Application Note: Humidity Measurements

Contents

1. Introduction

a) What is air humidity?

Air humidity value is the amount of water vapor present in the air. Air humidity can be expressed in terms of relative humidity and absolute humidity.

b) Relative vs absolute humidity

Relative humidity expresses in percentage (%) the quantity of water vapor present compared to the maximum amount that air can contain at given conditions (temperature, pressure). The range is from 0 to 100%. In terms of relative humidity, humans are most comfortable at 50%, but the acceptable broad range is 30 to 70% (Yunus A. Çengel 2007).

Absolute humidity expresses the absolute quantity of water vapor (kg) per unit of air weight (kg). The SI units are therefore “kg/kg” and is expressed with a fraction (e.g., 0.1 kg/kg). For Earth climate, the absolute humidity of air will vary approximately between 0 and 0.033 g of water per gram of air.

c) Examples of applications

Applications of humidity measurements include:

- Evaluating the human comfort in a given environment;
- Monitoring the performance of an HVAC equipment;
- Building a local weather station;
- Monitoring the environment of an experiment (refrigerator humidity);
- Calculating thermal comfort indexes.

2. Types of humidity measurements

a) Bulb temperature definitions

A dry bulb temperature is the temperature of a dry thermometer bulb, protected from the sunlight.

A wet bulb temperature (thermodynamic wet bulb temperature) is the lowest temperature of a surface saturated with water and exposed to atmospheric air. This temperature is always equal or inferior to the dry bulb temperature, because heat is absorbed from the bulb during the evaporation process. In moderate climates, the wet bulb temperature will generally be 0 to 20°C below the dry bulb temperature.

A natural wet bulb temperature is obtained by exposing a wet bulb apparatus to the ambient conditions of lighting and air velocity. This variable is used to calculate thermal comfort indexes such as the Wet Bulb Globe Temperature index (WBGT).

To avoid confusion between the two types of wet bulb temperature, they will be called “aspirated wet bulb” and “natural wet bulb” for the remainder of the text.

b) Wet bulb working principle

As the water evaporates on the surface, it absorbs heat from the thermometer. Thermal equilibrium is eventually reached and the temperature stabilizes. In a low-humidity environment, water evaporates more easily as the vapor pressure is low. Hence, the difference between dry and wet bulb temperature is large. In a high-humidity environment, water evaporates less easily since the vapor pressure is already high. Hence, the difference between the dry and wet bulb temperature is lower. This difference is called a ‘wet-bulb depression’. As the wet bulb temperature increases, it is increasingly difficult for live organisms to cool themselves by evaporative cooling. It is usually considered difficult for humans to stay alive when the wet bulb temperature is 35°C and above.

Aspirated wet bulbs designed according to ASHRAE Standards 41.6-1994 (RA 2006) and 41.1-1986 (RA 1991) can achieve an uncertainty of +/- 0.1°C (Brenner, Nellis, and Reindl 2011). This does not include the uncertainty of the thermometer itself.

c) Psychrometer sling

The psychrometer sling (also called whirling thermometer) is the traditional way to measure the thermodynamic wet bulb temperature (Yunus A. Çengel 2007).

To accurately provide the thermodynamic wet bulb temperature, the sling psychrometer must generate a minimum air velocity of 5 m/s at the bulb (Parson 2014). Above this value, equilibrium is reached and the temperature does not vary with air velocity. This minimum speed usually requires at least 2 rotations per second and should be maintained until the reading is stable (typically 2 minutes). The sling psychrometer is not well suited to continuous measurements, as it requires constant human labor.

Figure 1 Sling psychrometer with its two thermometers: the wet bulb (top) and the dry bulb (bottom) thermometers.

Figure 2 Using a sling psychrometer by imposing a fast rotation

d) Digital humidity sensors

Digital humidity sensors are now very common. Based on either the resistive or the capacitive properties of thin polymer films, they allow convenient, continuous measurements at a reasonable price. They can provide a digital signal of the temperature and relative humidity output, based on the inner components and the equations within the sensor. The equations used by the sensor chip are not always provided by the manufacturer.

There is a large range of quality for humidity sensors, and price varies accordingly. The SHT-20 and AM2301b are popular examples of low-cost digital humidity sensor (Figure 3).

The most common issue with this type of sensor is accuracy. After a few months of normal use, a large number of units will have drifted significantly away from their calibration. They are also sensitive to extreme events (temperature, condensation). For example, bad humidity sensors within HVAC systems are a very common source of problems. Sensor calibration should be verified at least once a year. The accuracy and durability depend greatly on the price of the device. The typical accuracy of the calculated relative humidity is ±2% for high-end models and ±10% for low-end models.

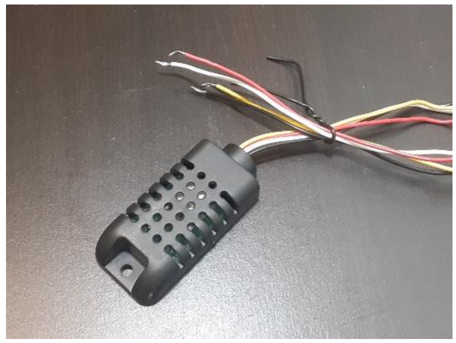

Figure 3 AM2301b digital humidity sensor

e) Pros and cons of wet bulbs vs digital humidity sensors

Wet bulbs and digital sensors both have pros and cons, which are summarized in Table 1.

Table 1 Pros and cons of wet bulb and digital sensors

	Static or natural wet bulb	Digital humidity sensor
PROS	Highly reliable	No maintenance
	Robust	No calculation
	Low cost	Any position
	Tolerates 100% RH	Faster reaction rate
	Simple working principle	Similar uncertainty than sling
	Used for WBGT index	
CONS	Higher uncertainty than sling	Expensive
	Cannot be upside down	Does not tolerate >95%RH
	Slower reaction time	Less reliable
	Can spill water	Not used for WBGT index
	Requires water fill-up	Complex working principle
	Occasional wick replacement	

Typical cost of the various instruments for humidity measurements (2022)

- Electronic humidity sensor: US$ 30 – 500 per unit
- Sling psychrometer: US$ 20 –100 per unit
- Professional cotton wick: US$ 1 per unit

3. Equations

Data from the psychrometric chart is essentially experimental. However, with reduced accuracy, correlations have been built that can be fed into a computer program.

The current RDL source code assumes the use of the aspirated value. Also, absolute humidity is currently not within the RDL source code and is not a possible output: it has to be done as post-treatment in a spreadsheet. However, both the natural wet bulb correlation and the absolute humidity are potential future developments.

a) Relative humidity from aspirated wet bulb

Over the years, multiple models have been used to estimate vapor pressure and relative humidity from the dry- and wet-bulb temperatures(Anon 2022). Such models include the Goff-Gratch equation, the Arden Buck equation, the Antoine equation and Jensen/Harrison equation.

Here a few methods are described. The method #2 is presently the one implemented in the RDL source code. The user could choose to implement a different set of equations.

Method #1: Antoine Equation

A first set of equations to calculate relative humidity is Antoine equation as described by (Parson 2014). The Antoine equation estimates the vapor pressure of pure substances. Each substance uses different coefficients. It must be noted that the does not take into account the impact of atmospheric pressure.

$$P\_sa = \exp(18.956 - 4030.18 / (Tdb + 235))$$

$$P\_swb = \exp(18.956 - 4030.18 / (Twb + 235))$$

$$P\_a = P\_swb - 0.667*(T\_a - T\_wb)$$

$$RH = P\_a / P\_sa \times 100$$

where

P_sa = saturation vapor pressure at the dry bulb temperature, millibar

P_swb = saturation vapor pressure at the wet bulb temperature, millibar

P_a = actual vapor pressure, millibar

RH = relative humidity (%)

Method 2: Jensen/Harrison

The method here was taken from (Butler and García-Suárez 2012), who described the work of (Jensen, Burman, and Allen 1990) and (Harrison 1965). The method includes atmospheric pressure as a parameter.

es(T_db) =exp[(16.78 * T_db - 116.9)/(T_db + 237.3)]

es(T_wb)=exp[(16.78 * T_wb - 116.9)/(T_wb + 237.3)]

A= 0.00066*(1.0 + 0.00115*T_wb)

e(T_db) = es(T_wb) - A * P * (T_db-T_wb)

RH [%] = 100 * e(T_db)/es(T_db)

Methode 3 : Buck equation (1981)

TBD

The equation is valid for temperatures above 0°C. A different set of constants must be used below 0°C.

b) Absolute humidity from aspirated wet bulb

Specific humidity equation by (Buck 1996):

w= 216.7 * e / Tk

where w = specific humidity

e = vapor pressure at dry bulb temperature

Tk = temperature in Kelvin

c) Relative humidity from natural wet bulb

The conventional relative humidity equations are based on the adiabatic-saturation temperature which requires an aspirated wet bulb temperature. The natural wet bulb temperature cannot be used with those equations without a significant level of error, especially if the air velocity is close to zero (e.g., inside a room).

However, alternative equations - of empirical nature - exist to approximately convert the natural wet bulb to an aspirated wet bulb temperature (Brake 2001) but they imply assumptions about air velocity or the convection coefficient.

d) Absolute humidity from natural wet bulb

TBD

4. Jericho humidity measurements

a) Jericho wet bulb description

With its 16 channels dedicated to resistive measurements, the RDL device can measure simultaneously up to eight (8) distinct humidity sensors, as you need both a dry and a wet bulb temperature to calculate the humidity at a given location. Figure 4 shows the Jericho dry and wet bulb setup in its large form factor (TH-2). The wet bulb apparatus is made of a thermistor, a 10-15 cm capillary wick, a small container (30 mL) with a lid and distilled water. The wet bulb can be made from either the TH-1 or TH-2 sensors, as seen in Figure 6.

Figure 4 Dry bulb and natural wet bulb temperature sensors

To create an aspirated wet bulb apparatus, a small 12V DC fan can be used (see Figure 5). Whether it is a natural or aspirated wet bulb, the bulb must be in a vertical position to ensure sufficient yet not excessive wetting (e.g., dripping).

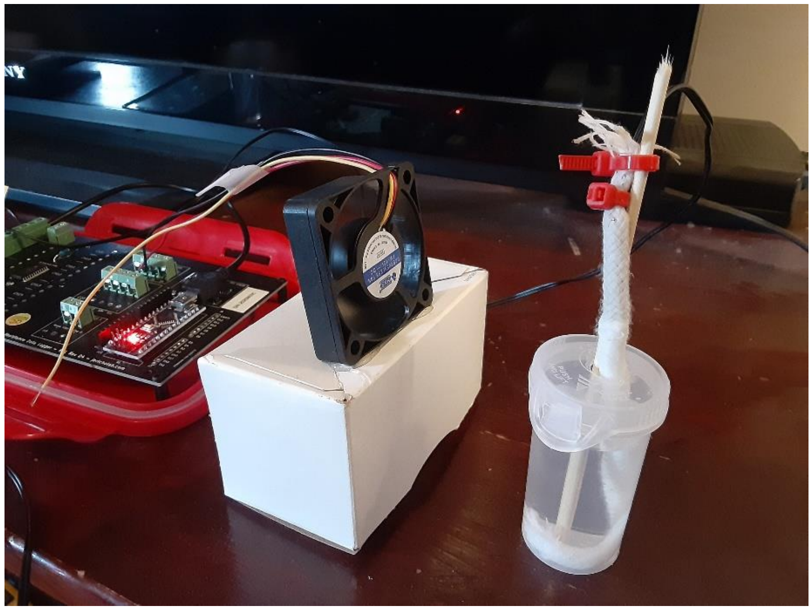

Figure 5 Self-made aspirated wet bulb temperature in the vertical position

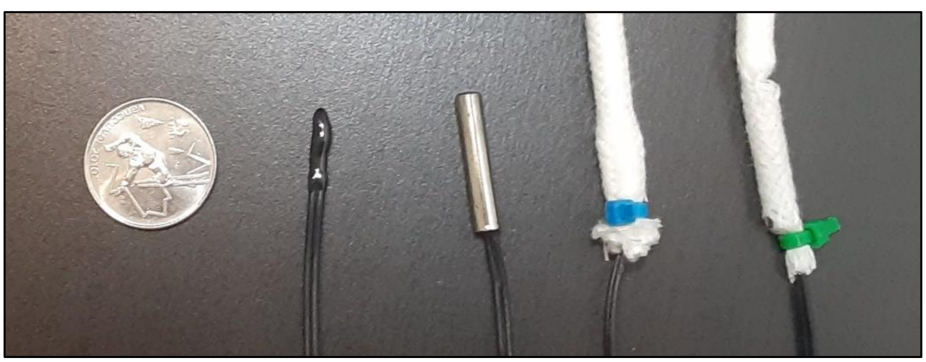

Figure 6 TH-1 (small) and TH-2 (large) thermistor probes with their wet bulb setup

The wick used is a polyester capillary sold for automatic plant watering purposes. To increase its capillary action, the wick is made of three inner ropes, as seen in Figure 7. For wet bulb purposes, these ropes are shortened to make space for the thermistor probe. A tie-wrap is then used to hold the thermistor inside the outer mesh.

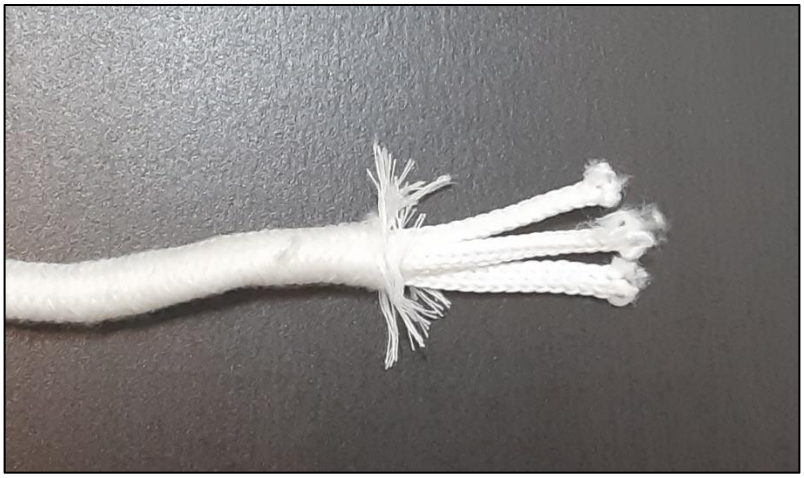

Figure 7 Capillary wick inner components before being cut

b) Jericho wet bulb operation instructions:

1. Clean the water reservoir with soapy water and rinse twice with distilled water.
2. Put some room temperature distilled water into the reservoir. Close the reservoir. Insert the thermistor probe completely into the wick. Wait 5 minutes for the wick to absorb water and stabilize in temperature. Start monitoring the temperature. Water temperature must reach the room temperature for accurate measurements.
3. For good accuracy, use distilled water (or deionized water). Distilled water should be used to avoid the accumulation of scale on the cotton wick overtime. Lime can also form on the wick. Both scale and lime will reduce the evaporation rate, which is a source of error. A wick that has changed color (e.g. green or orange) should be replaced.
4. If using a closed reservoir, the water quantity should last a few days depending on the climate. Reducing to a minimum the wick surface outside the reservoir will reduce the total water evaporation rate and extend the time between refills.
5. The water reservoir should remain upright to avoid spilling water.
6. Wet bulb temperature devices only work above freezing temperature (0°C).
7. The Jericho wet bulb device will be good as long as 1) the wick remains clean and saturated with water, and 2) the temperature sensor is calibrated.
8. The dry bulb thermometer should not be in the wake of the wet bulb thermometer. The distance should be sufficient so that the dry bulb is not exposed to the humidity coming out of the wet bulb. A distance of 30 cm should be sufficient in most cases.
9. Unless aiming for a ‘natural wet bulb’, radiative heat transfer to the wick must be avoided (sun, hot surfaces in the surroundings).

Assuming that the wick is already wet, the reaction time of a natural wet bulb thermometer is typically 1-2 minutes, but could be more, depending on the conditions. Therefore, a wet bulb is generally not appropriate to monitor rapid changes in humidity.

c) Jericho AM2301b description and operation

The AM2301b is a low-cost digital humidity sensor that uses the I2C sensor. In theory, its accuracy should be quite good according to its manufacturer specifications, but as seen in the examples section of the present document, it can drift significantly.

The I2C protocol is quite practical and the AM2301B is natively supported by the RDL source code.

This sensor should be used for testing only and preliminary results. For more accurate and reliable results, the SHT-20 sensor can be used.

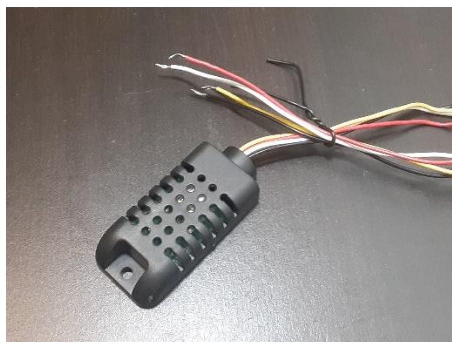

Figure 8 AM2301b digital humidity sensor

For operation, the following connections should be done to the I2C terminals of the RDL.
RED: 5V pin
BLACK: Ground pin
YELLOW: SDA (Data wire of the I2C protocol)
WHITE: SCL (Clock wire of the I2C protocol) (optional)

To function, the I2C sensors must be activated within the source code before uploading to the RDL ("i2cDisplay = 1"). See the user guide for more information.

5. Graph examples

a) Dry bulb, aspirated wet bulb and resulting relative humidity

In Figure 9 can be seen data from the RDL device: two raw sensor values (dry bulb temperature and wet bulb temperatures) and the calculated relative humidity.

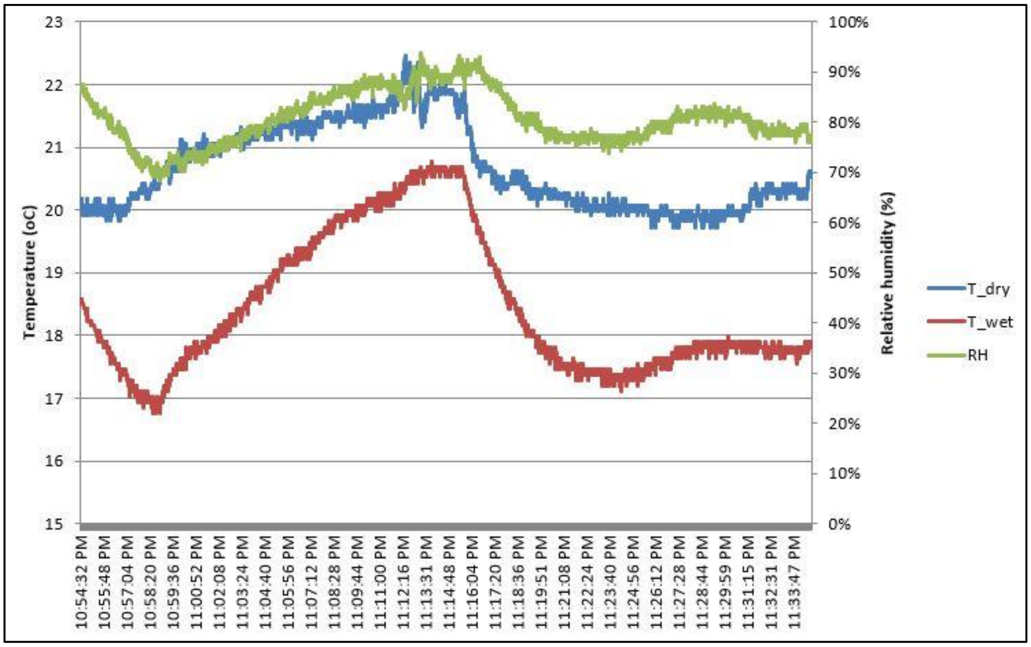

Figure 9 Example of data produced by the RDL: dry bulb, wet bulb and relative humidity of a bathroom during a 15 min shower

b) Dry bulb, aspirated wet bulb and resulting absolute humidity

c) Comparison between AM2301b, aspirated wet bulb and airport data (RH only)

d) Comparison between AM2301b, natural wet bulb and airport data (RH only)

To evaluate the device performance, the relative humidity output can be compared with reference values, such as the data from the nearest official weather station (Figure 11). It can be seen that despite the 4 km distance between the two locations, correlation is very good. A light shower around noon caused a spike in the relative humidity of both locations.

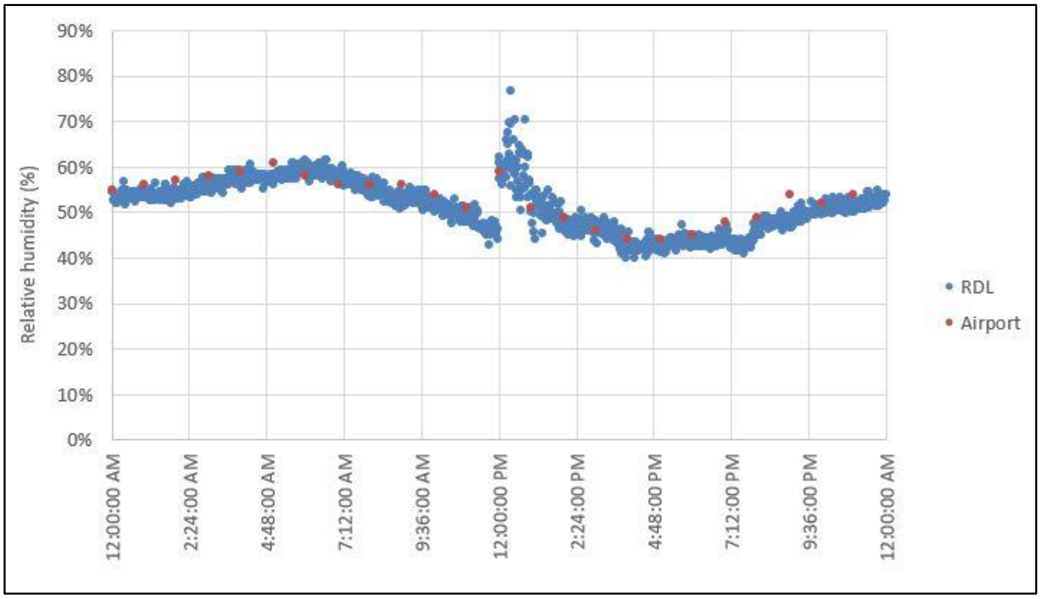

Figure 10 Comparison of RDL humidity data with nearest weather station data in Montreal, Canada

The data can also be compared with another humidity sensor, such as a digital humidity sensor. In Figure 11, the RDL values are compared with the output from the low-cost AM2301b digital humidity sensor, seen in Figure 3. Data from the digital sensor was also measured with the RDL, since it has the ability to communicate with digital sensors that use the I2C protocol. Due to the lower reliability of the digital capacitive humidity sensors, it can be hard to determine if there is something wrong with the wet bulb calculations or the digital sensor output. In this example, the discrepancy between the two readings is mostly within the 5% uncertainty of the digital sensor.

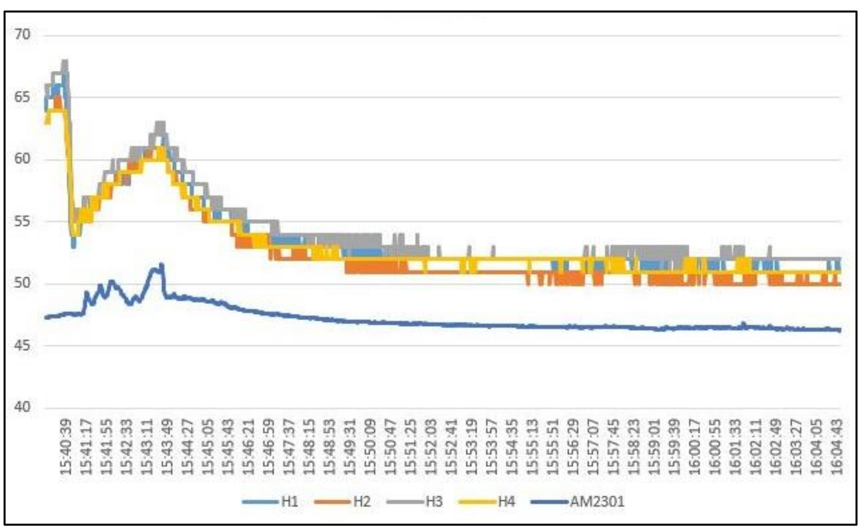

Figure 11 Comparison of 4 wet bulbs and one digital humidity sensor

Wet bulb wick

Professional wicks are usually made out of pure cotton and cost a few dollars per wick. As an alternative, one can also use polyester capillary wicks for plant watering or even shoestrings. The most important thing is that the wick/fiber has a good capillarity effect, so that the wick surface remains moist at all times, despite gravity, wind, etc.

6. HUMIDITY KEY TERMS DEFINITIONS

- Stevenson screen
  - A Stevenson screen (or 'weather screen) is a white wooden box with louvers that protects multiple measuring instruments from the sun and allows the circulation of air. It is usually made out of wood, but there are also miniature versions made of plastic for a single instrument (e.g., cotton wick of a wet bulb thermometer. It is common for people to build their own Stevenson screen, by following the key concepts. Two examples can be seen in Figure 12.

Figure 12 Traditional Stevenson screen made of wood (left) and a smaller plastic version (right)

- Natural wet bulb temperature
  - The 'natural wet bulb' is a static wet bulb that is not protected from the sun or wind. The measurement is therefore representative of the combined effect of air temperature, humidity, radiation and wind. It is used by the Wet Bulb Globe

Temperature (WBGT) comfort index, but it is not recommended to calculate the relative humidity.

- Static wet bulb temperature (or screen wet bulb temperature)
    - It is the temperature of damp cloth or wet thermometer when exposed to stagnant air (0 m/s) and protected from the sunshine and other radiant heat transfer. This temperature is close to the thermodynamic wet bulb temperature from an aspirated hygrometer or sling psychrometer. Calculations of relative and absolute humidity must take into account the type of wet bulb. The static wet bulb is used inside a Stevenson screen.
- Absolute humidity
    - Absolute humidity (or humidity ratio) is the total mass of water vapor contained in a given mass of dry air. It is not dependent on air temperature. In some cases, absolute humidity is defined per volume of air, instead of mass. In that case, the value is dependent on temperature.
- Thermodynamic wet bulb temperature
    - It is a synonym of 'adiabatic saturation temperature'. It is the coldest temperature achievable as a gas cool down to adiabatic saturation. It is achieved by evaporation of water in a flowing air. The sling psychrometer and the aspiration psychrometer are two ways to achieve the thermodynamic wet bulb temperature.
- Dew point
    - It is the temperature at which the given absolute humidity will be the maximum amount of water vapor that can be sustained (i.e., relative humidity = 100%). If the temperature goes below the dew point, condensation will occur. Water droplets or ice crystals will form in the air or on the surface.

Figure 13 Morning dew (Image: britannica.com)

- Hygrometer vs psychrometer
  - A hygrometer is defined as any instrument that can measure water vapor content of the atmosphere. The psychrometer is a sub-type of hygrometer, one which uses a dry bulb and wet bulb, whether static or dynamic.

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