

OWLSTONE NANOTECH INC

Humidity Generation and Humidity Measurement

The Complete Guide

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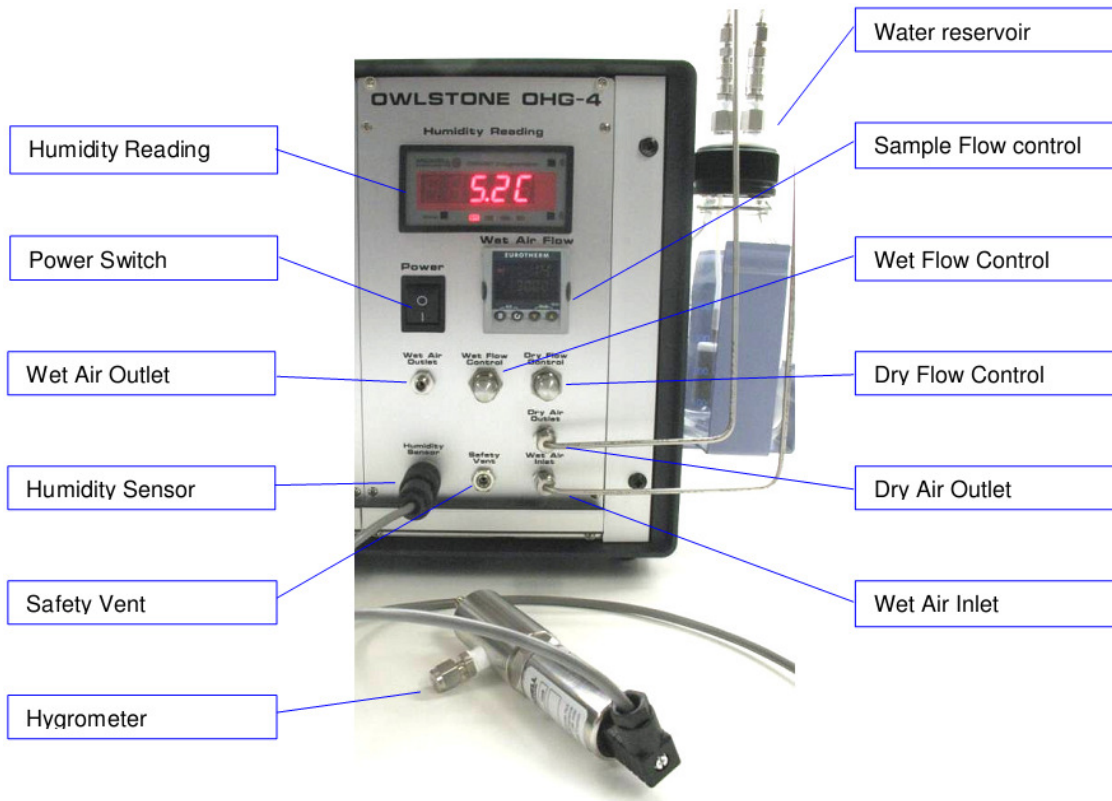
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OHG-4 (Owlstone Humidity Generator)

The OHG-4 is a versatile humidity generator that is used to produce a range of relative humidity concentrations from 1 to 90%rh ($\pm 1\%$). When used in the GEN-SYS, in combination with an OVG-4 and an OFC-1, it can generate a wide range of vapour standards, suitable for calibration of sensors, especially gas sensors.

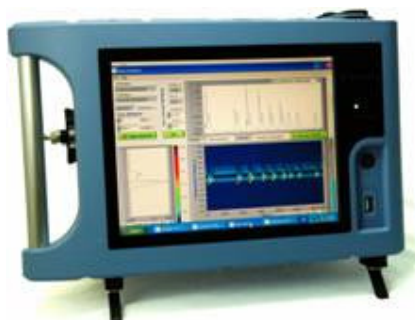


In the OHG, the airflow is controlled by a mass flow controller. A flow suitable for the application is set using the front panel Wet Air Flow control, this controls the mass flow controller (MFC). Downstream of the MFC the airflow is split into two flow paths, the first of which bubbles through the water reservoir. Downstream of the reservoir the two flows are recombined. The ratio of the two needle valve settings controls the humidity of the output air.

OHG-4 Operating Parameters and Ranges	
Parameter	Operating Range
Gas	Air/nitrogen
Inlet pressure	40psi
Inlet fitting	1/4" Swagelok quick connect
Outlet connection	1/8" Swagelok compression
Power supply	24V
Current rating	0.5A
Fuse	T1AH250V
Humidity, lower limit	~1%rh, lower limit dependant on customer gas line
Humidity, upper limit	No less than 90%rh
Wet gas outlet flow range	300-3000ml.min ⁻¹

Other Owlstone instruments

Gas Analyzer and chemical detector: Lonestar



A versatile gas analyzer and chemical monitor in a portable, self contained unit.

Incorporating Owlstone's proprietary FAIMS technology, the instrument offers the flexibility to provide both rapid alerts and detailed sample analysis. It can be trained to respond to a broad range of chemical scenarios and can be easily integrated with other sensors and third party systems to provide a complete monitoring solution. As a result, Lonestar is suitable for a broad variety of application ranging from online/at line process monitoring to lab based R&D.

More info: www.owlstonenanotech.com/lonestar

Calibration gas generator: OVG-4



The Owlstone Vapour Generator (OVG-4) is a compact, cost effective calibration gas system, which can generate NIST traceable, precise, repeatable and accurate concentrations of chemicals and calibration gas standards.

Incorporating permeation tube technology the OVG-4 can replace multiple gas cylinders resulting in significant cost and space savings as well as eliminating dangers associated with cylinders. The ability to generate arbitrarily complex gas mixtures makes the OVG-4 calibration gas generator suitable for a broad range of applications from calibration of explosive detectors in military and homeland defence to testing personal monitors in industrial health and safety applications.

More info: www.owlstonenanotech.com/ovg-calibration-gas-generator

Humidity Fundamentals

What is Humidity?

At any temperature, water vapour will be present in the air. There is a limit to the amount of water vapour which can exist in equilibrium with the air (the saturation pressure). The mass of water vapour in a unit volume of moist air is known as the absolute humidity (measured in g/m³).

$$H_A = \frac{m_w}{V_{net}}$$

- H_A is the absolute humidity (mass/volume)
- m_w is the mass of water
- V_{net} is the total wet air volume

This is very similar to the mixing ratio, which is the mass of water vapour per unit mass of dry air (measured in g/kg).

$$MR = \frac{m_w}{m_a}$$

- MR is the mixing ratio
- m_w is the mass of water (in a given volume)
- m_a is the mass of air (in a given volume)

The relative humidity is the ratio between the actual and saturation partial pressures of water vapour (measured in %). This is the value commonly mentioned in weather forecasts.

$$H_R = \frac{p_w}{p_s} \times 100$$

- H_R is the relative humidity (%rh)
- p_w is the partial vapour pressure of water
- p_s is the saturation vapour pressure of water (at the same temperature)

There are water vapour pressure equations which will give the approximate saturation pressure for a given temperature. One of the least complex is the Antoine equation:

$$\log_{10} p_w = A - \frac{B}{C + T}$$

- T is the temperature (°C)
- p_w is the partial vapour pressure of water (mmHg)
- A B and C are approximately constant for a small temperature range and constant atmospheric pressure:

		Antoine Constants		
T_{low}	T_{high}	A	B	C
1	99	8.07131	1730.63	233.426
100	374	8.14019	1810.94	244.485

Humidity Generation and Humidity Measurement

Other commonly used correlations include:

- the Geoff-Gratch equation,
- the Arden Buck equation,
- the Sonntag formula and
- the Magnus formula (this list is not exhaustive).

It is necessary to note that while these equations are generally more accurate than the Antoine equation, the most accurate method to determine the partial pressure of water vapour at a given temperature is to use an experimentally determined look-up table.

Worked Example: Effect of Heating and Compression

A closed system, at 1atm, 70°C and 50%rh can either be heated by 10K or compressed to 2atm. What are the two possible resulting relative humidities?

Since, for the isothermal compression, the temperature does not increase, the partial pressure of water will have doubled, and thus the relative humidity will have doubled. Thus:

$$H_{R2} = 100\%rh$$

For the isobaric heating, first, calculate initial saturation water vapour partial pressure and thus the partial vapour pressure of water:

$$p_{s70} = 611.2e^{\frac{17.62 \times 70}{243.12 + 70}} = 31.4kPa \rightarrow p_w = 0.7 \times 31.4 \times 10^3 = 15.7kPa$$

Then calculate the saturation vapour pressure after heating:

$$p_{s80} = 611.2e^{\frac{17.62 \times 80}{243.12 + 80}} = 47.9kPa$$

The pressure has not changed, so the partial vapour pressure of water has not changed. Therefore calculate the relative humidity:

$$H_{R3} = \frac{15.7}{47.9} = 32.8\%rh$$

Enhancement Factor

It should be noted that the above equations assume ideal gas behaviour in a vacuum. In order to correct for imperfections in modelling (and to account for the fact that most experiments are carried out in air), a water vapour enhancement factor is sometimes applied to the saturation vapour pressure calculated using the Antoine (or other) equation.

$$f = \frac{p_w}{p_w^*} \rightarrow p_w = f \times p_w^*$$

- f is the water vapour enhancement factor
- p_w is the experimental saturated vapour pressure
- p_w^* is the saturation vapour pressure of pure water

For temperatures between 223K and 333K, and pressures between 3kPa and 110kPa:

$$f = 1.0016 + 3.15 \times 10^{-6}P - \frac{0.074}{P}$$

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- P is the experimental pressure (Pa)

Water Vapour Concentration

In addition to absolute and relative humidities, there are several other methods of describing the amount of water vapour in air.

The volumetric concentration is given by:

$$C_V = \frac{p_w}{P}$$

- C_V is the concentration of water in air (as a ratio of water vapour volume to total wet air volume)
- p_w is the partial water vapour pressure
- P is the total system pressure

The mass concentration is given by:

$$C_m = \frac{W}{V} = \frac{C_V \times M}{22.4 \times \frac{T}{273} \times \frac{P}{P_{atm}}} = \frac{p_w \times M \times P_{atm}}{22.4 \times \frac{T}{273}}$$

- C_m is the concentration of water vapour (g/L)
- M is the molar mass (g/mol)
- T is the experimental temperature (K)
- 22.4 is the volume in L of 1mol of air at 0°C.

Dynamic Methods of Humidity Generation

In many applications it is desirable to generate a constant flow of air at a specified temperature and absolute humidity. There are three main methods of doing so; each method has several different implementations, with more advanced systems combining various ideas.

The flow rate of water per unit time is then given by:

$$q_w = \frac{p_w \times H_R \times q_A}{1000} = \frac{C_V \times M \times q_A}{22.4 \times \frac{T}{273} \times \frac{P}{P_{atm}}}$$

- q_w is the water flow rate (g/min)
- H_R is the fractional relative humidity
- q_A is the flow rate of air (L/min)
- M is the molar mass (g/mol)
- C_V is the concentration (volume per volume)
- P is the experimental pressure
- T is the temperature in kelvin.

At RTP (25°C and 1atm) this reduces to:

$$q_w = \frac{C_V \times M \times q_A}{24.5}$$

Worked Example: Calculating Water Flow Rate

How many grams per minute of water are required to maintain a relative humidity of 70% in an air stream flowing at 64L/min? Atmospheric temperature and pressure are 25°C and 1atm. The molar mass of water is 18g/mol.

First, calculate the saturation pressure:

$$\ln p_w = \ln 611.2 + \frac{17.62 \times 25}{243.12 + 25} \rightarrow p_w = 3160 \text{ Pa}$$

Then calculate the volumetric concentration:

$$C_V = \frac{0.7 \times 3160}{101325} = 21.8 \text{ ml/m}^3$$

Then calculate the water flow rate:

$$q_w = \frac{\frac{21.8}{1000} \times 18 \times 64}{24.5} = 1.03 \text{ g/min}$$

Dew-Point Generator

The simplest method involves the air stream being bubbled through water. As the air passes through the water, some of the water vaporises into the bubbles. In order to generate very high relative humidities, the stream of air is passed over a heated water bath, from which the water evaporates into the stream. This is called a dew-point generator, because the maximum dew-point of the generated wet air is the temperature of the water it was bubbled through.

It should be noted that some of the air will also dissolve in the water as it passes through. Thus mass flow should be measured after humidification.

Atomiser

For low relative humidities, the water can be injected directly into the stream of air. An atomiser is used to break the water into small enough droplets for the water to evaporate into the stream.

It is also possible to obtain commercially produced gas bottles at various mixing ratios. For high mixing ratios, these bottles do not have a long storage time, as condensation will form on the inside of the bottle.

Mixed-Flow Generator

It is common to use a split-stream or double-dilution principle to more accurately control the humidity of the air leaving the system. The idea is that if the air coming directly out of the system is too humid, then more air (at the same temperature) can be mixed in to reduce the relative humidity. In the split-stream method, the dry air stream is divided into two parts. One of these is then saturated (or partially saturated) with water vapour using any of the methods described above, and the still dry air is then mixed in to achieve the desired humidity output after the saturation process. The humidity achieved will depend on the humidity of the wet air, and the ratio of mixing. Double dilution uses the same principle, but the air being inputted after humidification comes from a different source to the humidified air.

Static Methods of Humidity Generation

It is also useful to be able to generate and maintain a constant humidity atmosphere within a contained volume. In addition to being able to use all of the constant flow methods to fill up a space with humid air, there are a couple more methods used for small spaces.

Two-Pressure Process

The two-pressure process utilises one chamber (the saturator) at high pressure, and another (the test chamber) at the desired pressure, both at the same temperature. Saturated air flows from the saturator into the test chamber. As it reduces in pressure, the desired humidity is achieved, and if the systems are at a constant temperature then the humidity in the test chamber is the ratio between the chamber pressures. This is given by:

$$H_R = \frac{P_T}{P_S} \times 100$$

- H_R is the relative humidity (%)
- P_T is the test chamber pressure
- P_S is the water vapour saturation pressure

As pressure, temperature and saturation partial pressure are related by the perfect gas relations and Antoine equation, it is unnecessary to directly measure the humidity. This can lead to faster and more accurate readings of the humidity in the test chamber.

Two-Temperature Process

The two-temperature process also uses a saturator and test chamber. While both of these are at the same pressure, the saturator is at a lower temperature. The air in the saturator is saturated, with the temperature of the chamber defining the wet air's dew-point. This air is then passed into the (warmer) test chamber. The mixing ratio will not change, and thus the relative humidity will decrease. By knowing the saturation vapour pressure at various temperatures, and the temperatures of the two chambers, any desired relative humidity can be achieved.

Saturated Salt Solutions

When placed in an enclosed volume, salt solutions will (given enough time) generate a certain, predictable humidity. The undissolved salt will absorb water, while water will evaporate from the solution. At a constant temperature, these rates will be constant, and thus a constant humidity can be generated. There must be both saturated solution and undissolved salt present for this to work. For given chemicals and temperatures, the humidity generated can be looked up; the humidity is given by the water activity or equilibrium relative humidity of the substance.

Humidity Measurement Methods

Most of the above humidity generation methods utilise some form of negative feedback to control the relative or absolute humidity in the wet air they output. In order for such a system to work, it is necessary to accurately measure the air's humidity. Humidity can either be measured directly; or indirectly, by measuring the dew-point and the temperature, and thus inferring the humidity. Some methods, such as the two-pressure

method, assume saturation and evaluate resulting humidities using measurements of just temperature and pressure. Temperature and pressure measurements can be performed by any standard apparatus including thermometer or pyrometer, manometer or Piezoelectric respectively.

Psychrometer (Wet- and Dry-Bulb Hygrometer)

The simplest type of hygrometer is a Psychrometer. This constitutes a pair of temperature sensors. These are placed in a wet air stream. One of the thermometers (the wet bulb) has a wet wick around it; evaporation causes this thermometer to read a lower temperature than the other. The difference in temperatures, and the absolute temperature of the wet thermometer can be used to calculate the relative humidity of the air.

$$p_w = p_s - AP(T_D - T_W)$$

- p_w is the experimental partial vapour pressure of water
- p_s is the saturation vapour pressure at temperature T_w
- A is the psychrometer constant (typically, values of A , for T_w above 0°C , are around 5×10^{-4} to 10^{-3})
- P is the experimental pressure
- T_D is the dry bulb temperature
- T_W is the wet bulb temperature

Alternatively, for a given Psychrometer, the values obtained can be looked-up in a reference table.

Mechanical Hygrometers

Mechanical hygrometers utilise the change in dimensions of various porous materials (such as wet paper and hair) as they absorb/exude water vapour. This change in dimensions can be used to move a needle or dial; which, when calibrated, will give the relative humidity.

Electrical Hygrometers

Electrical impedance sensors measure the changes in electrical capacitance or resistance of a hygroscopic material. The material will absorb or desorb water depending on the partial vapour pressure in the atmosphere around it, thus changing its electrical properties. These sensors measure relative humidity. While capacitive hygrometers can withstand condensation, resistive ones usually cannot.

Dew-Point Sensors

Dew-point sensors measure the temperature of the surrounding air, and the dew-point of a small sample thereof. The humidity of the air is then inferred from the dew-point temperature and the initial air temperature. Optical sensors cool a surface (usually a mirror) until condensation starts to form. This indicates that the surface is at the air's dew-point. Other methods of measuring dew-point include measuring the oscillation rate of a quartz crystal. When condensation forms on the crystal, this rate will change.

Others

Other sensors utilize changes in other properties, such as colour, thermal conductivity and acoustic transmission, to determine relative or absolute humidity. Electrolytic sensors relate the current flowing through a desiccant (usually phosphorus pentoxide) to the volumetric concentration of water vapour. Spectroscopic sensors use the emission spectra peaks of water to determine absolute humidity.

Appendices

Partial Vapour Pressure Equations

- Magnus Formula, where p_w is the saturation vapour pressure for water measured in Pa, and T is the temperature measured in °C:

$$\ln p_w = \ln 611.2 + \frac{17.62T}{243.12 + T}$$

- Sonntag Formula, where p_w is measured in Pa and T in K:

$$\ln p_w = -6096.9385T^{-1} + 21.2409642 - 2.711193 \times 10^{-2}T + 1.673952 \times 10^{-5}T^2 + 2.433502 \ln T$$

- The Arden Buck equation, where p_w is measured in hPa (hundreds of Pa) and T in °C:

$$p_w = 6.1121e^{(18.678 - \frac{T}{234.5})(\frac{T}{257.14 + T})}$$

- The Geoff-Gratch equation, where p_w is measured in hPa and T in K. T_{st} is the boiling point of water at 1atm (ie 273.16K) and p_{st} is the partial pressure of steam in hPa at 1atm (ie 1013.24hPa.)

$$\begin{aligned} \log_{10} p_w = & -7.90298 \left(\frac{T_{st}}{T} - 1 \right) \\ & + 5.02808 \log_{10} \left(\frac{T_{st}}{T} \right) - 1.3816 \times 10^{-7} \left(10^{11.344 \left(1 - \frac{T}{T_{st}} \right)} \right) + 8.1328 \\ & \times 10^{-3} \left(10^{-3.49149 \left(\frac{T_{st}}{T} - 1 \right)} \right) + \log_{10} p_{st} \end{aligned}$$

The Geoff-Gratch equation is usually considered to be the most accurate correlation.

Water Vapour Enhancement Factor

For higher pressures (up to 2MPa) the water vapour enhancement factor is given by:

$$f = e^{\alpha \left(1 - \frac{p_s}{p} \right) + \beta \left(\frac{p}{p_s} - 1 \right)}$$

- p_s is the saturation vapour pressure of water
- P is the experimental pressure
- $\alpha = \sum_{i=1}^4 A_i T^{i-1}$ and $\beta = e^{\sum_{i=1}^4 B_i T^{i-1}}$ where values of A_{1-4} and B_{1-4} can be looked up for given temperature ranges.
- T is the temperature (°C)

Bibliography

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- **Gas Mixtures** – Preparation and Control
Gary O. Nelson
ISBN 0-87371-298-6
- **A Guide to Measurement of Humidity** ISBN 0-904457-24-9
- **Practical Approaches to Humidity Generation and Measurement**
Bob Hardy
http://rhysystems.net/papers/PTC12/2004_PL_005.pdf
- **Saturation Vapor Pressure Formulations**
Holger Vömel
<http://cires.colorado.edu/~voemel/vp.html>

Useful Links

- Introduction to humidity
<http://www.shorstmeyer.com/wxfaq/humidity/humidity.html>
- Discussion of humidity generation methods
http://rhysystems.net/papers/PTC12_2004_PL_005
- Equations for vapour pressure
<http://trc.nist.gov/TDE/Equations/FEquations.html>
- In-depth discussion of two-pressure method
<http://nvlpubs.nist.gov/nist/nistpubs/jres/081/1/V81.N01.A05.pdf> -
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