Relative Humidity, Pressure and Temperature

Foreword

This technical note reviews 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. Examples are provided to illustrate the influence of temperature and pressure on relative humidity and to show how to convert relative humidity into dew point and absolute humidity.

This note is largely inspired from the textbook Chemistry by Theodore L. Brown and H. Eugene LeMay, JR. (Prentice-Hall, 1977).

Ideal Gas Laws

By definition, an ideal gas follows the following laws:

Boyle's Law: this law states that 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.

Charles's Law: this law states that at constant pressure, the volume of a given quantity of gas is proportional to absolute temperature (°K).

$$V = q \times T$$

where q is a proportionality constant that depends on the quantity of gas.

Charles's law can be stated in another form: at constant volume, the pressure of a given quantity of gas is proportional to absolute temperature.

$$P = j \times T$$

where j is a proportionality constant that depends on the particular sample of gas and its volume.

note: to convert temperature in °C into absolute temperature in °K, add the constant 273.15.

Dalton's Law of Partial Pressures: this law states that that 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.

$$P_t = P_1 + P_2 + P_3 + \ldots$$

where P_1, P_2, etc., are the partial pressures of gases 1, 2, etc.

Avogadro's Hypothesis: this hypothesis states that equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. For instance, one liter of any ideal gas at a temperature of 0°C and a pressure of 101.3 kPa, contains 2.688×10^{22} molecules.

note: the temperature of 0°C and pressure of 101.3 kPa is the standard temperature and pressure condition or STP.

Volume of a Mole of Gas at STP:

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 12 g of ^{12}C (Carbon 12).

It has been experimentally determined that the number of atoms in this quantity of ^{12}C is 6.022×10^{23}. This number is called Avogadro's number.

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.

Ideal Gas Law: this law states that the product of volume and pressure of a given amount of gas is proportional to absolute temperature.

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

where 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. Taking dry air near sea level as an example, the mole fractions of the three main components are as follows:

Nitrogen	: 0.78084
Oxygen	: 0.20948
Carbon Dioxide	: 0.00954

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:

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

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

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

Effect of a Change In Pressure

Dalton's law states that the total pressure of a gas mixture is equal to the sum of the partial pressures of its components. From this, it was derived 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.

Real Gases

Real gases fail to obey the laws of ideal gases to greater or lesser degree. The van der Waals equation corrects the equation established for ideal gases:

$$(P + an^2/V^2)(V - nb) = nRT$$

where a and b are constants that depend on the nature of the gas.

From the van der Waals equation, it is apparent that a real gas tends to behave like an ideal gas when the volume of gas is large.

The constant b of most common gases is less than. At STP, the number of moles n is equal to one when the volume V equals 22.4 l. Therefore, most real gases behave almost like ideal gases when placed in a large volume at moderate pressure (1000 kPa or less).

Vapor Pressure above a Liquid

Molecules in a liquid are closer one to another than they are in a gas. Therefore, 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, many 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 so 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.

The presence of gases other than vapor above a liquid does not affect the kinetic energy of molecules inside or outside the liquid and does not affect the magnitude of the intermolecular forces in the liquid. Therefore, vapor pressure above a liquid does not depend on the total pressure above the liquid.

Vapor Pressure Of Water

The vapor pressure of water, or saturation vapor pressure, increases strongly with increasing temperature:

Temperature (°C)	Water Vapor Pressure (kPa)
0	0.61
10	1.23
20	2.34
30	4.24
40	7.37
50	12.33
60	19.92
70	31.18
80	47.34
90	70.11
100	101.33 = 1 atm

Vapor Pressure of Water Mixed with Another Substance

If water is mixed with a non volatile substance to form a non electrolyte solution, the vapor pressure is proportional to the mole fraction of water in the solution (Raoult's law). Because of the electrostatic attraction between ions, electrolyte solutions do not exactly follow Raoult's law.

This can be explained as follows:

At a given temperature, the kinetic energy of all particles (molecules, ions) in the solution is the same. Essentially the same number of particles are at the surface in both the solution and pure water. However, in the case of the solution, only the water molecules can escape from the solution. As these represent only a fraction of the total number of particles present at the surface, vapor pressure is lowered.

The following table provides a few examples of saturated salt solutions (electrolyte solutions) at a temperature of 25°C:

Solute	Vapor pressure (kPa)	Pressure Ratio Solution/Pure Water
LiCL	0.358	11.3 %
MgCl	1.039	32.8 %
NaCl	2.387	75.3 %
KCl	2.673	84.3 %

Vapor Pressure above Ice

When water freezes, the molecules assume a structure which 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, it follows that the inter-molecular attraction forces are the strongest in ice. For that reason, vapor pressure above ice is less than the vapor pressure above liquid water.

Temp (°C)	Vapor Pressure Liquid (kPa)	Vapor Pressure Ice (kPa)	Ratio Ice/Liq.
0	0.611	0.611	1.00
-5	0.422	0.402	0.95
-10	0.287	0.260	0.91
-15	0.191	0.165	0.86
-20	0.126	0.103	0.82
-25	0.081	0.064	0.78
-30	0.049	0.037	0.75

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.

$D_v = M_w / V$, expressed in grams/m^3 or in grains/cu ft

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

$M_w = n_w \times m_w$, where :

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

$D_v = M_w / V = n_w \times m_w / V = m_w \times p / RT$, where:

m_w = 18.016 gram
p = partial pressure of water vapor [Pa]
R = 8.31436 Pa x m3 / °K x mole
T = temperature of the gas mixture in °K
$D_v = p / 0.4615 \times T$ [g / m^3]

1 gr (grain) = 0.0648 g (gram)
1 cu ft = 0.0283168 m^3

D_v [gr / cu ft] = 0.437 x D_v [g / m^3]

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.

$Q = M_w / (M_w + M_a)$

$Q = p\ m_w / (p\ m_w + (P_b – p)\ m_a)$

$Q = 1000\ p / (1.6078\ P_b – 0.6078\ p)$ [g / kg]

1 gr (grain) = 0.0648 g (gram)
1 lb = 0.4535923 kg

Q [gr / lb] = 7 x Q [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:

$r = M_w / M_a$

$M_w = n_w \times m_w = m_w \times p\ V / RT$
$M_a = n_a \times m_a = m_a \times p_a\ V / RT = m_a \times (P_b – p)\ V / RT$, 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 Pa x m3 / °K x mole
T = temperature of the gas mixture in °K
V = volume occupied by the air – water vapor mixture

$r = m_w\ p / m_a\ (P_b – p)$

$r = 621.97 \times p / (P_b – p)$ [g / kg]

1 gr (grain) = 0.0648 g (gram)
1 lb = 0.4535923 kg

r [gr / lb] = 7 x r [g / kg]

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:

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

$n_w = p V / RT$
$n_a = p_a V / RT = m_a \times (P_b - p) V / RT$, 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 Pa x m3 / °K x mole
T = temperature of the gas mixture in °K
V = volume occupied by the air – water vapor mixture

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

Relative Humidity

Relative humidity is the ratio of two pressures: $\mathbf{\%RH = 100 \times p/p_S}$

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 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 which 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

When considering the effect of temperature and pressure on the partial pressure of vapor, it is essential to make a difference between the following situations:

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

<u>Saturation:</u>

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.

<u>No Saturation</u>

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

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

a) <u>In an open space</u>: 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 and this results in a decrease of the partial pressure of vapor.

b) <u>In a closed container of fixed volume</u>: vapor occupies the entire volume of the container and this volume is constant. Therefore, the partial pressure p can vary only if there is a change in <u>absolute</u> temperature (degrees K) or a change in the amount of vapor. The partial pressure p does not vary with a change in total pressure.

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.

From the above it follows that:

a) 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.

b) in an open space, at constant moisture level and pressure, %RH decreases strongly as temperature increases.

c) in a closed container of fixed volume, %RH decreases as temperature increases, however not quite as strongly as in the situation of the open space.

Examples

a) Office Building: for practical purposes, an office building can be considered as an open environment. A localized increase in temperature created by a heater or an office machine, does not modify the value of the partial pressure of water vapor. Therefore, the local vapor pressure is the same as elsewhere in 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 temperature is 25°C and relative humidity 50 %, a localized increase of temperature to 30°C lowers relative humidity as follows:

p_S at 25°C = 3.17 kPa
p_S at 30°C = 4.24 kPa

p = 0.5 x 3.17 kPa = 1.585 kPa, corresponding to 50 %RH

Localized %RH = 100 x 1.585/4.24 = 37.4%

b) <u>Dew on a Chilled Mirror</u>: if the temperature of a mirror is lowered to precisely the value that makes dew appear at the surface of the mirror, 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 at 25°C = 3.17 kPa
p = 0.5 x 3.17 kPa = 1.585 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.

This example 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 maintained constant, the partial pressure of water vapor is increased 1.5 times. Because temperature is maintained constant, the saturation pressure p_S is not changed. If we assume that we had a condition of 50 %RH and 25°C before the compression, the condition after compression is 75 %RH and 25°C.

d) Injection of a dry Gas in a Closed Chamber

If, for instance, dry nitrogen is injected in a closed chamber where there is already air at a condition of 50 %RH and temperature is maintained 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 % in spite of the fact that a dry gas was injected in the chamber.

Relative Humidity Calibration

a) Method of Calibration

A frequent method of calibrating a relative humidity instrument is to place the humidity sensor in a closed container. By putting a known solution of water and another substance inside the container, a known humidity is established at equilibrium. This humidity value is used to provide a reference against which the instrument can be adjusted or calibrated.

b) Temperature Stability

Obtaining equilibrium conditions is one of the most critical requirements of the method. This means that there should be no difference of temperature between the humidity sensor, the solution and the head space above the solution. Unstable temperature during calibration will not permit this. A temperature stability of 0.02°C/min or better is required during the calibration process for the method to be accurate.

c) Temperature of Calibration

The relative humidity values generated by the different solutions used to the purpose of calibration, are affected by temperature. Therefore, a correction must be made for the temperature of calibration. However, no correction is required for the effect of temperature on the total pressure inside the calibration container.

The temperature of calibration may also be restricted by the design of the instrument. For instance, an instrument that provides a compensation for the effect of temperature on the humidity sensor does so by assuming that the temperature of calibration is always the same. In that case, the manufacturer provides a recommendation as to the range of calibration temperature that results in the best overall accuracy for the instrument.

d) Altitude

Because vapor pressure above a solution is not affected by total pressure, no correction is required for altitude.

e) Influence of Temperature Variations on Solutions

A saturated solution results of the dynamic equilibrium of two processes: formation of a solution and crystallization. If a saturated salt solution is used for calibration, attention must be paid to this equilibrium. Because solubility depends on temperature, a variation in the temperature of a saturated solution can disturb the dynamic equilibrium process in the solution. Time must be allowed for equilibrium when the temperature of a saturated solution is changed. This time period is usually significantly longer than the time required by the temperature of the solution to stabilize at a new value.

Non saturated solutions adapt faster to a change in temperature because they do not require a dynamic equilibrium between a crystal and a liquid. This is convenient for use in field calibrations where temperature is not precisely known ahead of time.

Most solutions release or absorb heat during their preparation. For that reason, solutions should be prepared in advance.

Are they all the same? Choosing the right humidity instrument

Selecting the right relative humidity instrument for a specific application can be confusing, largely because most instruments on the market have specifications that are almost identical. Consider, for example, the accuracy specification. Many instruments, of all cost and quality levels, specify accuracy of ± 2.0% RH or even better, regardless of the conditions to be measured. Is it possible that instruments that are so widely different both in design and cost are all equally good? Is an accuracy of range of 1.0% to 2.0% RH commonplace? What about the long term stability of the humidity measurement? What role should it play into the decision process when selecting a RH instrument?

This article will first look at the principle of operation of capacitive humidity sensors, and then we will examine the source of errors in an RH measurement, and finally discuss the steps necessary to select the correct instrument.

Principle of Operation

The capacitive humidity sensor consists of a hygroscopic dielectric material placed between a pair of electrodes which 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 also for the hygroscopic dielectric material used on the sensor.

By definition, relative humidity is also a function of both the ambient temperature and water vapor pressure. Therefore there is a relationship between relative humidity, the amount of moisture present in the sensor, and sensor capacitance. This relationship is the base 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 as opposed to being measured directly. Instrument performance is determined by all of the elements of the chain and not by the sensor alone. 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.

Classification of Errors

For the purpose of analysis, errors of measurement can be divided into two broad categories: Systematic and Random errors.

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.

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.

Generally, the values recommended by the instrument manufacturer for calibration were determined so as to minimize the linearity error. Calibrating at those values should produce an even plus and minus distribution of the linearity error. Careless selection of the calibration values can result in a different distribution of the linearity error and can be detrimental to instrument accuracy.

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 that 8% at 0°C and decreases by 30% at 100°C.

Sensor dielectrics 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 can not 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 as large and 15% to 20% RH.

While systematic errors are predictable and repeatable, random errors are not fully predictable because they are essentially dependant on factors external to the instrument. For example, errors resulting from sensor hysteresis, 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.

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 a number of 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.

Because of these points, it is not meaningful to state a sensor's hysteresis values without 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 adjusting the instrument output to the values provided by two or more reference humidity conditions. The accuracy to which these conditions are known is critical. 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 accuracy. In addition, no adjustment made during calibration 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 accuracy.

Long Term Stability

Another factor which is crucial, and in fact as important if not more so that instrument accuracy, 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 instruments 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. In addition, the stability of the instrument also significantly affects the value of the measurement data received from the instrument between calibration cycles. Both of these points help determine the overall cost of choosing an instrument.

Choosing a Humidity Instrument

Given all of the difficulties of measuring humidity and the confusing claims of the majority of suppliers of humidity instrumentation, how can a proper and accurate instrument be chosen for a particular application? Since specifications for instruments produce a large range of cost and quality for the same specifications, how can the user find the correct instrument?

The most important point to understand is there no real physical standard for relative humidity calibration. As a result, there has probably been more abuse in specifying humidity instruments than any other type of instrument. This abuse leads to specifications which are of limited value when comparing instruments from various manufacturers. Therefore the user finds that he or she must dig deeper into the specifications and claims of the instrument manufacturer. To achieve this goal, the end user must carefully examine the supplier’s claims and support documentation in the following areas: sensor linearity, temperature constants, calibration errors, long term stability of sensor and electronics, and hysteresis.

Wet Bulb / Dry Bulb - Description and Limitations

Summary

Wet- and dry-bulb temperature measurement is a commonly used technique for controlling relative humidity in environmental chambers. Actually, the wet- and dry-bulb technique enjoys wide acceptance.

ASTM standard E 337-84 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.

This kind of accuracy is acceptable in the case of environmental chambers where both temperature stability and uniformity are specified to within 1 degree C. This is so because an uncertainty of 1 degree C on temperature automatically results in an uncertainty of 5 to 6 %RH at high humidity. However, some chambers which are specified to within 0.3 - 0.5 degree C permit and require better humidity control.

Newer humidity measurement techniques such as the HYGROMER C-94 capacitive humidity sensor have greater accuracy than that of the wet- and dry-bulb technique. Of equal importance is the fact that the sensor offers superior control characteristics over a wide range of temperatures and humidity. Unlike other capacitive sensors, the C-94 sensor performs accurately even at high humidity and temperature. The HYGROMER C-80 sensor can survive conditions from -50 to +200 C and from 0 to 100 %RH.

Problem Areas in the Wet- and Dry-Bulb Technique

There is no question that the wet- and dry-bulb measurement technique has a sound theoretical basis. The problem is that this technique is simple only in appearance. And, it is so widely accepted that many users are not anymore critical or careful. This results in a number of problems which are reviewed in the following paragraphs.

Non-Observance of Basic Requirements

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

- Water temperature: the theory of the wet- and dry-bulb technique assumes that the temperature of the water used for the wet-bulb is equal to the temperature of the environment to be measured.

- Psychrometer Coefficient: the psychrometer coefficient 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.

- Purity of water: psychrometric charts are established under the assumption that pure water is being used for 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 of a 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. it is important to mount the thermometers 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. Costly service calls frequently result of the following:

- Dirty Wick: the wick should never be directly be 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 bothering 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 which is too old or which has been left to dry out, may not supply enough water. A properly wetted wick should have a glazed appearance.

Typical Accuracy of the Wet- and Dry-Bulb Technique

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

Considering only the uncertainties on temperature measurement and psychrometric coefficient, ASTM Standard #E 337-84 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. 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 appears to be the accuracy of temperature depression measurement.

Taking into account the many other potential sources of error, it can be assumed that the effective accuracy of the wet- and dry-bulb devices installed in most environmental chambers is not better than 3 to 6 %RH. The error tends to be the largest at low humidity and at low temperatures. At these conditions, 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
- Cannot be easily calibrated and trouble-shot

Water Activity Instruments: a comparison of two measuring techniques

A point-by-point comparison shows that there is no real advantage of the chilled mirror Aw meters over the lower priced instruments that use a relative humidity sensor.

Water Activity Measuring Techniques

Most laboratories measure water activity either with an instrument that uses a relative humidity sensor or with an instrument that uses a chilled mirror.

Instruments based on a relative humidity sensor are typically less expensive than the chilled mirror instruments. This raises the question of whether the chilled mirror Aw meters have enough inherent advantages such as speed, accuracy and measuring range to offset the disadvantage of both a higher price and higher maintenance requirements.

Speed of Measurement

The measurement of water activity is an indirect measurement. All Aw instruments measure the amount of water vapor in the air surrounding the product sample. The time required for the water vapor in the product sample to equilibrate with the air in the chamber varies significantly with the composition of the product and temperature stability between the product sample and the air. Typically the full equilibrium time requires 30 minutes or longer. Using a variety of methods to speed the measurement most Aw instruments available on the market today provide a reading of Aw in approximately 5 minutes.

Temperature Stability

Temperature stability always matters during Aw measurements. A temperature imbalance or the lack of temperature stability between the product sample and the chamber air volume can change the partial pressure of water vapor generated by the product sample. From this point of view all types of sensors, chilled mirror or relative humidity, are equally affected by temperature instability. When temperature is not stable, measurements take longer and/or are inaccurate. Therefore the product sample should always be in equilibrium with the measurement chamber. Since the length of time required to reach temperature equilibrium depends on the product sample and the difference in initial temperature of the product sample, be sure the instrument provides the capability to report temperature instability.