the percentage of water vapor present in proportion to the maximum amount of water vapor possible at the given temperature).

Aluminum Oxide sensors are good for very dry and clean conditions where quick measurement is not required.

Pros:

- Small size of sensor
- Suitable for inline use
- Wide measuring range
- Good for measuring very dry environments (as low as -75° to -100° C dew point temperatures)

Cons:

- Susceptible to contamination, condensation deposited on the sensor can cause significant calibration shift
- Slow response times (up to 24 hours in worst cases)
- Long stabilization times
- Require frequent calibration
- Potential for significant drift over time
- Considerable hysteresis

Choosing the Right Humidity Measurement Technology

Considering the wide variety of environmental variables that influence water vapor and affect measurement, it's important to know precisely which type of instrument and technology will enable you to measure most accurately in any given application. It is important to know the various factors of your application that will affect different types of measurement technology.

Consider these 10 questions to ask and answer as you select the instrument and associated technology:

1. Why do we need to measure humidity?
2. What parameter will we require to quantify water vapor?
3. What is the expected range of measurement?
Temperature? Relative Humidity? Pressure?
4. What level of performance will we require? Uncertainty?
Long term stability? Response time? Resolution of output?
5. What type of output will we require?
6. What is the most appropriate mechanical configuration?
7. What is the composition of the air or gas to be measured?
8. What are the installation requirements?
9. What are we willing to pay for the required performance?
10. What should I expect from the manufacturer for support after the sale?

The answers to these questions will steer you in the right direction for choosing technology and configuration of your hygrometer.

Given the difficulties of measuring humidity, the confusing claims made by many suppliers of humidity instrumentation, and the broad range of cost and quality for apparently identical specifications, how does one choose a proper and accurate instrument for a particular application?



Because there is no real physical standard for relative humidity calibration, inaccurate specifications for humidity instruments is a rampant problem among instrument providers – more common than with many other types of instrument. This abuse leads to specifications that are of limited value when comparing instruments from various manufacturers. You must dig deep into the specifications and claims of instrument manufacturers.

Carefully examine the supplier's claims and support documentation in the following areas:

- sensor linearity
- temperature constants
- hysteresis
- calibration errors
- and long-term stability of sensor and electronics



Be sure to read Part 2 of our series to learn more about making accurate humidity measurements in common applications.



Myth/Fact

Not all humidity sensor specifications are created equally.

Accuracy specifications are created by manufacturers, and each manufacturer assigns them differently. Accuracy may be stated in a very narrow band based on a short period of time in a benign environment.

That's why it's important to evaluate accuracy specifications with a critical eye.

Ask:

- What is the humidity range and temperature range for the specification?
- What happens to the specification as the sensor ages?
- Are there any contaminants that affect the accuracy?
- Do certain humidity and temperature conditions affect the long-term stability of the sensor? (i.e. high temperature + high humidity)
- Does the specification include all sources of error such as hysteresis, temperature dependency, linearity and calibration?
- What were the type, condition and uncertainty of the standard used for the determination of the specification?

The answers to these questions will help you understand the significant differences between a \$175 hygrometer and a \$1500 hygrometer, and what you can expect in its level of performance.

Conclusion

While no scientific measurement is absolutely true, reaching humidity measurements that are as accurate as possible is crucial across industries. Multiple factors play into the accuracy of your measurement, so it's important to understand:

- How relative humidity works
- How an accurate measurement is achieved
- How measurement technology works, including various methods and the pros and cons of each technique
- The air/gas composition of the area you are measuring
- The requirements of your specific application and
- The claims and support documentation for the suppliers you're considering

>> About Rotronic

Rotronic offers a comprehensive line of instrumentation for the measurement of key environmental parameters. As a leader in humidity measurement, Rotronic produces an extensive line of reliable humidity probes, humidity indicators and meters, humidity data loggers and fixed installed humidity transmitters to precisely measure relative humidity, dew point, water activity, temperature and other psychrometric parameters. Rotronic also offers a fast Humidity / Temperature generator – calibrator as well as humidity sensors and custom designed modules for OEM customers. Instrumentation from Rotronic also measures the important parameters carbon dioxide and differential pressure.

Applications covered by the wide range of Rotronic instruments range from commercial HVAC and building management systems, to weather stations, test and research laboratories, industrial process measurement/control, and product quality control.

From Rotronic you are assured guaranteed reliability: you work with validated software, you work with officially accredited calibration laboratories, and you have access to many products which fulfill international regulations (GAMP / FDA compliance) and no matter where you are, with 9 subsidiaries and more than 40 distributors worldwide, you can rely on a competent and efficient sales and service network.

Learn more at www.rotronic.com. If you have any questions, please contact your local Rotronic representative. Local contact information can be found here: www.rotronic.com