REPUBLIC OF SLOVENIA

MINISTRY FOR THE ENVIRONMENT AND SPATIAL PLANNING
SLOVENIAN ENVIRONMENT AGENCY

Vojkova 1b,
1000 Ljubljana p.p. 2608,
tel.: +386(0)1 478 40 00 fax.: +386(0)1 478 40 52

WMO

WMO CIMO Training Workshop on Metrology for the English-speaking countries of Region V (South-West Pacific)

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Relative humidity

M.Sc. Drago Groselj
Head of Calibration Laboratory Service

Contents

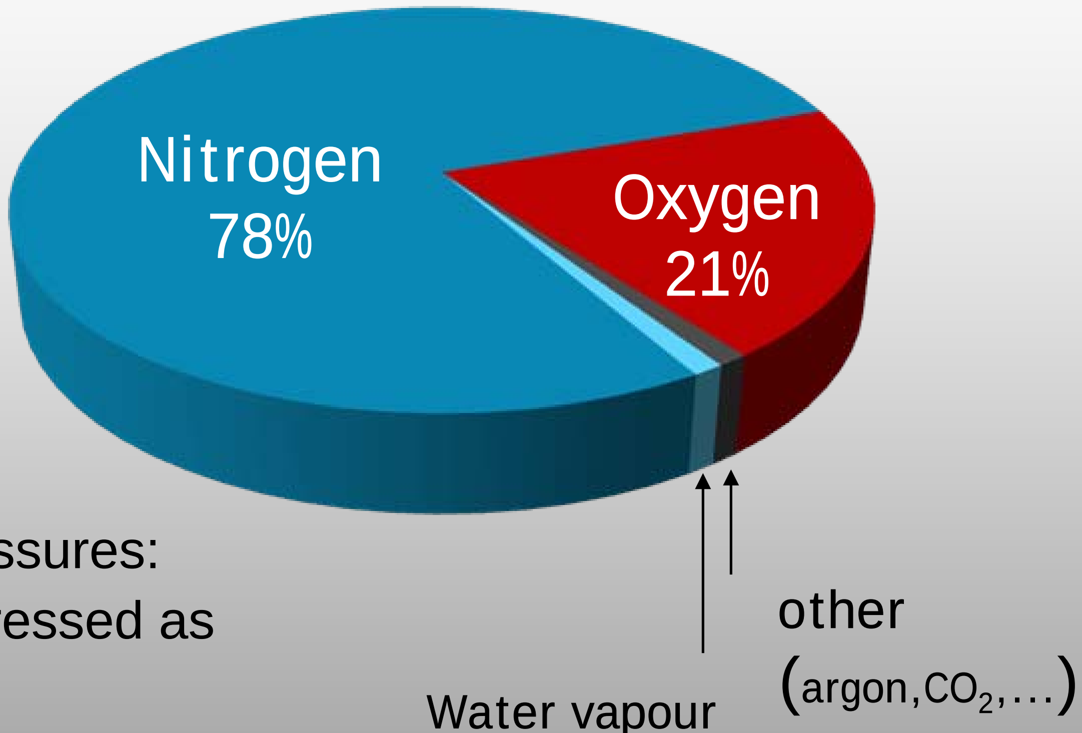
- ✓ Concepts and definitions
- ✓ Introduction to measurement methods:

  dew-point, psychrometer, impendance themometer, mechanical
- ✓ Humidity generators:

  Two-temperature, two-pressure, climatic chambers, salt solutions
- ✓ Calibration tips…and traps
- ✓ Humidity calculators

Concepts and definitions

Composition of air
(by volume)



Up to 0.5% at 0 °C

Up to 4% at 30 °C

- ***Dalton's law*** of partial pressures: total pressure can be expressed as sum of partial pressures

$$p_{\text{total}} = p_{N_2} + p_{O_2} + p_{H_2 0} + p_{\text{other}}$$

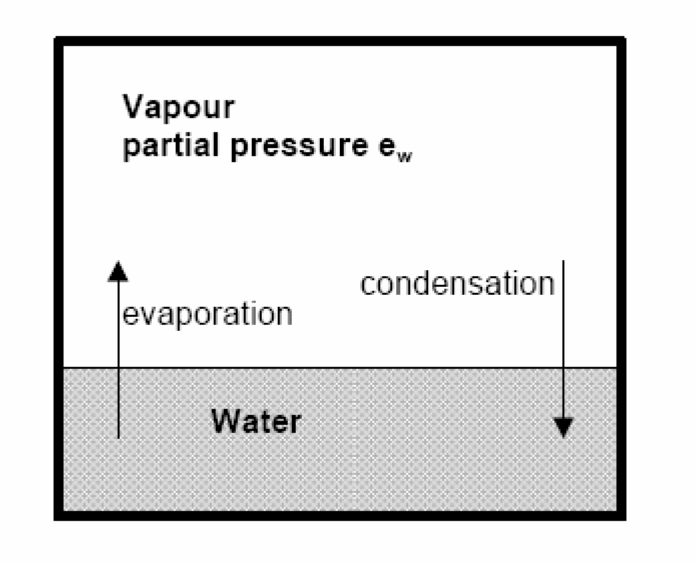
Concepts and definitions

- ✓ There are a number of ways of specifying humidity, as relative humidity RH (%), dew point DP (^oC) or absolute humidity (g/m^3).
- ✓ Naturally they should all convert to the same humidity when compared.
- ✓ The measurement of humidity is an attempt to find the partial pressure of water vapour.
- ✓ The most fundamental standard is the gravimetric hygrometer. Certain amount of dry gas is weighed and compared with the weight of the test gas in the same volume (NIST, NPL, NRLM).

Relative humidity

- **RH** is the ratio of the actual water vapour pressure to the saturation water vapour pressure over a plane liquid water surface at the same temperature.
- For the actual water vapour pressure *e* and the saturation water vapour pressure e_s,

$$RH\ (in\ \%) = e/e_s \times 100$$



Dew/frost point temperature

- **The dew point (DP**) is the temperature to which a humid air must be cooled for water vapour to condense into liquid water.

  This is the temperature at which air becomes saturated in equilibrium with water.

  In the range just below 0ºC where either frost or dew (**super cooled water**) can form, the dew and the frost point differ.

- **The frost point (FP)** is the temperature at which **frost forms** on cooling a gas.

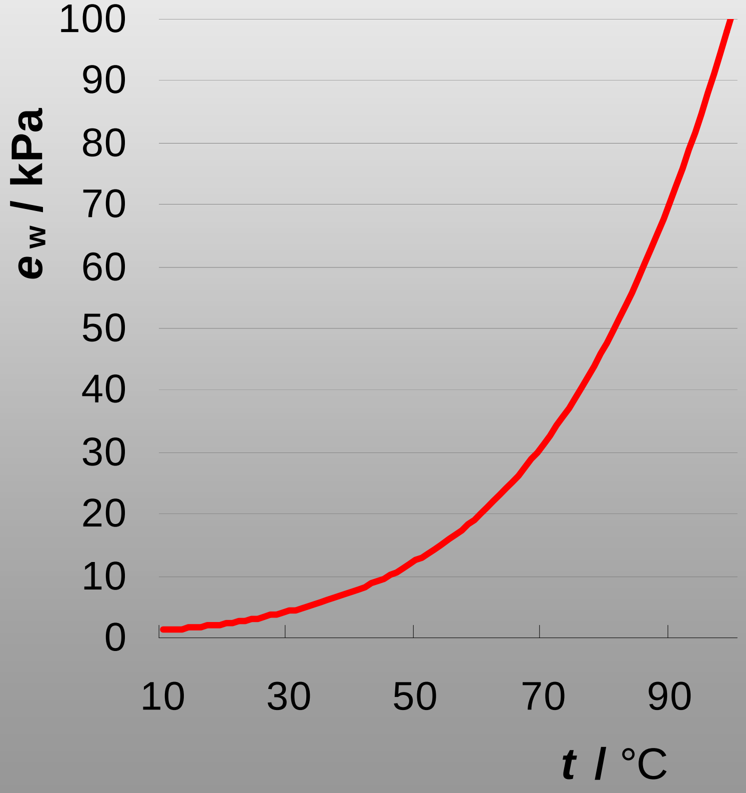
  This is the temperature at which air becomes saturated in equilibrium with ice.

Calculation of vapour pressure

A relatively simple equation for the calculation of the **saturation vapour pressure** $e_w(t)$ in the pure phase with respect to water is the Magnus formula (**WMO**):

$$e_w(t) = 611.2 \cdot e^{\frac{17.62 \cdot t}{243.12 + t}}$$

- range -45°C to 60°C
- $e_w(t)$ [Pa]
- t [°C]
- uncertainty 0.6% of value



Saturation vapour pressure over ice:

$$e_i = 611.2 \cdot e^{\frac{22.46 \cdot t}{272.62 + t}}$$

- range -65°C to 0.01°C
- $e_i(t)$ [Pa]
- t [°C]
- uncertainty 1% of value

Calculation of vapour pressure

- In literature are may expressions of saturated vapour pressure available but worldwide accepted **Hardy formula** based on ITS-90:

$$e_w(t) = e^{\left(\frac{C_1}{t} + C_2 + C_3 \cdot t + C_3 \cdot t^2 + C_3 \cdot \ln(t)\right)}$$

- range 0°C ÷ 100°C
- uncertianty 0.005% of value

$$e_i(t) = e^{\left(\frac{D_1}{t} + D_2 + D_3 \cdot t + D_3 \cdot t^2 + D_3 \cdot \ln(t)\right)}$$

- range -100°C ÷ 0.01°C
- uncertianty 0.5% of value

where:

$e_w(t)$ - saturation vapour pressure at temperature t over water [Pa],
$e_i(t)$ - saturation vapour pressure at temperature t over ice [Pa],

gi, ki - constants available in literature [1].

Conversion between DP/FP and RH

- There is no simple direct formula for converting in either direction between DP and RH. Conversions include the intermediate step of calculating the actual vapour pressure of water and the saturated vapour pressure of water at the temperature of interest.

$$t_d = \frac{243.12 \cdot \ln\left(\frac{e_w}{611.2}\right)}{17.62 - \ln\left(\frac{e_w}{611.2}\right)}$$

- range -45°C to 60°C
- $e_w(t)$ [Pa]
- t [°C]
- uncertainty 0.04°C

$$t_f = \frac{272.62 \cdot \ln\left(\frac{e_i}{611.2}\right)}{22.46 - \ln\left(\frac{e_i}{611.2}\right)}$$

- range -65°C to 0.01°C
- $e_i(t)$ [Pa]
- t [°C]
- uncertainty 0.08°C

Water enhancement factor

- The “effective” saturation vapor pressure over water or ice in the presence of other gasses differs from ideal saturation vapor pressures. The effective saturation vapor pressure is related to ideal by:

$$e(t,p) = e(t) \cdot f(p)$$

$f(p) =$ enhancement factor

$$f(p) = 1.0016 + 3.15 \cdot 10^{-6} \cdot p - \frac{0.074}{p}$$

- Range -50°C to 60°C
- p barometric pressure [kPa]
- uncertainty 0.08% of value

The correction is small: approximately 2 parts per thousand!

Water enhancement factor

- Latest Greenspan enhancement factor formula:

$$f(t,p) = e^{\left[\alpha\cdot\left(1-\frac{e_s(t_i)}{p}\right)+\beta\cdot\left(\frac{p}{e_s(t_i)}\right)\right]}$$

$$\alpha = \sum_{i=0}^{3} A_i \cdot t^i$$

$$\ln(\beta) = \sum_{i=0}^{3} B_i \cdot t^i$$

Ai, Bi - constants available in literature [1]

The final formulae for relative humidity can be expressed as:

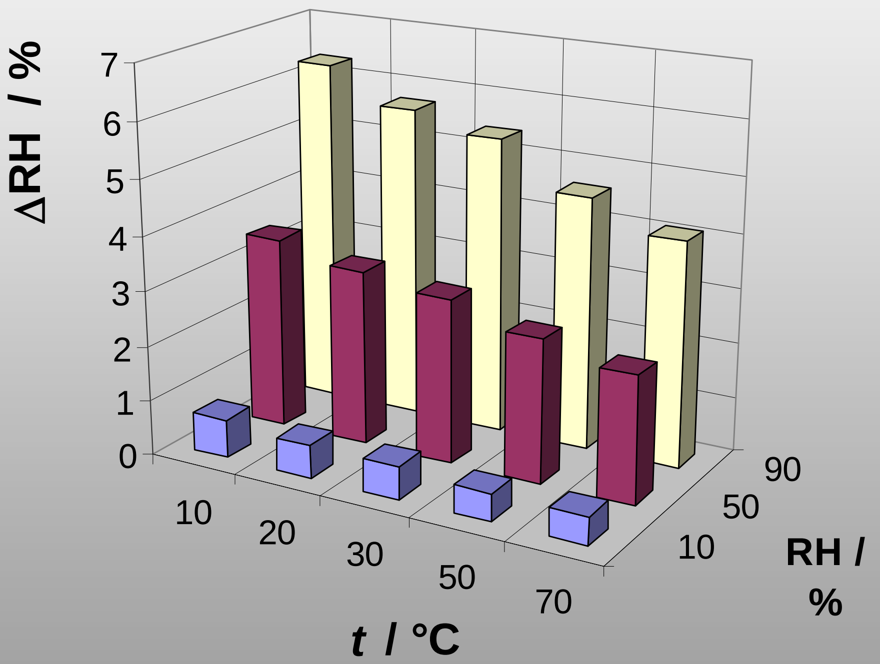
$$RH = 100\cdot\frac{e(t_a)\cdot f(t_a,p)}{e_s(t_{d/f})\cdot f(t_{d/f},p)}$$

Effect of pressure

- $p_{total} = p_{oxygen} + p_{nitrogen} + p_{water} + p_{others}$
- For example what is the effect of doubling pressure on an RH of 40% at constant temperature?
- Since P_{total} has doubled, P_{water} has doubled, and since T is constant the RH has doubled. i.e. RH = 80%.

The effect of temperature errors

- The effect of a 1°C error in temperature is shown in graph.
- Various ambient temperatures are plotted.
- It can be seen that 1°C error in temperature determination equates to about 5% error in RH for most temperatures.



Classification of humidity instruments

Type	Class	Measurement range	Typical Measurement Accuracy
Gravimetric hygrometer	Primary	-50°C ÷ 100°C	0.1°C dew point
Chilled mirror hygrometer	Fundamental (transfer)	-90°C÷ 90°C dew point	0.2°C dew point
Electrolytic hygrometer	Fundamental	1 to 2000 ppmv	5% of reading ppmv
Psychrometer	Fundamental	5% RH ÷ 95% RH 0°C÷ 100°C ambient	1% - 5% RH
Resistance hygrometer	Secondary	5% RH-100% RH	1% - 5% RH
Polymer RH sensor	Secondary	5% RH -95% RH	2%-5% RH
Mechanical hygrograph	Secondary	10% RH-100% RH	2%-10% RH

Introduction to measurement methods

- Condensation – dew point mirror
- Wet and Dry bulb - psychrometer
- Electrical impedance (resistance or capacitive)
- Mechanical - hygrograph

Dew point mirror hygrometer

- The principle is simple, place a temperature controlled mirror in the air stream and cool it until dew forms on the mirror.
- This is a direct measurement of dew point.
- The temperature of the air stream is monitored and from these two measurements the other parameter can be calculated - RH.
- In operational systems such as the one shown the control of the mirror temperature is automatic. The thickness of the water layer is monitored with a reflected light beam irradiating a light detector.

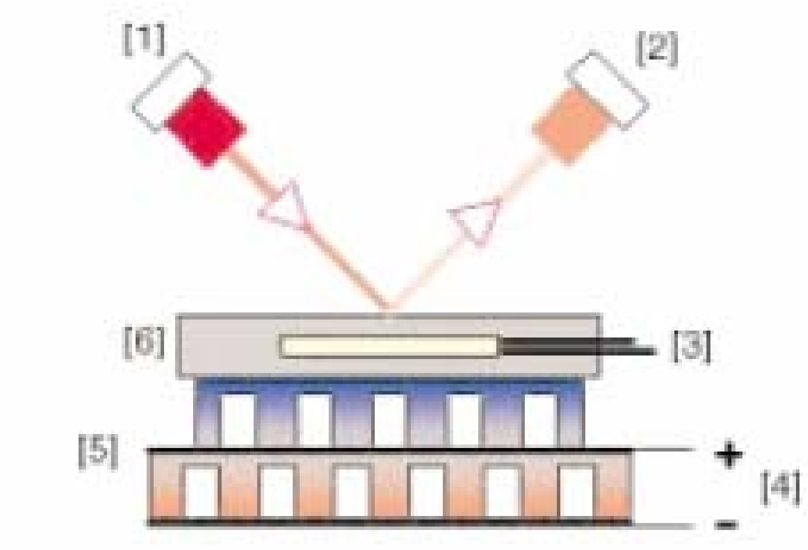


Figure 1

Key:
[1] LED light source
[2] Photodetector
[3] Resistance thermometer PT100
[4] Peltier supply
[5] Peltier thermoelectric two stage heat pump
[6] Mirror

Dew point mirror hygrometer

Advantage	Disadvantage
Uncertainty around 0.2°C	Expensive
Can provide precise measurement	Contamination can cause incorrect readings
Good long term performance	Dew points below 0°C require careful interpretation
Wide measurement range	Can be slow in response

Dew point mirror hygrometer

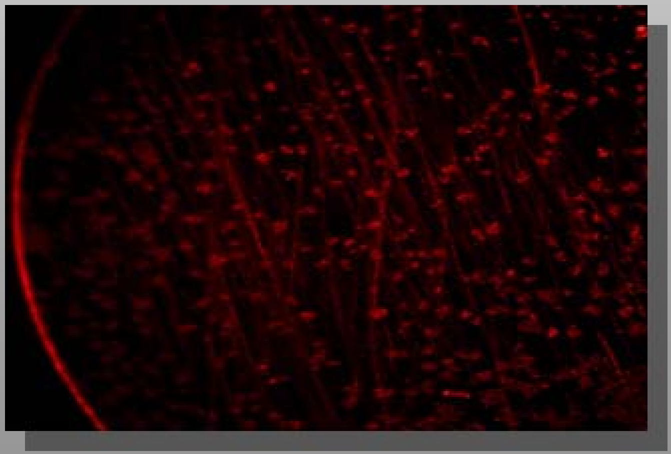
- Main uncertainty sources:

  - non-soluble contaminants on mirror surface

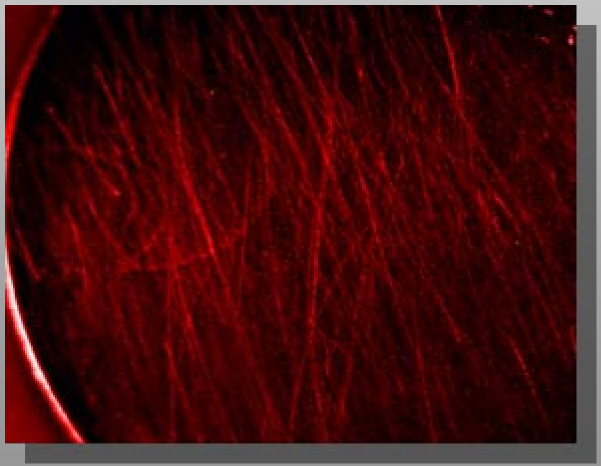
  - soluble contaminants on mirror surface

- **Be careful**: sometimes dew isn't dew. The mirror should be monitored at dew points lower than 0°C to define either is a frost or dew point so the correct formula is used in RH calculation.

Ice at –10°C



Super cooled water at –11,1°C



Calculation of RH value

Relative humidity is determined from dew/frost point measurements by following formula:

$$RH = 100 \cdot \frac{e_s(t_{d/f})}{e_s(t_a)}$$

Where:

- $e_s(t_{d/f})$ saturation vapor pressure at dew/frost point temperature $t_{d/f}$
- $e_s(t_a)$ saturation vapor pressure at air temperature t_a

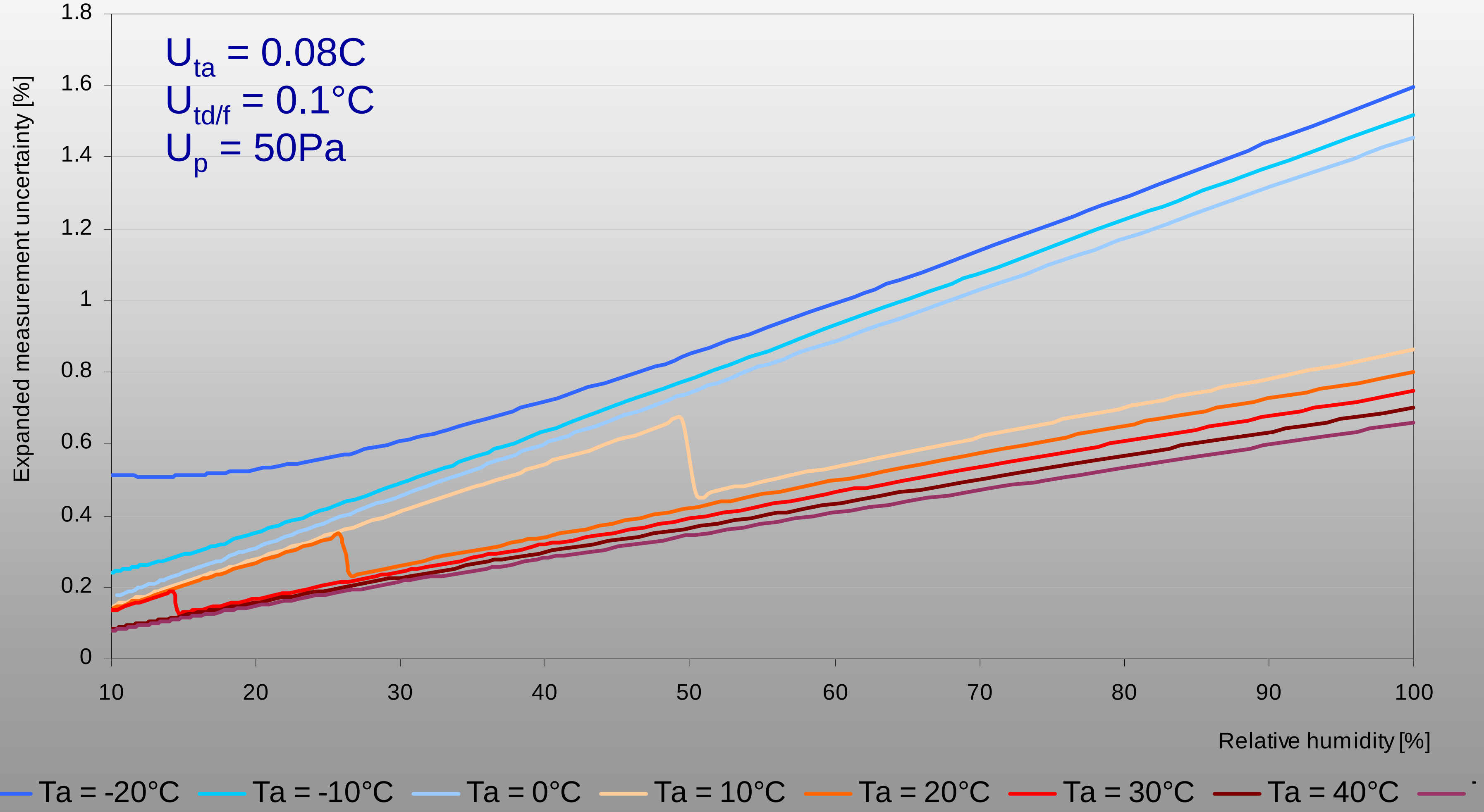
If we include also water enhancement factors the final formula for dew point hygrometers become:

$$RH = 100 \cdot \frac{e_s(t_{d/f}) \cdot f(t_{d/f}, p)}{e_s(t_a) \cdot f(t_a, p)}$$

Where:

- $e_s(t_{d/f})$ saturation vapor pressure at dew/frost point temperature $t_{d/f}$
- $e_s(t_a)$ saturation vapor pressure at air temperature t_a
- $f(t_{d/f},p)$ enhancement factor at dew/frost point temperature $t_{d/f}$
- $f(t_a,p)$ enhancement factor at air temperature t_a

Expanded uncertainty of DP hygrometer



Example

Assume we have measured dew/frost point temperature -10°C, air temperature 20°C and air pressure 101.325kPa:

- dew point temperature -10°C:

$$e_{sw}(-10°C) = 286.52Pa$$
$$e_s(20°C) = 2339.25Pa$$
$$f(-10°C, 101.325hPa) = 1.00398$$
$$f(20°C, 101.325hPa) = 1.00399$$

$$RH = \frac{e_{sw\,(-10\,°C)} \cdot f_{\,(-10°C, 101.325kPa)}}{e_{s\,(20°C)} \cdot f_{\,(20°C, 101.325kPa)}} \cdot 100 = 12.25\%$$

- frost point temperature:

$$e_{si}(-10°C) = 259.90Pa$$
$$e_s(20\,°C) = 2339.25\,Pa$$
$$f(-10°C, 101.325hPa) = 1.004$$
$$f(20°C, 101.325hPa) = 1.00399$$

$$RH = \frac{e_{si\,(-10\,°C)} \cdot f_{\,(-10°C, 101.325kPa)}}{e_{s\,(20°C)} \cdot f_{\,(20°C, 101.325kPa)}} \cdot 100 = 11.11\%$$

Practical recommendations

- Filter the air supply to the device to avoid contamination of the mirror with dust, droplets or mist.
- The mirror should be regularly cleaned with deionised or distilled water. Alcohol can be used to remove oil based contaminants.
- Use a cotton bud to clear the mirror. Drops should pull away cleanly – drops that continue to adhere are a sign of mirror contamination.
- The mirror should be cleaned daily or at least weekly.
- When using the device a viewing microscope should be employed to confirm the existence of a dew or a frost point.
- These devices can be calibrated in terms of temperature alone.

Psychrometer

- An aspirated Wet & Dry bulb hygrometer consists of two matched temperature sensors over which humid air is drawn.
- One sensor is enclosed in a porous medium (wick) which is maintained wet by capillary action from a reservoir of water.
- Water evaporates from the wick at a rate related to the humidity and temperature of the air.
- The evaporation causes the wet sensor to chill. The difference between the dry bulb temperature and the wet bulb temperature is the “wet bulb depression”.
- Uncertainties of around 2 – 5% RH obtainable.
- Response times are slow

Psychrometer

Advantage	Disadvantage
Simple, cheap, reliable and robust.	Some skill is required to use and maintain the instrument.
Can have good stability	A large air sample is required for measurement.
Wide range of humidity	The sample will be humidified by the wet sock.
Tolerate high temperatures and condensation.	Measurement is complicated below 10°C (dew or ice point).
	Wick can become contaminated.
	Results have to be calculated from tables or software.
	Whirling types are prone to serious errors.

RH calculation

Basic formula (Sprung), adopted by WMO:

$$RH = 100 \cdot \frac{e_s(t_w) - A \cdot p \cdot (t_d - t_w)}{e_s(t_d)}$$

Where:
$e_s(t_w)$ is the saturation vapour pressure of the wet bulb;
$e_s(t_d)$ is the saturation vapour pressure of the dry bulb;
p is the pressure of the air;
t_d is the temperature of the dry bulb;
t_w is the temperature of the wet bulb;
A is the psychrometer coefficient.

Psychrometer coefficient depends on air flow speed (>2.2m/s), thermodynamic properties of water and vapor pressure and geometry of wet bulb thermometer and is dificult to determine precisely.

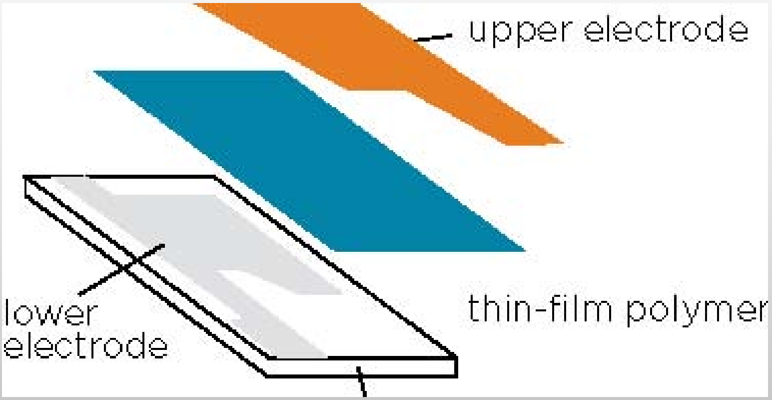
Practical recommendations

- The wick used should of the type supplied with the instrument, fit properly, clean and be absorbent.
- Wicks should be cleaned before use by boiling in water with little detergent for approximately 10 minutes.

- Water used must be highly pure – either deionized or distilled.
- The wick must be changed daily or at least weekly depending on the contamination level in the environment (dust, pollen, salt spray etc).
- Use the correct psychrometric tables, a psychrometer is said to be aspirated if the air velocity past the bulbs is greater than 3 m/s.
- Failure to ensure the conditions above will usually lead to the psychrometer over-estimating humidity.

Capacitive hygrometer

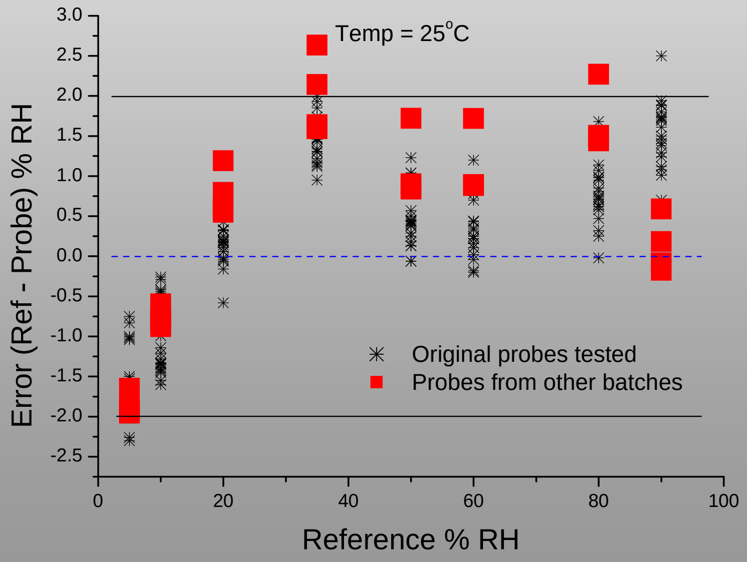
- They are constructed from polymer material with a hygroscopic dielectric and are designed to provide an electrical response corresponding to relative humidity.
- The thin-film polymer either absorbs or releases water vapor as the relative humidity of the ambient air rises or drops.



- ➢ They can achieve uncertainties of around 2 – 3% RH.
- ➢ They may suffer calibration shifts after experiencing high temperatures (> 40^{o}C) or high humidities.
- ➢ May suffer drift and hysteresis.
- ➢ Can be damaged by aggressive chemicals.
- ➢ Capacitive sensors can usually tolerate condensation.

Capacitive hygrometer

- ✓ In the picture below are the corrections for 26 Vaisala HMP45 humidity probes.
- ✓ Note the characteristic ‘S’ response.
- ✓ Note also the corrections become larger at high and low humidities.

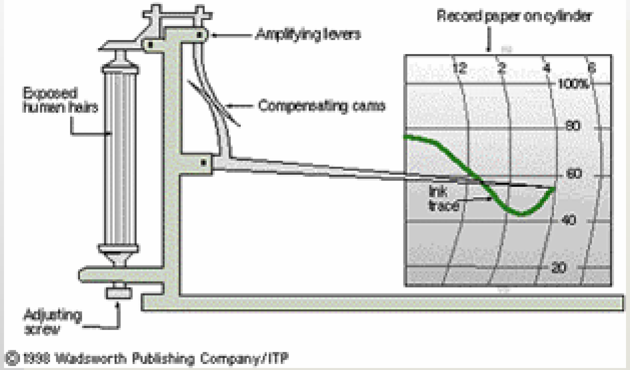


Practical recommendations

- Take care to avoid mechanical and thermal shocks.
- Sensors should be protected from steam, water sprays and direct sunlight.
- Appropriate filters should be used – these are condition dependent.
- Don’t breath on the sensor to confirm it is working – the sensor will be contaminated.
- In general to not immerse the sensors in liquids – water will almost certainly destroy a resistive sensor.
- For the Vaisala sensor shown a quick check of performance can be made by removing the sensor and replacing it with a 70pF capacitor – the output should read 100% RH.

Hygrograph

Measurement method: the dimensions of various organic materials (hair, horse hair) vary with their moisture content. The length of human hair increases by 2 to 2.5% when relative humidity changes by 0 to 100%



Disadvantages:

a) Temperature dependence.
b) Hysteresis (>5%).
c) Nonlinear when using hair.
d) The response time of the hair hygrometer depends on air temperature.
e) After the hair hygrometer is exposed in low temperature and low humidity for a long time, reading error increase due to the increasing of delay.
f) Hair is highly sensitive to contamination such as dust, ammonia, oil and exhaust gas.
g) If a hair hygrometer is left in the low humidity condition for a long time, its reading changes causing large errors.

Humidity medium

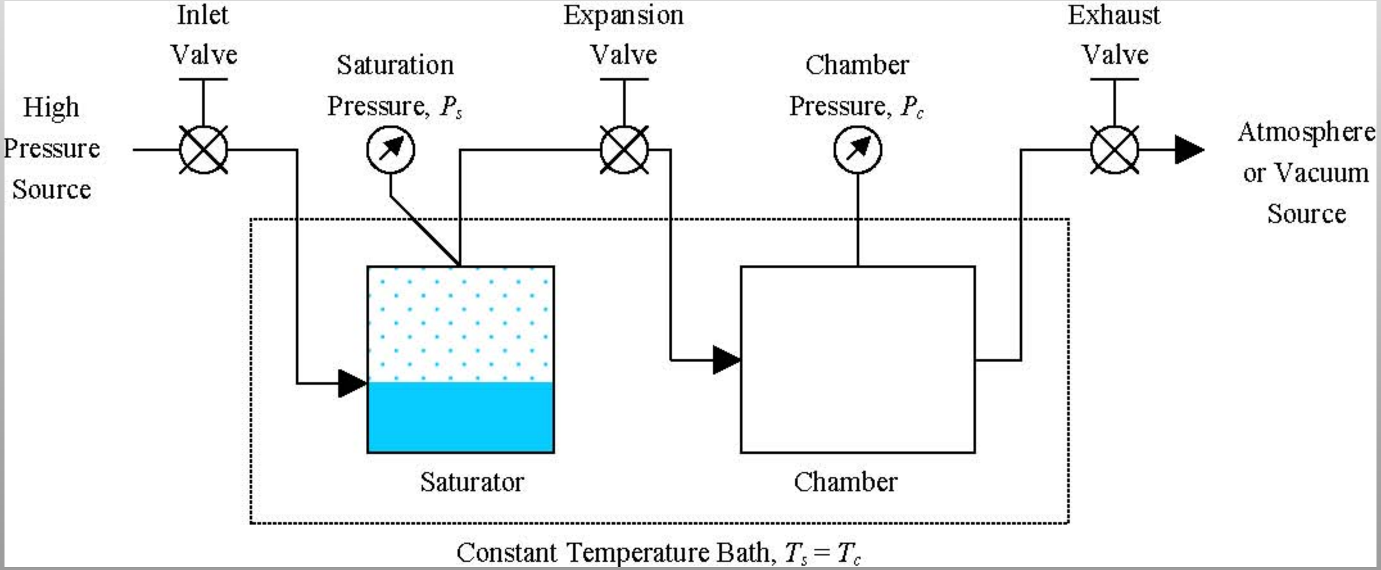
- **Humidity generator**
  - Two - temperature humidity generator
  - Two - pressure humidity generator
  - Split stream humidity generator

- **Climatic chamber**

- **Salt solutions**

Two - pressure humidity generator

“Two-pressure" humidity generation process involves saturating air with water vapor at a known temperature and pressure. The saturated high-pressure air flows from the saturator, through a pressure reducing valve, where the air is isothermally reduced to test pressure at the test temperature.



Two - pressure humidity generator

System uncertainty is dependent on the accurate measurement of temperature and pressure and the stability of these measurements.

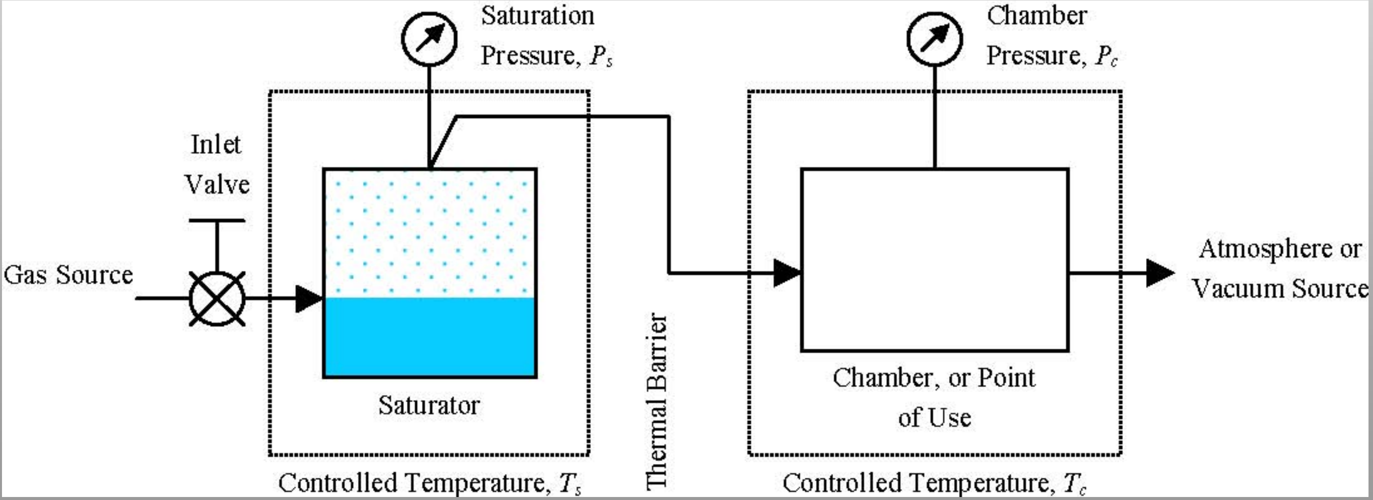
$$RH = \frac{p_C \cdot e(t_S) \cdot f(p_S, t_S)}{p_s \cdot e(t_c) \cdot f(p_c, t_c)} \cdot 100$$

Where:

- p_s pressure in saturator
- p_c pressure in chamber
- $e(t_s)$ saturation vapor pressure at temperature t_s in saturator
- $e(t_c)$ saturation vapor pressure at temperature t_c in chamber
- $f(p_s,t_s)$ enhancement factor at temperature t_s and saturator pressure p_s
- $f(p_c,t_c)$ enhancement factor at temperature t_c and saturator chamber p_c

Two - temperature humidity generator

In a two-temperature system, a stream of gas is saturated with respect to the liquid or solid phase of water at a low temperature and then **warmed isobarically** to a higher temperature for use. Measurements of the temperature and pressure of the cool, saturated gas stream, and in the warmer test chamber (or other point of use), are all that is required to determine the resulting humidity content of the gas stream.



Climatic chamber

- ➢ control the humidity of a parcel of air by controlling the temperature of a body of water within the chamber separately from that of the chamber air temperature.

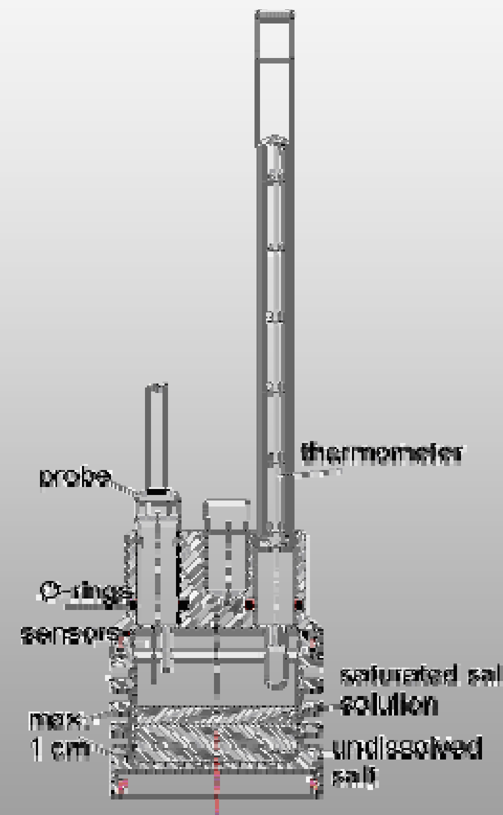
  - range -20°C÷40°C (10%÷95%)
  - temporal and spatial stability
  - slow to change dew points
  - long settling times, of the order of ½ an hour.

- ➢ mix two streams of air, one saturated and one dry into the chamber.

change in RH is faster

Salt solutions

- ✓ The water vapor concentration, and therefore the relative humidity over a salt solution is less than that over pure water.
- ✓ This is because water is present in both the gas and the liquid phase, whereas the scarcely volatile salt molecules are only present in the liquid.
- ✓ They dilute the water and hinder escape of water molecules into the air.
- ✓ The rate of return of water molecules to the liquid surface is proportional to their concentration in the gas, where there are no salt ions to interfere.
- ✓ The system therefore adjusts to an equilibrium where there are fewer water molecules in the air than there would be over a pure water surface. The RH is therefore lower than 100%.
- ✓ A less well known problem is that the salt solution is bad at dehumidifying.



Saturated salt solutions

Temperature [°C]	LiCl [%]	$MgCl_2$ [%]	NaCl [%]	K_2SO_4 [%]
0	*	33.7±0.3	75.5±0.3	98.8±1.1
5	*	33.6±0.3	75.7±0.3	98.5±0.9
10	*	33.5±0.2	75.7±0.2	98.2±0.8
15	*	33.3±0.2	75.6±0.2	97.9±0.6
20	11.3±0.3	33.1±0.2	75.5±0.1	97.6±0.5
25	11.3±0.3	32.8±0.2	75.3±0.1	97.3±0.5
30	11.3±0.2	32.4±0.1	75.1±0.1	97.0±0.4
35	11.3±0.2	32.1±0.1	74.9±0.1	96.7±0.4
40	11.2±0.2	31.6±0.1	74.7±0.1	96.2±0.4
45	11.2±0.2	31.1±0.1	74.5±0.2	96.1±0.4
50	11.1±0.2	30.5±0.1	74.4±0.2	95.8±0.5

Salt solutions

Typical sources of errors in humidity calibration

- Temperature difference between the humidity probe and calibration chamber.
- Insufficient stabilization time. The recommended stabilization time for reliable calibration is from 10 to 20 minutes.
- Very narrow range between the calibration points
- Dirty or wet equipment

How to use salt solutions for calibration

- The dry salt is spread about 3 mm deep in a shallow tray that occupies most of the bottom of an airtight box.
- Water is added to moisten the salt. Do not add more water than is needed to make the salt look damp.
- The instrument is then laid on a grid supported above the tray. Electronic sensors can be inserted through a hole in the box which is made reasonably airtight with a split rubber bung.
- Allow one hour for equilibration when the instrument is bulky. 20 minutes for small sensors.

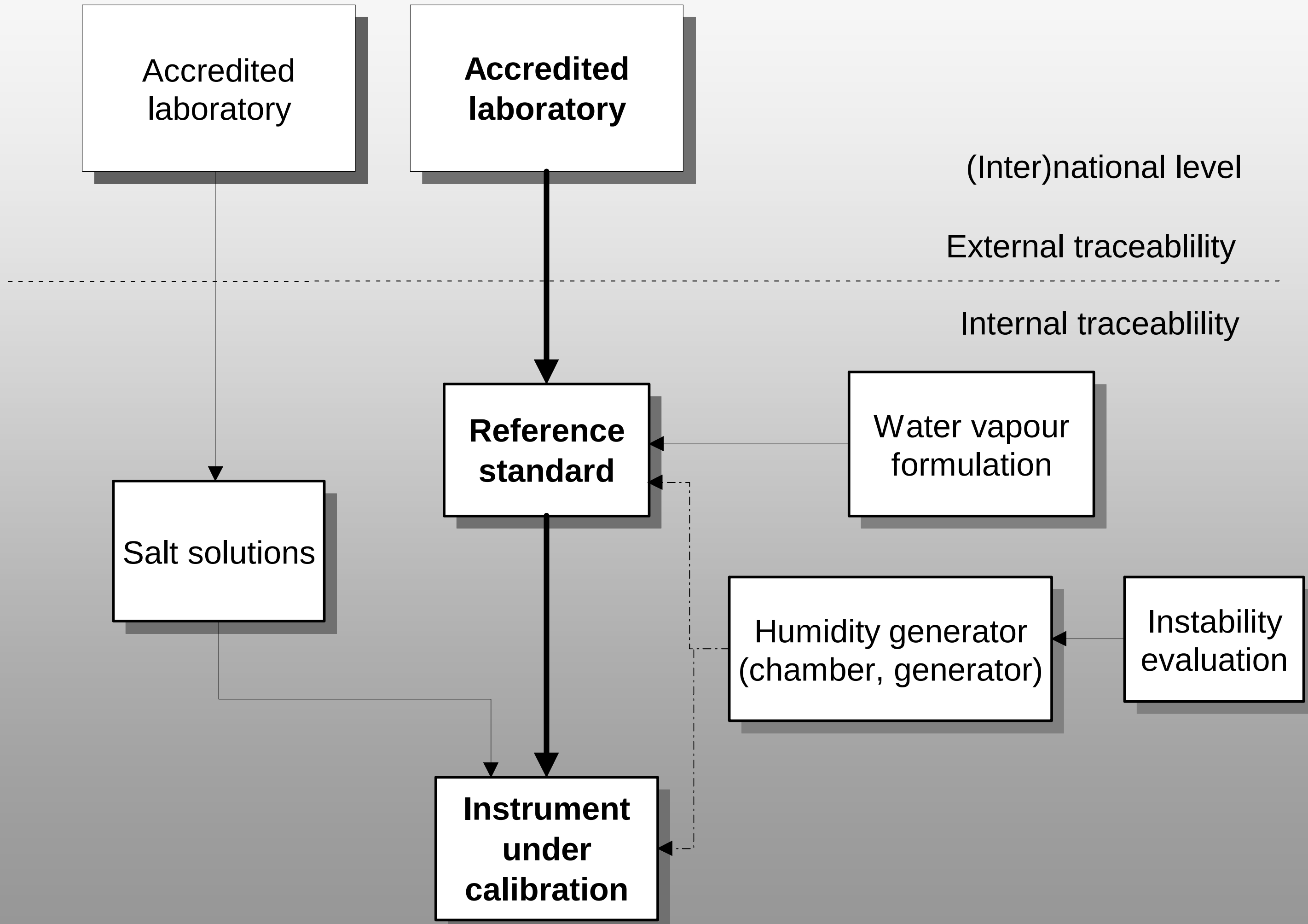
Calibration tips and…

- Calibrate in the units the device is to be used in – if it is an RH probe then calibrate in RH.
- If it is a DP probe then calibration should be in DP.
- A wet and dry bulb psychrometer requires more than a temperature calibration. It must be calibrated for humidity as well (to determine its psychrometric coefficient).
- You must also check that the air speed of aspirated psychrometers are greater than 3 m/s.

…traps

- Leaks – ambient humidity leaking into the system either raising or lowering the humidity
- Saturation – water condensing in the pipes etc leading to 100% RH
- Water droplets or mist in the air stream
- Temperature gradients within the system
- Excessively high flow rates implying excessive pressure gradients

Traceability chart



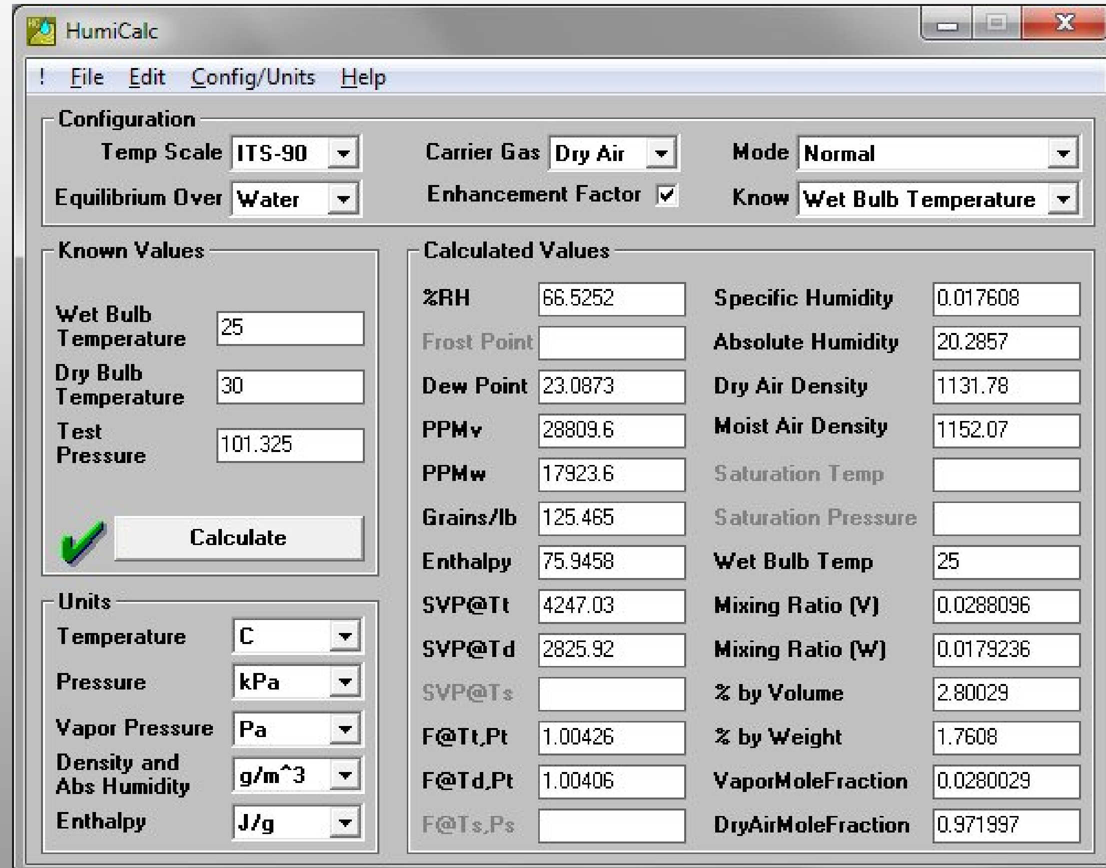
Behavior of humidity probes in the field

Placing humidity probes in the field leads to:

- ✓ Contamination of sensor;
- ✓ Drift in electronics;
- ✓ Contamination of the filter.
- ✓ Most failed at high RH.
- ✓ Probes can return a reading of up to 110 %RH – this implies the sensor is wet.

Humicalc by Thunder Scientific

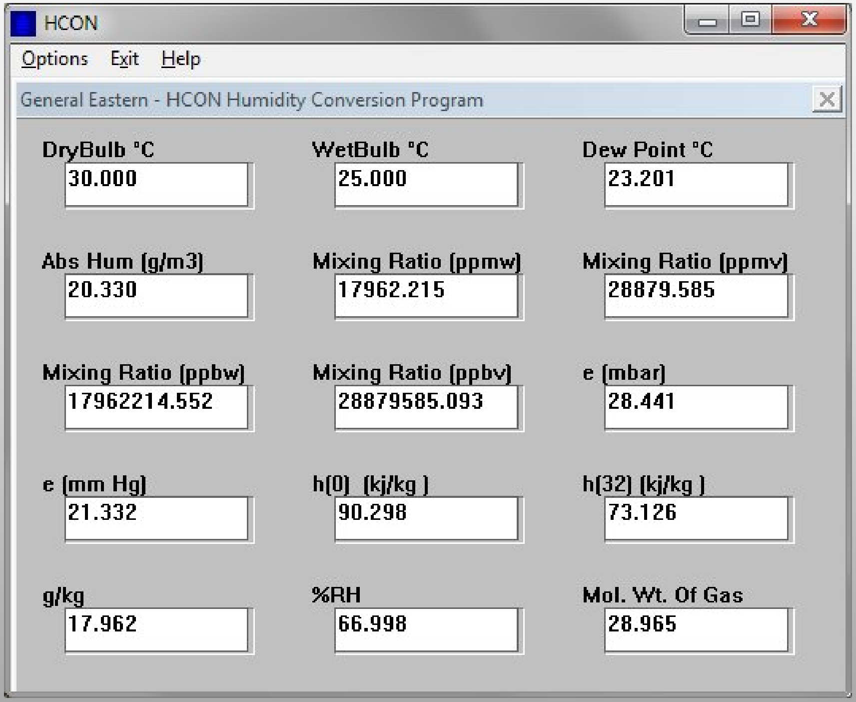
- Two-pressure generator calculation
- Two-temperature generator calculation
- Dew point mirror calculation
- Pscyhrometer calculation
- Uncertainty calculation – not included in free version



Free to download at:
http://www.thunderscientific.com/software/humicalc.html

HCon by General Eastern

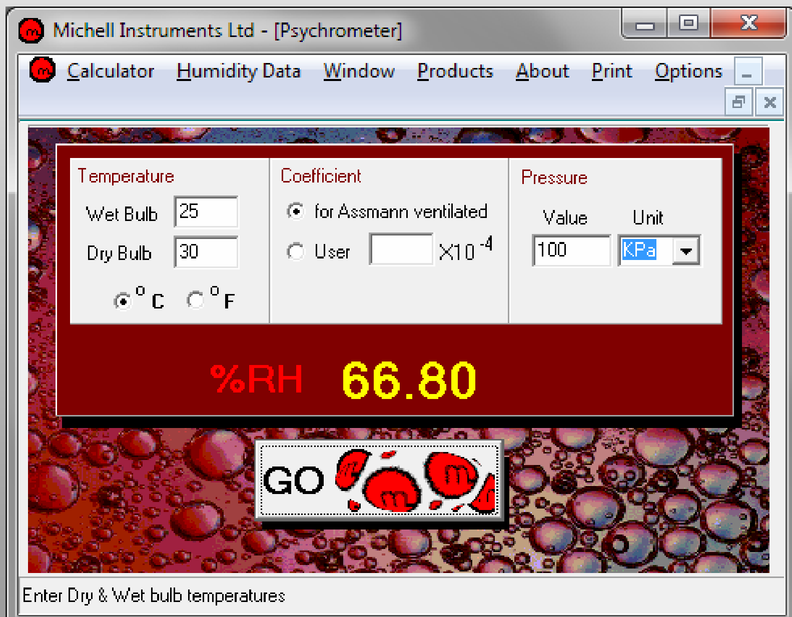
- By specifying two parameters the RH, DP etc can be calculated.
- Watch out for the wet bulb/dry bulb calculation – it takes an average of the aspirated and non-aspirated formulas.

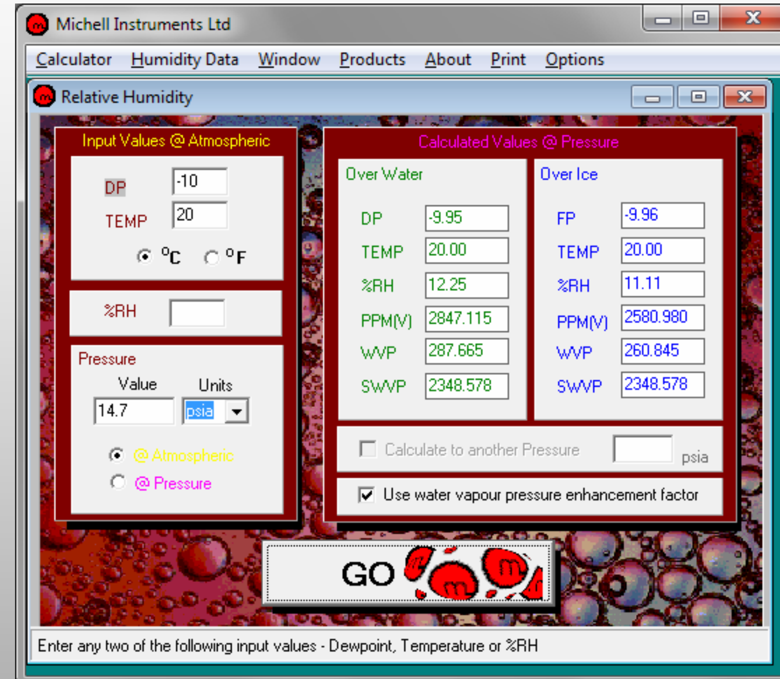


Free to download at:
http://www.ge-mcs.com/en/ndt-software/285-software-download/1720-1142.html

Humidity calculator by Mitchell

- Dew point mirror calculation
- Pscyhrometer calculation





Free to download at:
[http://www. http://michell.com/uk/support/sware-downloads.htm](http://michell.com/uk/support/sware-downloads.htm)

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