
A Guide to the Measurement of Humidity

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87 Gower St.
London
WC1E 6AA

ISBN 0-904457-24-9

Published 1996

NPL 
National Physical Laboratory



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This Guide to the Measurement of Humidity has been prepared by the National Physical Laboratory and the Institute of Measurement & Control, supported by the National Measurement System Policy Unit of the Department of Trade and Industry.

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The Humidity Panel wishes to acknowledge the extensive support it has received by way of technical and editorial comments from sources including the following:

Able Instruments and Controls; AEA Technology; Aromascan plc; Assessment Services Ltd; Automatic Systems Ltd; Avery Berkel; BOC Ltd; Boots Company Ltd; Bowater Industrial Division; British Measurement and Testing Association; British Aerospace plc; British Rototherm Company Ltd; British Standards Institute; Brownell Ltd; Canada Centre for Inland Waters; Carrington Marketing; Central Science Laboratory; Climatic Systems Ltd; Comark Ltd; Courtauld Institute of Art; Courtaulds Chemicals; David Mostyn Consultancy Ltd; Defence Research Agency; Delta Electronics Testing; Domnick Hunter Ltd; EA Technology; Gallaher Ltd; Hawco Ltd; Humitec Ltd; IDC Abbot Laboratories Ltd; Ilford Ltd; Infrared Engineering Ltd; Instituto Nacional de Técnica Aeroespacial, Spain; International Moisture Analysers; JS Industrial Services; Kodak Ltd; Leather Technology Centre; Lee Dickens Ltd; Linde Gas (UK) Ltd; Metropolitan Police Forensic Laboratory; Michell Instruments Ltd; Ministry of Defence; Ministry of Agriculture Fisheries and Food; Moisture Control and Measurement Ltd; Munters Ltd; Museums and Galleries Commission; National Research Laboratory of Metrology, Japan; National Museum of Wales; National Institute for Standards and Technology, USA; National Physical Laboratory; Norwegian Metrology and Accreditation Service; Novatron Ltd; Nulectrohms Ltd; Panametrics Ltd; Pedigree Petfoods; Penny and Giles International plc; Process Measurement Technology; Protimeter plc; Rexam Industrial Packaging; Ricardo Consulting Engineering; Robert Mackison; Rotronic Ltd; RS Components Ltd; Satra Footwear Technology Centre; Scottish Museums Council; Sensair Ltd; Servomex; Silsoe Research Institute; Sira Test & Certification Ltd; Skye Instruments Ltd; Sontay Ltd; South Yorkshire Trading Standards; Synergy Associates; Systech Instruments Ltd; Unitemp Ltd; University of Southampton; Vaisala (UK) Ltd; Vapac Humidity Control Ltd; Weston Research Laboratories Ltd.

This Guide refers to other publications that provide information or guidance. Editions of the publications listed are current at the time of publication, but reference should be made to the latest editions.

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CONTENTS

	Page
1. SCOPE	5
2. INTRODUCTION	5
3. CONCEPTS, TERMS AND DEFINITIONS FOR HUMIDITY	5
3.1. What is humidity?	5
3.2. Humidity terms and definitions	6
4. SIGNIFICANCE OF TEMPERATURE AND PRESSURE FOR HUMIDITY MEASUREMENT	10
4.1 The effects of temperature on humidity measurement	10
4.2 The effects of pressure on humidity measurement	12
5. INTRODUCTION TO METHODS FOR MEASURING HUMIDITY	14
5.1 Direct or indirect approach?	14
5.2 Operating principles of various hygrometers	14
6. SELECTION OF A TYPE OF HYGROMETER	19
6.1. Identifying measurement needs	19
6.2 Strengths and weaknesses of particular methods	21
6.3 How to buy an instrument for measuring humidity	24
6.4 Advice on interpretation of the manufacturer's data sheet	25
6.5 British and international standard specifications	28
7. PERFORMANCE AND CALIBRATION	29
7.1 Calibration and traceability	29
7.2 Approaches to calibration	30
7.3 Practical methods of laboratory calibration	30
7.4 Uncertainty of measurement	33
7.5 Other issues	37
8. RECOMMENDED PRACTICES IN HUMIDITY MEASUREMENT	39
8.1 General practical recommendations	39
8.2 Recommendations specific to ranges of measurement	41
8.3 Practical recommendations for specific types of hygrometer	42
9. QUALITY ASSURANCE OF HUMIDITY MEASUREMENTS	45
9.1. Measurement accreditation	45
9.2. Competence in humidity measurement	45
10. TABLES, CHARTS AND FORMULAE	46
10.1 Tables	46
10.2 Charts	50
10.3 Formulae	53
10.4 Use of software	55
11. EXAMPLES AND CALCULATIONS	56
11.1 Example 1: Relative humidity - ambient monitoring	56
11.2 Example 2: Dew-point measurement with respect to water or ice	56
11.3 Example 3: Effects of pressure and temperature change on dew point	57
11.4 Example 4: Calibration of a humidity test chamber	59
12. FURTHER READING	62
INDEX	66

FOREWORD

This Guide has been written to meet the need for a basic advisory document for users of humidity instrumentation. For humidity, as for other fields of measurement, a consistent and harmonised approach is increasingly important, as is a common understanding of the terms used to define and describe humidity measurement. This Guide brings together information about humidity measurement which exists already in the public domain but is in many cases difficult to obtain, poorly expressed, or widely misunderstood.

The Guide is intended to be readily accessible; practically applicable; widely acceptable; and to contain objective criteria against which good practice can be judged. The advice given here is carefully selected to represent conventional good practice in humidity measurement, to be consistent with recognised standard specifications relevant to humidity, and to be free from any commercial bias.

While this document provides a general introduction to humidity measurement, certain aspects are not dealt with here. This is not an in-depth scientific treatment of the subject. The history and development of the field of humidity measurement are not recorded here. The related but separate subject of moisture measurement in liquids and solids is not addressed. For these and other topics connected with humidity measurement, the "Further reading" Section is provided as a starting point for those wishing to develop a more detailed understanding.

It is in the interest of many groups that information about sound measurement practices should reach all those who can benefit. Accordingly, this document has been written in a collaboration between the Institute of Measurement and Control, the National Physical Laboratory and an independent panel of experts involved in the supply, calibration and use of hygrometers, and in consultation with a wide circle of hygrometer users in the UK and further afield. The creation of the document was made possible by support from the National Measurement System Policy Unit of the Department of Trade and Industry, and by the voluntary effort of many of the individuals involved. Finally, much of the credit for the on-schedule production of this Guide rests with the project leader, Dr Stephanie Bell of the National Physical Laboratory, who has been the principal author, editor and collator of the various contributions from the panel of experts. All those concerned with humidity measurement owe this team a considerable debt of gratitude.

Professor J S Anderson
President
The Institute of Measurement and Control

1. SCOPE

This Guide provides advice for those wishing to select and use instruments for measuring humidity. The Guide introduces the main concepts and practical techniques involved in measuring humidity in air and other "inert" gases, and explains how to make such measurements validly and meaningfully.

2. INTRODUCTION

The presence or absence of water vapour in air or other gas influences a vast range of physical, chemical and biological processes. Humidity measurements are important for a wide range of industries and to some they are a critical aspect of business costs, product quality, and health and safety.

There are many different techniques for measuring humidity. The subject is also complicated by the confusing variety of ways of expressing humidity. As for other fields of measurement, a consistent and harmonised approach to humidity measurement is increasingly important, as is a common understanding of humidity terms and definitions.

Humidity is a relatively difficult quantity to measure in practice, and the accuracy achievable is not as good as for many other areas of measurement. For example, the mass of objects can be found by weighing in a typical laboratory to within one part in 100 000. Similarly, atmospheric pressures can often be measured to within five parts in 10 000. Humidity, however, can commonly be measured to only about three parts in 100, i.e. with an uncertainty in the result of ± 3 percent.

To make a reliable humidity measurement at any given level of accuracy, it is necessary to use an appropriate measuring technique in a sound way. To do so, one must be able to define the measurement task, select a suitable method of measurement underpinned by a reliable calibration, carry out the measurement correctly without introducing errors, and interpret the result of the measurement.

3. CONCEPTS, TERMS AND DEFINITIONS FOR HUMIDITY

3.1. What is humidity?

The word "humidity" denotes the presence of water vapour in air or other gas. Water vapour is the gaseous form of water, and can be thought of much like any other kind of gas. It is normally transparent, and makes up about one hundredth (or one percent) of the air around us.

Humidity arises in practice because, in the same way that hot water gives off steam, so water at lower temperatures - including ice - also gives off water vapour. Wherever there is water or ice, there is evaporation (or its opposite, condensation). The extent to which this happens depends upon a number of factors, the most important of which is temperature. Similarly, other liquid or solid materials - most of which have some water content - will give off (or sometimes soak up) water vapour. Of course, water vapour can also be found in places where there is no liquid or solid nearby, for example in remote parts of the Earth's atmosphere.

Air (or empty space, or any other gas) has a given capacity to absorb water vapour. This capacity depends mainly on temperature. Generally speaking, the hotter the air, the more water vapour it can hold. The graph in Figure 1 illustrates this. At any particular temperature, air

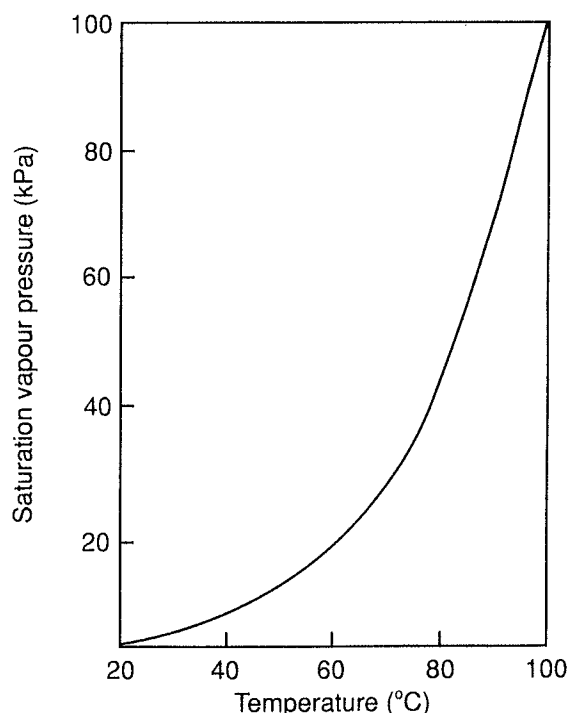


Figure 1 Saturation vapour pressure of water increases with temperature.

that contains its full capacity of water vapour, is said to be "saturated". The "relative humidity" of the air expresses how fully saturated it is with water vapour. A variety of other ("absolute") measures are used to express how much water vapour is actually present (irrespective of temperature or level of saturation). Definitions and explanations of the most important of these terms are given in the next Section.

3.2. Humidity terms and definitions

Many terms specific to humidity are derived from the ancient Greek words *hydor* (water), *hygros* (wet) and also *psychros* (cold).

Meanings of general terms relevant to humidity

Some vocabulary specific to humidity (and other common words with specialised meanings in this context) are as follows:

Absorption (of water vapour) - retention (of water vapour) by penetration into the bulk of a material

Adsorption (of water vapour) - retention (of water vapour) as a surface layer on a material

Condensate - condensed material, e.g. liquid water or ice

Desorption - release of adsorbed or absorbed substance

Desiccant - any substance which exerts a drying action by chemically absorbing water vapour

Dry-bulb temperature - measured air temperature, usually paired with a "wet-bulb" temperature to derive a value of relative humidity. (See "wet- and dry-bulb hygrometer", Section 5.2.)

Humidity - the presence of water vapour in air or other gas. Some people use "humidity" to mean relative humidity only. Strictly speaking, "humidity" also refers to all kinds of absolute indications of humidity. For very low humidities, other more specific terms tend to be used.

Hygrometer - any instrument for measuring humidity

Hygrometry - the subject of humidity measurement

Hygroscopic - tending to absorb water vapour

Inert gas - chemically nonreactive gas, such as nitrogen, helium, argon, etc.

Moisture - commonly used to refer to liquid water or water vapour in any form, "moisture" is also the term particularly used to mean water that is absorbed or bound into any material

Probe - the part of an instrument that houses the sensor remotely from the main body of the instrument, e.g. at the end of a connecting electrical lead. In some situations the word "probe" may be used to refer to an entire hygrometer. Also loosely used interchangeably with "sensor" and "transmitter". "Probe" may also refer to a tube used to extract gas for measurement.

Sensor - the active or sensing part of a measuring instrument. There are some cases where a whole hygrometer is referred to as a "sensor". Also loosely used interchangeably with "probe" and "transmitter".

Transmitter - Instrument which normally gives an electrical output (analogue or digital) rather than a displayed result. The sensing head may be an integral part of the transmitter or may be connected via an external cable. Also loosely used interchangeably with "probe" and "sensor".

Wet-bulb temperature - temperature indicated by a thermometer sheathed in wet wicking, and influenced by the rate of evaporation from the wicking. Usually paired with a "dry-bulb" temperature to derive a value of relative humidity. (See "wet- and dry-bulb hygrometer", Section 5.2.)

Definitions of measured quantities

Many of the following definitions are based on those in the British Standard BS 1339 : 1965 (confirmed 1981, under revision in 1996), "Definitions, formulae and constants relating to the humidity of the air". As given below, the definitions are explanatory rather than rigorous. For rigorous definitions, BS 1339 or other definitive documents listed in Section 12 "Further reading" should be consulted. In practice, the usage of some terms varies according to the context: for example the terms in the field of air-conditioning are sometimes different from the terms used in meteorology for the same quantities. In each case a preferred term is given below, but qualifying notes indicate where there are common alternatives in use.

Units of measurement for expressing the quantities are given, and may have alternative forms, e.g. "grams per cubic metre" is given by " g m^{-3} ", alternatively written " g/m^3 ".

Formulae inter-relating some of these quantities are given in Section 10 (Tables, charts and formulae).

Absolute humidity - The mass of water vapour present in unit volume of moist air of a given temperature and pressure. SI (metric) units are grams of water per cubic metre of air (g m^{-3}). Older references may be in terms of pounds per million cubic feet (lb ft^{-6}) or in grains per cubic foot (gr ft^{-1}). (One grain ≈ 0.0648 gram.).

NOTE. In chemical engineering the preferred term for this concept is "volumetric absolute humidity", while "absolute humidity" is used to denote the quantity referred to in this document as "mixing ratio". In meteorology the preferred term is "vapour concentration". Other terms such as "vapour density", "mass concentration" and "moisture content by volume" are also sometimes used to mean the same thing.

USAGE: It is important not to confuse the particular quantity "absolute humidity" with the general category of "absolute measurements of humidity".

Dew point (or dew-point temperature) - The temperature at which dew, or condensation, forms, on cooling a gas. This is, in effect, the temperature at which air becomes saturated in equilibrium with water. Expressed in degrees Celsius ($^{\circ}\text{C}$) or occasionally in other units of temperature (e.g. in degrees Fahrenheit ($^{\circ}\text{F}$) in USA). See also frost point.

USAGE: When used as a noun, the two-word expression is not hyphenated:

e.g. " ... a dew point of 10°C ... " " ... dew points between -10°C and 0°C ... "

When used as a modifier, or adjective, the expression has a hyphen:

e.g. " ... dew-point hygrometer ... "

Usage as a single word is also widely accepted (in either context):

e.g. " ... dewpoint of 10°C ... " " ... dewpoint hygrometer ... "

Negative dew points, with respect to supercooled water below 0°C , are always shown with a minus (-) sign. Where there is any risk of ambiguity, a plus (+) sign may also be used for positive dew points:

e.g. " ... a range of dew points between -5°C and $+5^{\circ}\text{C}$... "

The term "dew point" is often used generally to include "frost point" (see below). However in the range just below 0°C , where either frost or dew (supercooled water) can form, the values of dew point and frost point differ. (See Section 10, Tables 6 and 7.)

The use of initials (e.g. "dp") is not a recognised abbreviation, but it occurs widely, and is used to distinguish clearly between dew-point temperatures and other values of (air) temperature. For example a dew point value might be expressed in the form "... 10°C dp ..."

Enthalpy (of humid gas) - Measure of the total energy in a humid gas. Enthalpy is a function of the gas temperature and pressure, and of the moisture content, since water absorbs energy on changing from condensed state to vapour. Enthalpy is a useful concept in air conditioning, where it is important to know how much of the "stored" energy will be consumed, or released, when the temperature or water content is raised, or lowered. Enthalpy of a gas can be defined as the sum of "sensible" and "latent" heat for each component in the gas. (See below for definitions of sensible heat and latent heat.) Values of enthalpy are conventionally expressed relative to a datum point (i.e. a zero or base line). For a dry gas, this is normally the heat content at 0 °C. For water vapour, the enthalpy is usually expressed relative to the heat content of liquid water at 0.01 °C. Expressed in terms of energy per quantity of dry gas, i.e. kilojoules per kilogram (kJ kg^{-1}) (or other units, for example British thermal units per pound, Btu/lb).

Equilibrium relative humidity (ERH) (over a substance) - The value of relative humidity of the air at which there is no net exchange of moisture with any nearby substance. This is used for indirectly indicating or controlling the condition of moisture-sensitive substances such as paper. Expressed as a percentage (%). (See also water activity.)

Frost point (or frost-point temperature) - The temperature at which frost forms on cooling a gas. This is, in effect, the temperature at which air is saturated in equilibrium with ice. It is the exact counterpart to dew point (though values differ). Expressed in degrees Celsius, °C, or occasionally in other units of temperature, i.e. in degrees Fahrenheit (°F), in USA. (See also dew point.)

Humidity ratio - Mixing ratio

Latent heat - Heat stored in a substance but not directly related to its temperature. For example, heat is stored in a gas because this heat was originally supplied to evaporate it. "Latent" means "hidden". Expressed in energy per unit mass of substance, i.e. joules per kilogram (J kg^{-1}). (See also enthalpy, sensible heat.)

Mixing ratio - Mass of water vapour per unit mass of dry air with which it is associated. It is a dimensionless ratio, but is often expressed in grams of water per kilogram of dry gas (g kg^{-1}) or in other units of mass.

For low levels of moisture content, this may be expressed in parts per million by weight, i.e. mass of water vapour per million parts mass of dry gas (ppm_w or $\text{ppm}(w)$).

NOTE: In chemical engineering this quantity is normally termed "absolute humidity" - but must not be confused with the definition of "absolute humidity" given above. Mixing ratio is also alternatively known as "humidity ratio".

Moisture content - A humidity term best reserved for general descriptive or qualitative use only. Use of this term to identify a measured quantity should be avoided, as there is a risk of confusion because "moisture content" has been used in the past to mean both mixing ratio and specific humidity. Moisture content is also a term particularly used to refer to the proportion of water held in liquids or solids.

Mole - Amount of substance which contains as many elementary entities as there are atoms in 12 grams of carbon 12. Expressed in moles (symbol, mol).

NOTE: When the mole is used, the elementary entities must be specified as atoms, molecules, etc.

Mole fraction - The mole fraction of a component is the ratio of the amount (number of moles) of that component to the total amount of substance present. Expressed as a dimensionless ratio.

Partial pressure (of water vapour) - The part of the overall pressure exerted by the water vapour component in a gas. Expressed in units of pressure such as pascals (Pa) or in multiples; kilopascals (kPa) or megapascals (MPa), with non-SI alternatives such as millibar (mbar) or millimetres of mercury (mmHg). $100 \text{ Pa} = 1 \text{ mbar} \approx 0.75 \text{ mmHg}$.

Parts per million - Abbreviated as "ppm", it must always be stated whether this is by mass (weight) or by volume, and whether the figure is the ratio of water vapour to dry gas, or to total (moist) gas.

Parts per million by volume (ppm_v, ppm(v)) - Volume of water vapour per total volume of gas, for an ideal gas. Sometimes expressed relative to the total volume of *moist* gas (mole fraction times one million) or sometimes relative to the total *dry* gas. For small numbers of parts per million, the two are almost identical; at higher humidities they become significantly different.

Parts per million by weight, or mass (ppm_w, ppm(w)) - Sometimes used to express the amount (mass) of water vapour relative to the total *dry* gas (mixing ratio times one million), but sometimes to express the amount relative to the total *moist* gas (specific humidity times one million). For small numbers of parts per million, the two are almost identical; at higher humidities they become significantly different.

Percentage saturation - The ratio of the actual mixing ratio to the saturation mixing ratio at the same temperature, expressed as a percentage (%).

NOTE. Under ordinary climatic conditions the percentage saturation is almost identical to the relative humidity.

Relative humidity - The ratio of the actual vapour pressure to the saturation vapour pressure over a plane liquid water surface at the same temperature, expressed as a percentage. This is commonly understood when the term "X percent relative humidity" is used. For actual vapour pressure, e , and saturation vapour pressure, e_s ,

$$\text{relative humidity (in \%)} = \frac{e}{e_s} \times 100 . \quad (1)$$

USAGE: The phrase "relative humidity" is commonly abbreviated *RH* although this is not an a recognised abbreviation. Values of relative humidity are commonly expressed in units of percent relative humidity (%rh).

Care must be taken when expressing uncertainties, changes or fractional differences in relative humidity. For example, the difference between 50 %rh and 52 %rh is 2 %rh. This can also be expressed as a difference of 4% of value. It is important to distinguish clearly between these two kinds of statement.

Saturation vapour pressure (of water) - maximum pressure of water vapour that can exist at a given temperature. Expressed in units of pressure e.g. in pascals (Pa), or in non-SI units such as millibars (mbar) or millimetres of mercury (mm Hg).

Sensible heat (of a gas) - energy that resides in a gas according to its temperature. Expressed in terms of energy per mass of gas, e.g. in joules per kilogram (J kg⁻¹), or equivalent units. (See also enthalpy, latent heat.)

Specific humidity - mass of water vapour per unit mass of humid air. May be expressed as a dimensionless ratio, or in grams of water per kilograms of humid gas (g kg⁻¹) or in kilograms per kilogram (kg kg⁻¹)

Vapour pressure - that part of the total pressure contributed by the water vapour. Expressed in units of pressure e.g. in pascals (Pa), or in non-metric units such as millibars (mbar) or millimetres of mercury (mm Hg).

Water activity (of a substance) - Water activity (a_w) is the relative humidity which is eventually reached in a closed space where a hygroscopic substance, such as a foodstuff, has been placed. It is the same as equilibrium relative humidity (ERH) except that it is expressed on a scale of 0 to 1 (no units), instead of 0% to 100%. Water activity is particularly used in connection with foodstuffs. (See also equilibrium relative humidity.)

4. SIGNIFICANCE OF TEMPERATURE AND PRESSURE FOR HUMIDITY MEASUREMENT

4.1 The effects of temperature on humidity measurement

The effect of temperature on humidity is highly significant. Failure to take this into account can sometimes lead to errors so large that the measurement is meaningless. In many situations, the largest single source of uncertainty in a humidity measurement is the effect of temperature differences from place to place in the process, room or chamber. The importance of considering the temperature effects carefully cannot be overstated when relative humidity is the parameter of interest. (See graphs (a) and (b) in Section 10.2.)

Temperature and instruments

All hygrometers have some temperature dependence. In some instruments (such as well designed psychrometers and condensation hygrometers) the effects may be small, but this is not always true. In instruments which rely on an electronic sensor, the effect of temperature is almost always significant. However some instruments have temperature compensation built in. In general, calibration at the temperature of use (or close to it) is essential.

Temperature and condensation

One common cause of error in humidity measurement is the occurrence of unwanted condensation. Condensation can occur at cold spots which are below the dew point of the gas. In sampling systems, any condensation totally invalidates the sampling process, since it changes the water vapour content of the gas. To prevent condensation, sample systems should always be kept at a temperature above the maximum dew point, by heating them if necessary.

Temperature and absorption or desorption of water

Many materials contain moisture as part of their structure; particularly organic materials, salts, and anything which has small pores. The quantity of water in these materials depends on the humidity of the surrounding gas, and on the temperature. When the temperature changes, water migrates from the material to the surrounding gas or vice versa. Like condensation, this can cause changes in the measured humidity. However, unlike condensation, there is not usually a critical temperature: whenever the temperature changes, water moves between the material and the gas.

When measuring low dew points, desorption or absorption of water vapour as the temperature changes can produce very large errors in measurement. Even in normal ambient conditions, absorption or desorption can begin to be significant, depending on the type of material.

Temperature and saturation vapour pressure of water

The saturation vapour pressure of water depends strongly on temperature. Near room temperature, the air's capacity to hold water vapour doubles for every 10 °C increase in temperature. The steepness of this variation gradually changes across the temperature range. At 80 °C the saturation vapour pressure doubles for every 20 °C rise. At -60 °C the saturation vapour pressure doubles for only a 5 °C rise in temperature. (See Section 10 Tables 6 and 7.)

Temperature and relative humidity

Relative humidity is highly dependent on temperature - especially so because vapour pressure appears twice in the formula for relative humidity,

$$\text{relative humidity (in \%)} = \frac{e}{e_s} \times 100 . \quad (2)$$

(e is the water vapour pressure, and e_s is the saturation vapour pressure at the prevailing ambient temperature.)

Roughly speaking, at room temperature, a change in dew point of 1 °C corresponds to a change in relative humidity of 6 percent of the relative humidity value. For example at 50 %rh, an uncertainty in dew point of ± 1 °C corresponds to an uncertainty of ± 3 %rh.

A change of 1 °C in the measurement of the ambient temperature has almost exactly the same significance. The size of the effect under different conditions is illustrated below in Table 1.

Overall, a useful rule of thumb is that ± 1 °C uncertainty in either dew point or temperature leads to an uncertainty of ± 6 percent of the relative humidity value.

Table 1. Effect of a temperature change of 1 °C at various levels of temperature and relative humidity. The change in the relative humidity levels is not symmetric.

Relative humidity	Temperature				
	10 °C	20 °C	30 °C	50 °C	70 °C
10 %rh	± 0.7 %rh	± 0.6 %rh	± 0.6 %rh	± 0.5 %rh	± 0.5 %rh
50 %rh	± 3.5 %rh	± 3.2 %rh	± 3.0 %rh	± 2.6 %rh	± 2.3 %rh
90 %rh	± 6.3 %rh	± 5.7 %rh	± 5.4 %rh	± 4.6 %rh	± 4.1 %rh

A note on temperature measurement in air

A thermometer indicates its own temperature. It is important to note this because a thermometer may not always be at the same temperature as its surroundings. Thermometers can be influenced by the temperatures of other objects nearby (not the ones which are intended to be measured). Thermometers can also suffer from time lags, and self-heating errors may affect electrical resistance thermometers. All these effects are at their worst when a measurement is undertaken in air, as opposed to in liquid. Errors from these sources can easily amount to several tenths of a degree, so the effects on relative humidity can be significant, as shown above.

4.2 The effects of pressure on humidity measurement

Since all measurements of humidity stem from the measurement of a vapour pressure of water, it follows that variations in overall pressure of the gas system may have an effect on the measured humidity. Throughout this Guide, the values of pressure are given in absolute terms (atmospheric pressure being 101325 Pa, or 1013 mbar), and not in "gauge" pressures (where atmospheric pressure would have a value of zero).

In a gas mixture such as room air, the total pressure $P_{(total)}$ of the system can be expressed as the sum of partial pressures:

$$P_{(total)} = P_{(nitrogen)} + P_{(oxygen)} + P_{(water)} + P_{(others)} \quad (3)$$

It therefore follows that if any of the partial pressures of the component gases varies the total pressure $P_{(total)}$ will vary. Also, if the total system pressure is changed either by compression or expansion, each of the component partial pressures will be changed by a similar factor to $P_{(total)}$.

This basic rule can be applied to any measure of humidity to predict the effect of changes in either component or overall pressures. Below are some simple examples showing the effect of pressure change.

Effect of doubling pressure on a relative humidity of 40 %rh at constant temperature, without changing composition

Relative humidity is expressed as a ratio of vapour pressures (the actual vapour pressure relative to the saturation vapour pressure). Doubling $P_{(total)}$ will yield a similar doubling of $P_{(water)}$. If the saturation vapour pressure remains unchanged (i.e. if temperature is unchanged) then a relative humidity of 40 %rh would be doubled to 80 %rh.

As a general approximate rule, the actual relative humidity value can be multiplied by the fractional change in total system pressure to give the resultant value of relative humidity. (Where the result exceeds 100 %rh, condensation will occur.)

The rule is similar for other measures of concentration in terms of mass per unit volume, such as absolute humidity (g m^{-3}).

Effect of doubling system pressure on mixing ratio, without changing composition

The mixing ratio of water in a gas system is simply the ratio of the mass of the water vapour to the mass of the dry gas.

If any gas is compressed or expanded without adding or removing components, then the mass of all components is unchanged. Therefore the mixing ratio is unaltered by the pressure change. This can also be deduced from the fact that the definition of mixing ratio does not involve pressure or temperature.

The rule is similar for other dimensionless measures of concentration (those expressed in mass per unit mass, or volume per unit volume), such as mole fraction and specific humidity, including cases where these are expressed in terms of parts per million.

Effect of doubling system pressure on dew-point temperature, without changing composition

The dew-point temperature of a system is directly related to the water vapour pressure of that system. From equation (3) it can be seen that a doubling of total pressure $P_{(total)}$ will yield a doubling of the water vapour pressure, $P_{(water)}$. Reference to vapour pressure tables (see Section 10) will allow the new dew-point temperature to be calculated.

For example, for a system of pure water vapour with a dew point of +10 °C, the water vapour pressure is about 1228 Pa. If the system pressure is doubled, the resultant water vapour pressure will be $2 \times 1228 = 2456$ Pa, which equates (from Table 6) to a dew-point temperature of about +20.8 °C.

For dew points in the presence of air or other gases (rather than pure water vapour alone), a correction may need to be made for the water vapour enhancement factor (see below).

Water vapour enhancement factor

The examples above assume that all the component gases exhibit "ideal gas" behaviour. In practice a small, pressure-dependent correction may be required: the "water vapour enhancement factor". In air, this numerical correction is less than 1% of value when pressure is doubled from atmospheric pressure. For a tenfold increase from atmospheric pressure, the effect is between about 1% and 10% of value, depending on the dew point of the gas. Further details are given in Section 10.

Tables or equations giving the saturation vapour pressure of water are usually true for "pure" water vapour only, in the absence of air or other atmospheric gas. If other gas is present, then the values of vapour pressure need to be adjusted. For example, the presence of air in normal climatic conditions raises the saturation vapour pressure by about 0.5% above the "pure" value.

5. INTRODUCTION TO METHODS FOR MEASURING HUMIDITY

5.1 Direct or indirect approach?

The different measures and units for humidity measurement are all interrelated, some of them as functions of temperature and pressure as well as moisture content. This means that there is often a choice of which humidity parameter to measure. Relative humidity in particular can be measured directly using some kinds of instrument, but can also be derived indirectly from measurements of temperature and dew point (or other absolute measures of humidity). See Section 10.3 for method of calculation.

5.2 Operating principles of various hygrometers

Humidity influences a vast range of physical, chemical and biological processes. It follows from this that there are many kinds of humidity-related effects which can be exploited to indicate changes in humidity. Descriptions of some of the most important methods for measuring humidity are given below, broadly in order of prevalence.

Mechanical

Mechanical hygrometers exploit the expansion and contraction of organic materials with changes in humidity. The sensing element may be human hair, catgut, goldbeater's skin (cow's intestine), textile or plastic. Changes in length are amplified through the action of levers to move a pointer on a dial, or a pen recording on a chart. Ornamental "weather house" hygrometers - where the figure of a man or woman appears depending on the humidity - also operate on this principle.

Wet- and dry-bulb (psychrometer)

A wet- and dry-bulb hygrometer consists of two matched temperature sensors over which humid air is drawn. One sensor is enclosed in a porous medium (wick or "wet sock") which is maintained wet by capillary action from a reservoir of water.

Water evaporates from the wick at a rate related to the humidity of the air. The evaporation causes the wet sensor to be chilled. The temperatures of the wet and dry sensors are used to calculate the humidity of the air. Details of the calculation are given in Section 10.3. Alternatively the humidity can be found from a set of look-up tables (BS 4833 - See Section 12 "Further reading"). Some forms of psychrometer are equipped with automatic calculation of humidity from the temperature readings, so that relative humidity or dew point may be read directly.

An aspirated psychrometer with a fan for adequate air flow over the thermometers is the recommended basis for this measurement. Other approaches, such as Mason's (non-aspirated) psychrometers and whirling (hand aspirated) psychrometers, are less successful realisations of this principle and are prone to errors, as are "home-made" psychrometers.

Electrical impedance (capacitive or resistive)

This general type of sensor is fabricated from a hygroscopic material, the electrical properties of which alter as it absorbs water molecules. Changes in humidity are measured as a change in the sensor's electrical capacitance or resistance or some combination of the two. The majority of modern impedance sensors use thin-film technology. Electrical hygrometers are often portable and compact. The common form of this instrument is a small wand-shaped probe connected by a cable (or directly attached) to the main body of the instrument. Specially shaped probes are often available for particular purposes. They are often equipped with a filter to protect against contamination. (Response times are faster, though, without this protection.) Impedance hygrometers are usually also fitted with a temperature sensor. Readings are displayed directly, sometimes with a choice of units (e.g. relative humidity or dew point), and output of an electrical signal (e.g. analogue voltage) may also be available.

There are several distinct types of electrical sensors.

Capacitive sensors respond most closely to relative humidity, rather than dew point, with best linearity at low relative humidities. In general capacitive sensors are not damaged by condensation (i.e. relative humidity of 100 %rh), though calibration may shift as a result.

Resistive sensors respond most closely to relative humidity, rather than dew point. Linearity of resistive sensors is best at high humidities. Most resistive sensors cannot tolerate condensation. However, some are "saturation guarded", with automatic heating to prevent condensation.

One type of resistive sensor is sometimes referred to as "**electrolytic**" because of the use of a polyelectrolyte as the hygroscopic element of the sensor. This should not be confused with electrolytic sensors which use electrolysis as the sensing mechanism (see "Electrolytic (phosphorous pentoxide)" below).

Dew-point type impedance sensors are a special case of impedance hygrometer, used to measure in absolute units rather than relative humidity. Following a similar general principle, the sensor may feature aluminium oxide or other metal oxides, or a silicon base for the active element. This type of sensor responds to the partial pressure of water vapour. Commonly the signal is converted into other absolute units, resulting in values displayed by the instrument in dew point or parts per million by volume. These sensors can have a wide range of measurement, including very dry gases.

Condensation

Dew-point temperature can be measured by cooling a sample of gas until condensation appears, and observing the temperature at which this happens.

In an optical dew-point hygrometer, condensation in the form of dew or frost is induced on a small mirror within the instrument. The onset of condensation is sensed optically, by detecting changes in how the mirror reflects or scatters light. The reading may be recorded at the instant of condensation, or the mirror may be held at that temperature and a continuous reading obtained. Designs vary, with some in probe form, while others employ sampling through a tube. While the probes may be reasonably compact, the main body of the instrument is usually relatively large, and not portable. Readings are displayed as a dew-point temperature, and output is usually also available in electronic signal form.

Other (non-optical) condensation dew-point sensors detect condensation electrically, or by other methods such as the change in frequency of a resonating quartz crystal.

Saturated lithium chloride

The sensing medium, which is a hygroscopic salt, absorbs water from the air. An electrical voltage is applied across the salt and a current passes according to the amount of water vapour that has been absorbed. At the same time, the current also heats the salt. Eventually a balance is achieved between the absorption and the heating. The temperature at which this occurs is related to the water vapour pressure. The instrument is usually in probe form, with readings displayed in terms of dew point.

Electrolytic (phosphorous pentoxide)

The sensor consists of a film of powerful desiccant, phosphorus pentoxide (P_2O_5), which strongly absorbs water vapour from the surrounding gas. A voltage is applied across the P_2O_5 , and electrolysis takes place, dissociating the water into its constituents - hydrogen and oxygen. The current that flows in this process is related (by Faraday's Law) to the amount of water electrolysed. Thus the value of current indicates the humidity of the gas being measured. These sensors are suitable for measuring very low humidities, though they require a steady (known) flow rate of gas. This instrument measures water concentration by volume, with readings displayed in one of the absolute units, such as parts per million by volume or vapour pressure. It is normally used in a flow sampling configuration, rather than in probe form. (See also "electrolytic" under "electrical impedance" above for another sensing method known by this description.)

Spectroscopic

In general, a spectroscopic technique is one where the composition of a gas mixture is found by analysing how substances absorb (or emit) light of particular wavelengths or frequencies. Every chemical substance has a characteristic frequency "signature", and these may lie in the ultraviolet or infrared parts of the spectrum. Spectroscopic measurement can be a useful approach if concentrations of other substances are to be measured, as well as that of water vapour.

The spectroscopic technique used for high or moderate humidities is based on **infrared absorbance**. Water absorbs infrared radiation at several wavelengths in the range 1 μm to 10 μm . The intensity of transmitted radiation is measured at one of these wavelengths and compared with that for a reference wavelength, using a photocell for detection. The amount of this radiation absorbed by the gas is proportional to the spatial concentration (or partial pressure) of water vapour.

Spectroscopic techniques can also be used to measure extremely low concentrations of water vapour, reportedly down to a few parts per billion (ppb, i.e. parts in one thousand million). There are several versions of this sophisticated technology, including **APIMS** (atmospheric pressure ionisation mass spectrometry), **FT-IR** (Fourier-transform infrared spectroscopy), and **TDLAS** (tunable diode laser absorption spectroscopy).

Colour change

There exist humidity indicators which show changes in humidity as a colour change on a paper strip or other material. The sensing material is impregnated with cobalt chloride. The colour change takes place as a result of a moisture reaction with this chemical. Other colour-change measurements involve pumping gas through a vial filled with crystals which change colour according to the humidity of the gas.

Others

The list above is far from exhaustive. Other methods which have their uses in particular applications include:

Acoustic - transmission of sound in air (or other materials) can indicate humidity

Adiabatic expansion - cooling of air on expansion produces a "cloud" if the dew-point temperature is reached

Gravimetric - weight of absorbed moisture

Lyman-alpha - absorption and emission of ultra-violet light by air indicate the partial pressure of water vapour

Optical fibre - loss or reflection of light by fibre coatings indicates changes in humidity. As well as being used as a sensing method, optical fibres are increasingly used in place of metal conductors in signal processing circuits.

Optical refractive index - the speed of light in air depends on its composition, including water vapour

Piezoelectric (quartz oscillator) - the resonating frequency of a quartz crystal indicates the mass of water it has absorbed from the air

Pneumatic bridge - water vapour pressure is found from the change in overall pressure when the water vapour is removed

Thermal conductivity - heat loss from a hot wire is affected by water vapour as well as other constituent gases

Thermal rise - heat of adsorption or desorption of water from a desiccant

Zirconia - water vapour is detected by measuring the oxygen content of the gas and comparing this with the normal amount of oxygen present.

Some of the methods listed in this Section also lend themselves to measurement of moisture content in solids and liquids.

Table 2 gives a simplified overview of some of the features of the main hygrometer types. In the chart, broad indications of the properties of different measuring methods are given. The notes in brackets give additional information, or list features which are sometimes available, but not always. Manufacturers or suppliers of instruments should be consulted for specific details, especially as the technologies are continually being improved. Guideline uncertainties are given for using the different types of instrument. In exceptional cases, instruments may perform a little better than suggested here. In other cases, they may perform worse than the poorest estimates in the table, due to particular circumstances of use.

More detailed information about strengths and weaknesses of each method is given in Section 6.

Table 2. Summary of some of the features of the main types of humidity measurement

Sensor type	Absolute or relative humidity	Typical range (extended range in brackets)		Typical units in which readings are displayed	Contamination tolerance ² (bracketed ratings after cleaning)	Sampling, configuration	Guideline best humidity uncertainty in use ³ (±)
		Humidity	Temperature ¹				
Mechanical	R	20 %rh to 80 %rh	Near room temperature	%rh	* * *	Whole immersion	5-15 %rh
Wet- and dry-bulb aspirated (Psychrometer)	R	5 %rh to 100 %rh	0 °C to 100 °C (also useable above and below this range)	%rh (often hand-calculated from temperature readings)	* (* *)	Whole immersion (or sample gas flow)	2-5 %rh
Resistive	R	5 %rh to 95 %rh (and up to 99 %rh)	-30 °C to +60 °C (-50 °C to 200 °C)	%rh	* *	Probe (or whole immersion)	2-3 %rh
Capacitive	R	5 %rh to 100 %rh (and down to near 0 %rh)	-30 °C to +60 °C (-40 °C to 200 °C)	%rh	* *	Probe (or whole immersion)	2-3 %rh
Impedance dew-point types	A	Dew points of -85 °C (or below) to +60 °C	Most temperatures up to +60 °C, avoiding saturation	Dew point, vapour pressure	* *	Probe	2-5 °C
Condensation	A	Dew points below -85 °C to +100 °C	-85 °C to +100 °C (main body of instrument at room temperature)	Dew point	* (* *)	Sample gas flow (or probe)	0.2-1.0 °C
Lithium chloride	A	Dew points of -45 °C to +60 °C, gas always over 11 %rh and not saturated	-20 °C to +60 °C (some use -40 °C to +100 °C)	Dew point	*	Probe	2-4 °C
Electrolytic (phosphorous pentoxide)	A	Below 1 ppm _v to 1000 ppm _v	Near room temperature	ppm _v , or vapour pressure	*	Sample gas flow	3-10 percent of reading
Spectroscopic	A	Extremely wide range, depending on type	Very wide range (main body of instrument at room temperature)	ppm _v (and others)	* * *	Gas sample (line-of-sight sampling at high humidity)	3-10 percent of reading in high range, much more at low end.
Colour change	R	20 %rh to 80 %rh	Near room temperature	%rh	* *	Paper test card (or pump with glass vial)	10-20 %rh

¹ Where temperature ranges are stated these are the operating ranges for humidity measurement, not the ranges of any temperature sensors which may be integral in the instruments.

² General tolerance of contamination is indicated, with three stars [* * *] for good tolerance and one [*] for poor tolerance.

³ Guideline uncertainties assume traceable calibration and do not include any contributions which might result from non-ideal conditions of use. The uncertainties are given at a level of confidence of approximately 95% (i.e a coverage factor of $k=2$). See Section 7 for more information on uncertainty of measurement.

6. SELECTION OF A TYPE OF HYGROMETER

6.1. Identifying measurement needs

To ensure "fitness for purpose" it must be clear first of all what is the purpose. Is a humidity measurement needed at all? If so, what use is it to the business or process? To be useful, how should the results be expressed? Is the measurement to meet a practical need, or to comply with a documented specification (and is the specification meaningful and realistic?). Once the need and aim of making the measurement is clear, it is important to decide what factors are relevant to achieving this aim. The user should consider the following issues. (Some of these are dealt with in more detail in Section 6.2, where strengths and weaknesses are listed for each method of measurement.)

Measurements required

Relative or absolute - Which unit or scale of measurement? The quantity of interest may be relative humidity, dew point, or some other measure of the concentration of water vapour.

It is best to select a method of measurement which intrinsically detects the quantity of interest. Many hygrometers display results in terms of two or more humidity parameters. This is often useful, but it should be understood that normally only one parameter is being measured, and the other values are the result of numerical conversions. Because of this an instrument might give a reliable indication of only one of the parameters shown, while providing a less good indication of the other parameters.

Range (humidity and other variables) - Different types of measurement are suited to different ranges of humidity. It is best to avoid using an instrument at the upper or lower extreme of its range of measurement. Ranges of temperature, flow rate, and pressure or vacuum also need to be specified in order to select the best instrument. For example, where use at elevated pressure is planned, the construction of the instrument may be as important as the operating principle. On the other hand, for some types of measurement, a correction may have to be applied to the results if the pressure varies. (Conversions between units, pressures, etc. are discussed in Sections 4 and 10.)

Performance - It is worth deciding if any particular performance characteristics are important for the application in question. There may be a need to set criteria for sensitivity, stability (in terms of repeatability or reproducibility), uncertainty, response time, resolution, linearity or hysteresis). These concepts are all explained below in Section 6.4.

Output, readout - The humidity result may simply be shown as a number on a digital display, or on a numbered scale. It may be given as an electrical voltage or current signal (analogue output). Several parameters or units of humidity may be shown, together with temperature. Readings may be given continuously or at intervals. The instrument may record readings on a paper chart. Readings may be stored electronically in memory in the instrument, or be downloaded in digital form directly into a computer through a "serial link". At the other extreme, humidity values may even need to be hand-calculated from indirect results such as temperature readings.

Instrument format and usage

Configuration - A hygrometer may be hand held, or mounted in a duct or on a wall, used on a bench top or under some other arrangement. It may need to be mounted in a particular orientation. The sensor may be housed in a remote probe (which may be specially shaped to suit a particular purpose), or it may be located in the main body of the instrument. It may be powered by battery, by mains electricity, or may need no electrical supply at all. There may be a limitation on the length of the cable joining the probe to the main body of the instrument. Size of the hygrometer relative to the sampling space may be relevant.

Sampling - Sampling is an important issue in all humidity measurement and is discussed in some detail in Section 8, Recommended Practices. The sampling approach may be that of "immersion", where the instrument sits wholly or partly in the environment to be measured; or the gas may be "sampled" by extracting it to the instrument through a tube. Some immersion sensors benefit from being in still air, some from being in moving

air, and for some the flow rate of air is critical. When measuring gases with very low water content, the quality of the sampling pathway is critical; hygroscopic materials in the pathway can change the water content of the sample. Also, care must be taken with certain types of hygrometer which may themselves affect the environment, by giving off either water or heat. (Indeed any instrument introduced at the wrong temperature will influence its environment, affecting the measurement result.) Conversely, moisture and heat from the operator may affect measurements using hand-held hygrometers.

Type of gas - In gases other than air, chemical compatibility may be an issue. Calibration specific to the gas in question may be required.

Materials of construction - Aside from considering the hygroscopic nature of materials, other aspects of suitability may need to be addressed. Some materials may be chemically incompatible with the environment of interest. Materials may be unacceptable for other reasons, such as avoidance of plastics and glass for reasons of hygiene or safety.

Ease of use - Some hygrometers are straightforward to use. Others require some skill.

Error detection - Some hygrometers warn the user of errors in the instrument itself, or of incorrect usage, for example if the proper humidity range is exceeded, or if the batteries are running low.

Use for control or monitoring - In some cases the user simply needs to measure humidity. In others, the humidity measurement is fed into a process of control of humidity. If so, then access to the electrical output in some form is usually necessary. For use in control of humidity, the response time and the degree of hysteresis are usually important.

Hazardous areas - In areas where there is some hazard, such as an explosive atmosphere, suitable precautions must be taken. For example, extraction of sample gas to remote probes may reduce the risk in some cases, while other sensors can be designed to be "intrinsically safe", by limiting the electrical power to a level low enough that it cannot ignite the atmosphere. Where this is a concern, an appropriate certification of intrinsic safety should be sought.

End use - Humidity itself may be of interest, or humidity may be used as an indication of the moisture content of other solid or liquid substances. If so, it may give no more than a very indirect indication of the actual *content*, though ERH and water activity are proper indications in a different way of the condition or equilibrium of materials with the environment.

Cost and upkeep

Cost - Some methods are more expensive than others, and the best method need not be the most expensive one. When comparing different prices for the same type of instrument, variations may reflect the provision of special features, or may simply be an indication of differences in quality. As well as the initial expense, lifespan, maintenance and calibration costs need to be taken into account.

Calibration - Method of calibration, and ease of doing so, should be considered even when there does not appear to be a call for highly accurate results. "Field" or *in-situ* methods of calibration are more readily available for some hygrometer types than for others.

Robustness - Both hygrometer sensors and casings vary in their robustness against condensation, drying out, temperature extremes, dust, chemical or other contamination, vibration, or even simple handling.

Quality, reliability, lifespan - Quality is not always easy to judge. Aside from general impressions, compliance with a quality accreditation or published standard specification may be some indication. When choosing a "brand name", a manufacturer that specialises in hygrometers may be a better choice than one making a wide variety of instruments. Recommendations from other users may be the best guide. Some types of hygrometer tend to have a long lifespan; others less so.

Versatility - If more than one kind of use is envisaged, the adaptability of the hygrometer should be borne in mind.

Interchangeability - It may be desirable to have a set of hygrometers which can be used interchangeably, or to substitute other probes for use with the main body of the hygrometer. It may be necessary to replace components of the sensor which might fail. In any of these cases, it is important to consider how interchangeable the instruments or components really are. Interchangeability is best ensured by calibration against a consistent reference. However, replacing a key component of an instrument may invalidate its previous calibration.

Maintenance - Some types of hygrometer need routine cleaning, regeneration, or replacement of parts.

Availability of spares - It may be worth knowing about spare parts; whether they can be fitted by the user, and whether they are freely available locally and quickly. Any consumable supplies, such as charts, should be available and clearly coded or identified, as they are not always interchangeable.

After-sales service - The availability of a warranty, or of a good maintenance or service contract may be a factor in the decision.

6.2 Strengths and weaknesses of particular methods

Below are listed some key strengths and weaknesses for each of the main methods of measuring humidity. A general indication is given of the uncertainty associated with each type of instrument, assuming they are traceably calibrated, and excluding any uncertainties due to particular conditions of measurement.

Mechanical

Mainly suited to normal room conditions. Uncertainty of measurement around $\pm 5\%$ rh to $\pm 15\%$ rh.

- + May not need electrical power or batteries
- + Chart types provide a permanent record
- + May be cheap to buy
- Slow response to changes in humidity
- May suffer from hysteresis
- Easily upset by vibration or transportation

Wet- and dry-bulb (psychrometer)

Principally suited to large spaces and medium or high humidities. Uncertainty of measurement around $\pm 2\%$ rh to $\pm 5\%$ rh, at best.

- + Psychrometers are relatively simple, cheap, reliable and robust instruments
- + Can have good stability
- + Wide range of humidities
- + Tolerates high temperatures and condensation
- Some skill is usually required to use and to maintain the instrument
- Results may have to be calculated from temperature readings (although some are automatic)
- A large air sample is required for the measurement
- The sample will be humidified by wet-sock evaporation
- Airborne particles or water impurity may contaminate the wick; this can and should be remedied by regular cleaning or replacement
- Measurement can be complicated below about $10\text{ }^{\circ}\text{C}$, by doubt between presence of water or ice on wick when this falls below $0\text{ }^{\circ}\text{C}$
- "Whirling" types and non-aspirated types are prone to serious errors, as are "home-made" psychrometers

Electrical impedance (capacitive, resistive, dew-point types)

Resistive and capacitive sensors are used for a variety of applications in ambient conditions, including use for control of air conditioning and other processes. Some are used in more extreme environments. "Dew-point" types are distinct from others in this group in that they cover much lower levels of humidity, in absolute units, and are used in control and monitoring of relatively dry gases. They include aluminium oxide and other metal oxides, and silicon-based sensors. Relative humidity types can achieve uncertainties of 2% to 3% of value, at best, while dew-point types have uncertainties of around 2 °C in dew point, at best, to 5 °C at low dew points.

In general, impedance sensors are:

- + Often easy to use
- + Increasingly available with integral memory functions for storing results
- + Adaptors available for use in stacks of paper, hoppers of grain, etc.
- May suffer calibration shifts if used at high temperatures (above 40 °C) and/or high humidities (performance varies)
- May suffer drift and hysteresis
- Can be damaged by aggressive chemicals

Capacitive sensors in particular ...

- + Usually tolerate condensation (though calibration may shift)

Resistive sensors in particular ...

- May be damaged if condensation occurs (though some sensors are protected)

Dew-point impedance sensors in particular ...

- + Usually tolerate condensation (though calibration may shift)
- + Can have wide measuring range
- May be slow to settle at very low (absolute) humidities
- Some tendency to drift

Condensation

Optical dew-point hygrometers are often used as reference standards for calibrations, particularly at low humidities (but also at high humidities). Uncertainty in dew point around ± 0.2 °C to ± 1.0 °C, depending on range.

- + Can provide precise measurement
- + May have good long-term performance
- + Wide range of measurement
- Usually requires some skill to operate
- Optical dew-point hygrometers are generally expensive
- Contamination can cause incorrect readings - the mirror must be cleaned with purified water
- Dew-point readings just below 0 °C need careful interpretation, depending on whether the condensate is ice or water. (It helps if the hygrometer is fitted with a viewing microscope.)

Saturated lithium chloride

Long established method used historically to measure a wide range of ambient conditions. Dew-point uncertainty at best ± 2 °C to ± 4 °C.

- + Can be cheap
- Will not operate below 10 %rh
- Does not tolerate condensation
- Slow response
- Affected by contamination from hygroscopic materials or solvents
- Some skill required, especially for maintenance

Electrolytic (phosphorous pentoxide)

Long established method for use in dry environments. Uncertainty ± 3 to ± 10 percent of reading at best.

- + Compatible with some corrosive gases
- + Can have good sensitivity
- Measuring cells have a limited life, after which they must be re-coated (and re-calibrated)
- Flow rate of gas is critical
- Damaged by exposure to normal ambient humidities, and by periods of extremes of dryness (below 1 ppm_v)
- Slow response at lowest humidities
- Hydrocarbons, butadiene, ammonia and some other contaminants prevent proper operation
- Adds traces of hydrogen and oxygen to the gas sample, which can re-combine, leading to errors

Spectroscopic

Uses range from measurement of gases in ovens and combustion processes to measurement of trace components in high purity process gases. Uncertainty can be around ± 3 to ± 10 percent of reading, but more than this at ultra-low humidities.

General points about spectroscopic methods are:

- + Suitable for use with almost any gas, including corrosive and reactive ones
- + Can be used to measure concentrations of other substances at the same time
- + Gases at high temperatures can be measured
- + Non contact measurement
- + Fast response
- + High sensitivity
- Sophisticated technology
- Expensive
- Difficult to calibrate
- Carbon dioxide may interfere with the humidity measurement if present in quantity

Infrared absorbance in particular is used in industrial processes where the environment may be dirty, with high moisture content, and at high temperatures.

- + Can be designed for use in hostile environments

Other spectroscopic methods such as **APIMS** (atmospheric pressure ionisation mass spectrometry), **FT-IR** (Fourier-transform infrared spectroscopy), and **TDLAS** (tunable diode laser absorption spectroscopy) can be used to measure extremely low concentrations of water vapour. Uncertainties rise dramatically at the very low extreme of measurement range.

- + Can measure extremely low concentrations of water vapour
- Long path length required for sensitivity at low moisture levels

Colour change

Mainly used in display cases in locations such as museums, or as wall-mounted damp indicators. Uncertainty may be in the region of $\pm 10\%$ rh to $\pm 20\%$ rh.

- + No battery or electrical power needed
- + Can be observed remotely (if visible) without disturbing environment
- + Cheap and simple
- Only gives a very coarse estimate of humidity
- Difficult to calibrate

6.3 How to buy an instrument for measuring humidity

To buy a hygrometer that is fit for its intended purpose, there are a number of actions which will help at the purchasing stage.

Specification - setting criteria

After setting some main criteria, with the help of Sections 5 and 6 above, it may be possible to select a preferred type of measurement, or rule out unsuitable methods. However, the guidelines given are general ones, and do not cover all special cases. New developments or specially adapted instruments may be available.

Finding suppliers

If a list of hygrometer suppliers is not to hand, this information can be found from a number of sources. Business directories, available in most libraries, list companies according to the type of business or product. Technical magazines and journals carry advertisements for hygrometers. Exhibitions devoted to instrumentation, or to particular areas of trade or industry, can offer a chance to speak with a selection of suppliers and manufacturers, and to see demonstrations of instruments. Trade associations and professional societies may also be able to direct users to sources of information.

Getting the supplier's help

When approaching a supplier with an enquiry, give as much detail as possible about the intended conditions of use, and the reason for making the measurement. Suppliers should be ready to answer questions about issues such as those listed in Section 6.1 above, and should be able to say whether the hygrometers they sell will meet your criteria. Some suppliers offer prospective customers a questionnaire to complete, so as to clearly understand their needs. Most suppliers will be prepared to demonstrate their instruments.

Further investigation

If quality or accuracy (or both) are important, then it may be worth considering at the purchasing stage:

- How the instruments are calibrated - Does this give confidence in their ability to meet the specification? Can the supplier, if requested, provide an instrument complete with a certificate of calibration, with evidence of suitable quality assurance, such as NAMAS or equivalent accreditation? (See Section 9.1.)
- Quality accreditations - Approval to a standard in the BS EN ISO 9000 series (BS 5750) for quality management systems, and NAMAS or equivalent accreditation for calibration and testing, can both give confidence in the quality of the product. (See Section 9 for details about quality assurance and accreditation.)

- Test reports - Have there been any independent tests of this type or model of instrument? If a report of a test by an impartial expert is available, the results may be of some interest. However, a historic test report on a single instrument needs careful interpretation. It can guarantee little about the actual instrument offered for sale. A product test report is no substitute for a calibration certificate for a particular instrument.
- Visit the company if there are important questions that could be resolved by doing so.

6.4 Advice on interpretation of the manufacturer's data sheet

Before buying a hygrometer, most potential users read the manufacturer's data sheet to see whether the instrument's performance specifications meet the requirements of the intended application. Clearly the manufacturer's data are provided to aid in the process of marketing the instrument, and care should always be taken to ensure that the specifications are a true indication of practical performance. In the end, calibration or other testing of the instrument is the only way to demonstrate whether or not a specification is met.

Detailed below are technical terms used to make statements about instrument performance, as typically found on manufacturers' data sheets. They are:

- range
- resolution
- uncertainty (accuracy)
- repeatability
- reproducibility
- non-linearity
- hysteresis
- response time
- long-term stability
- temperature coefficient

This list is not exhaustive, although it indicates the most important specifications to consider when selecting an instrument. Practical considerations such as dimensions, power supplies and output signals, may have little or no significance to the measurement performance characteristics of the unit. However, these practical elements should be carefully selected if the instrument is to meet the full working requirement of the application. (See Section 6.1.)

Each characteristic is explained separately below. However, although separately defined, it is not always possible in practice to distinguish between some of them.

Formal definitions of these terms are given in the ISO document *International vocabulary of basic and general terms in metrology* (Second edition, 1993). Performance of hygrometers is discussed further in Section 7.

Measuring range

The stated measuring ranges for temperature and humidity provide guidance as to the upper and lower temperature and humidity environments to which the instruments sensors can be applied. Often an additional specification: operating range (electronics) is also stated; this confirms the conditions in which the instrument's electronics (other than the sensor, or probe) can safely operate. Where a maximum or minimum humidity is stated, it is often the case that the humidity sensor will be damaged if these limits are exceeded.

Resolution

Where an instrument features a display of its measured values, the indication will have a resolution of, say, 0.1 %rh or 1 %rh. Specification of this on the data sheet simply informs the user to what degree of precision the measurement can be noted. Resolution may not significantly affect the uncertainty of measurement, except in the case of a coarse resolution of, say, 1 %rh, where the display will round the actual value up or down to

the nearest significant figure, thereby introducing an additional error of up to ± 1 %rh, depending on the method of rounding.

Uncertainty (accuracy)

The uncertainty of a measurement is defined as the parameter characterising the range in which the "true value" can be expected to lie. It defines a "margin of doubt" about a reading or estimated value, together with a level of confidence (normally 95%) that the "true value" will lie within this range. Fuller information on uncertainty of measurement is given in Section 7.4 below.

Often, the uncertainty for an instrument is specified for ideal operating conditions at a temperature of 20 °C or 23 °C. However, further contributions such as hysteresis, linearity, reproducibility and temperature dependence will need to be taken into account when estimating the overall uncertainty for an instrument. The method of use may make an important contribution to the overall uncertainty achieved.

Strictly speaking, "accuracy" is a qualitative term only. For example, an instrument or measurement might be described generally as "accurate" or "not accurate". If accuracy is to be quantified, it should be expressed in terms of uncertainty, for example, "... an uncertainty of ± 5 %rh ..." (not "... an accuracy of ± 5 %rh ..."). However, the word "accuracy" continues to be used loosely in specifications to refer to the maximum difference that can be expected between the reading given by an instrument and the "true value" being measured.

Repeatability

In general terms, the repeatability of an instrument is the closeness of agreement of multiple readings repeated under the same conditions of measurement. To quantify repeatability, the spread or dispersion of results may be quoted, e.g. in terms of a standard deviation of a number of readings. (See Section 12, Further Reading, for sources of information on statistical calculations.)

Reproducibility

In general terms, reproducibility is an instrument's capacity to reproduce a previous measurement. This may be at a later date, or after undergoing significant changes in conditions, for example after a change of operator, or of location. To quantify reproducibility, the spread or dispersion of results may be quoted, e.g. in terms of a standard deviation of a number of readings. (See Section 12, Further Reading, for sources of information on statistical calculations.)

Non-linearity

In an ideal world, if a calibration were carried out at two points in a measurement range (high and low) the instrument would behave similarly at values in-between. However, it is usual to find some deviation from this ideal, due to non-linearity of the sensor. In other words most sensors exhibit a calibration curve, as opposed to a straight line. This is illustrated in Figure 2. The deviation from the ideal calibration line will have a maximum or minimum, usually expressed in the form: "Non-linearity ± 0.5 %rh", at a given temperature. It should also be noted that linearity characteristics can be significantly affected by temperature. When having an instrument calibrated, linearity is a factor to bear in mind when deciding how many measurements are needed and at what intervals through the range of measurement.

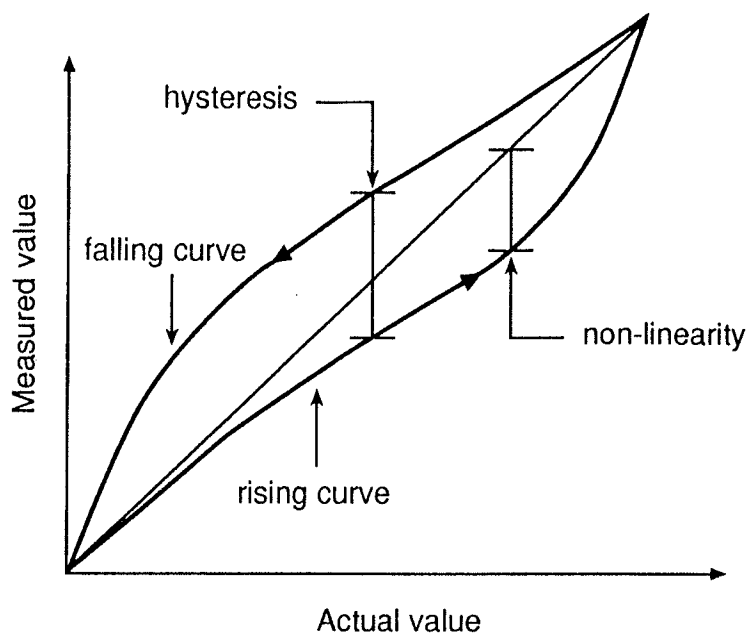


Figure 2. Illustration of non-linearity and hysteresis

Hysteresis

Hysteresis, in general terms, is the dependence of a reading upon whether the condition is approached from above or below the value of interest. For example, given a humidity cycle of say 10 %rh to 50 %rh to 90 %rh and back to 50 %rh, most hygrometers would not give an identical reading on both occasions at 50 %rh. This is illustrated in Figure 2. Hysteresis is related to repeatability, but includes any "directional" effect. Hysteresis should be considered if the measurement is to be used for control purposes, for example to activate on-off control of air conditioning.

Response time

Response times are included in specifications to provide an indication of how long the instrument takes to react to changes in the applied condition. While the sensor itself may have a particular response time, any screening of the sensing element, e.g. by a protective filter, will slow down this response. Effective air movement will speed it up. (Constant and specified air flow is required for a response time test.) Response times are practically always slower for falling humidity than for rising humidity.

Quantitatively, response times are usually quoted in terms of the time taken to register 63% of a step change in the applied condition (although other conventions are sometimes used, e.g. 90%).

Response times are usually quoted for the hygrometer alone, at constant temperature. However, response times of the associated sampling systems may be much greater. Optimistic specifications of response time may raise false expectations for the user to see stable measurements after very short time periods. However, for most relative humidity measurements, the time taken for the sensor and nearby materials to equilibrate with respect to temperature is by far the most significant factor influencing the response time. For measurements of dry gases, equilibration of moisture in the sampling system is usually the key influence.

Long-term stability

The measurement characteristics of any instrument will change with respect to time, due to gradual changes in electrical or material components. Estimates of long-term stability, or drift, refer to the likely change in the instrument's measurement performance with respect to time. Regular checks of calibration should be made to quantify this potential problem. Although it may sometimes be desirable to adjust the hygrometer reading in the light of drift, performance could be compromised by the adjustment process, and the overall drift characteristics could be masked by frequent adjustments.

Quantitatively, drift may be expressed in terms of a time span and a figure. However, if an instrument was subject to drift of less than 4 %rh per year, it would not follow from this that the drift over six months would be less than 2 %rh (though it could be expected to be somewhat less than the annual figure). Drift is not always consistent, and measurements of drift always include some contribution from short-term variability.

Temperature coefficient

Temperature variation has a most significant influence on relative humidity itself. In addition, every humidity sensor has a temperature coefficient, which can be simply explained as a change in measurement characteristic at a different temperature. A temperature coefficient might be expressed, for example, as 0.1 %rh per °C, which could result in an additional 5% error when measuring at a temperature 50 °C away from the calibrated temperature.

6.5 British and international standard specifications

Manufacturers' instrument specifications may make reference to published standard specifications which are recognised nationally or internationally. Standard specifications are important in contributing to harmonisation of practices in measurement as well as in other fields.

Some such specifications relate to particular designs of hygrometer, e.g.

BS 2842 : 1992, British Standard Specification for Whirling hygrometer

BS 5248 : 1990, British Standard Specification for Aspirated hygrometer.

Conformance of a product to a standard such as these means that it is made to a recommended pattern consistent with others in widespread use. Certain standard specifications of this type also explain how to operate the instruments correctly.

Although these specifications lead to harmonisation in the manufacture of instruments, conformance to a standard specification does not guarantee any particular level of performance from an instrument. Most importantly, it does not eliminate the need to calibrate an instrument. What is more, conformance to a standard specification cannot always be taken as an endorsement of that type of measurement: for example, whirling hygrometers are prone to errors, even if calibrated and used as recommended. (Aspirated hygrometers, on the other hand, are much more satisfactory.)

Other standard specifications, such as the BS EN ISO 9000 series (BS 5750), may endorse a supplier's organisational and quality procedures, but do not guarantee any particular standard of humidity measurement. Test reports or calibration certificates from independent NAMAS or nationally accredited laboratories can provide useful confirmation of instrument performance.

Standard specifications may also apply to many wider aspects of the product, relating to the packaging, labelling, fire resistance, etc. These may not always have a bearing on the measuring qualities of the instrument. If an unfamiliar specification number is quoted, it may be worth checking its relevance.

7. PERFORMANCE AND CALIBRATION

7.1 Calibration and traceability

Specification versus calibration

Performance criteria for an instrument can be described in terms of a specification of the kind discussed in the previous section. This will give limits within which the behaviour of the instrument can be expected to fall. For instance if an instrument is specified to have an uncertainty of $\pm 3\%$ of reading, then the user can reasonably hope that if the instrument is used correctly, the value of humidity it indicates will be correct, give or take 3% of the result. However, this performance cannot be relied upon unless verified by calibration of the instrument. A specification is not the same as a calibration, and is no substitute for one.

What is calibration?

Calibration is the process of comparing a measuring instrument against an authoritative reference for the same type of measurement, to identify any bias or systematic error in the readings. The outcome of a calibration is normally a certificate listing any corrections that need to be applied to the values indicated by the instrument, together with an estimate of the uncertainty in the calibration, and other relevant information. For example a calibration of a given instrument at, say, 50 %rh, might show it to read too high by 1 %rh. If so, a required correction of -1 %rh would be shown on the certificate.

Calibration is often taken to mean "adjustment of the instrument to read correctly". This is not true. Calibration and adjustment of an instrument are quite separate concepts, and the two should not be confused. Thus, when arranging for the calibration of any instrument, it is important to establish clearly whether or not the instrument is to be adjusted as well as calibrated. If so, it should be specified whether calibration information is required only after adjustment, or whether results are also required for the initial or "as found" condition.

Any calibration corrections identified on a certificate of calibration should be applied to measured values obtained using that instrument. If the calibration corrections cannot be applied, the quoted uncertainty in the results should include an allowance for this. (See Section 7.4 below for discussion of uncertainty of measurement.)

Traceability of measurement

Traceability to authoritative standards is the best way to ensure accuracy of measurements, and leads to consistency of measurements among users at different times and locations. A traceable measurement is one which can be related to appropriate measurement standards, generally national or international, through an unbroken chain of comparisons. In the UK this normally means that the calibrations have been undertaken by the national standards laboratory (e.g. NPL in the UK) or by an accredited laboratory (e.g. NAMAS), or by a national or accredited laboratory in another country with which there is a reciprocal recognition agreement.

Measurement standards are defined at a primary level, by a single authoritative measuring instrument (usually one serving the whole country as a "national standard"). The primary standard is used to calibrate other instruments, and these in turn can be used as references or "transfer standards" to calibrate further instruments, and so on.

Some humidity parameters (e.g. dew point) are realised at national standard level. Others may be derived from these indirectly, further down the calibration chain. For example, on the basis of traceable measurements of dew point (and of pressure, if necessary), values of vapour pressure of water may be derived, using recognised conversions or tables (See Section 10). On the basis of traceable measurements of dew point and temperature, values of relative humidity may be derived. Confidence in the traceability of such derived quantities depends on the traceability and soundness of the measurements involved, and on the recognition of any numerical conversions used.

7.2 Approaches to calibration

Calibration by the user or externally

With suitable expertise, calibrations can be carried out successfully by the user without sending instruments to an outside laboratory. However, setting up an in-house calibration facility may require considerable investment in equipment and training. It is often better to have the work done by an expert laboratory, and perhaps one which holds a recognised measurement accreditation.

Calibration with or without recognised measurement accreditation

Some laboratories hold recognised accreditation (such as NAMAS, in the UK) for calibration or testing; others do not. An absence of accreditation does not necessarily mean a lack of quality management, or a poor standard of measurement. However, in the absence of recognised accreditation, it falls to the user to make a personal judgement of the quality of the measurements provided. The user can audit laboratories directly, or simply trust!

Field calibration versus laboratory calibration

The ideal environment for a calibration of an instrument is usually considered to be a laboratory, where controlled and stable reference conditions can be provided. However, there are often good reasons for calibrating hygrometers *in situ*, "in the field". The reasons for field calibration might be for convenience, for cost, to avoid disturbing the instrument, or perhaps to calibrate it under the exact conditions of use.

A humidity calibration may be performed in the field using some portable method of generating reference conditions of humidity, such as calibrated capsules of saturated salt solution, or perhaps by comparison of instruments under the prevailing environmental humidity. Such calibrations may be carried out by the user, or by a laboratory offering a "site" calibration service.

7.3 Practical methods of laboratory calibration

Humidity calibrations are normally carried out by comparing the instrument against a calibrated humidity reference, in a stable humidity environment.

A single-point humidity calibration is generally only of limited value, because it gives no information about behaviour at other values of humidity. Three measurement points, spaced at intervals in the humidity range of interest, is usually considered a minimum number, at each temperature of interest. The actual number of calibration measurements required may be decided on the basis of the linearity of the instrument, if this is known.

Environments for humidity calibration are most commonly provided using a humidity generator or a humidity-controlled (and temperature-controlled) chamber. Arrangements differ significantly depending on the range of absolute or relative humidity concerned.

Humidity generation

The main methods of humidity generation are as follows:

Dew-point generator - Gas is humidified by bubbling it through (or flowing it over) water or ice at a given temperature. Depending on the efficiency of the design, this will produce gas with a dew point more or less close to the temperature of the saturator.

Two-temperature generator - Gas is humidified at a given temperature, defining its dew point, or vapour pressure. The gas is then fed to a chamber at another (higher) temperature. By varying one or both temperatures, it is possible to obtain any chosen value of relative humidity or dew point.

Two-pressure generator - Gas is humidified at elevated pressure and then expanded to a lower pressure (at the same temperature). As the total pressure of the gas falls, so does the partial pressure of water vapour. Knowing the initial humidity allows the humidity after expansion to be found. By varying the initial pressure or temperature or both, it is possible to obtain any chosen value of relative humidity or dew point.

Mixed-flow generator - Gas is humidified by any convenient method, and is then mixed with drier gas. The value of humidity achieved depends on the mixing proportions and on the water content of the two gas streams.

Salts - Saturated (or unsaturated) salt solutions, and certain other chemicals, can be used to generate an environment of a particular relative humidity in an enclosed space. The value of relative humidity obtained depends on the particular chemical salt, the concentration of the solution, and the temperature of use, among other things. (See the following section on salt solutions.)

Humidity chambers - Test chambers are available with both temperature and humidity control based on steam or spray injection, or on one of the principles outlined above.

Bottled gases - Cylinders of compressed gas are available which supply gas of fixed humidity, at a selection of values of a few hundred ppm_v or below. The method relies on a special coating on the cylinder interior.

Used appropriately, any of the above methods can provide a stable humidity for use in comparing one hygrometer with another (calibrated) one. This may mean supplying a flow of gas to pass through both instruments to be compared, or placing both instruments in a chamber where they are exposed to the same humidity. Humidity generators can be calibrated, but only at national standard level are they accurate and authoritative enough to act as absolute references.

"Bench-top" humidity calibrations - comparisons at normal room temperature and humidity - can sometimes be carried out if the conditions are stable. This method may be satisfactory where the instrument being calibrated is for use in these conditions, and where high accuracy is not required. However, this does not normally permit measurement at more than one humidity and so gives no information about other parts of the measurement range.

Calibration using salt solutions

Salt solutions generate characteristic values of relative humidity which depend on the particular chemical salt, the concentration of the solution, and the temperature of use. *Saturated* salt solutions, with solid salt present, have the special property that a stable concentration is maintained - and hence a constant relative humidity - even if water migrates to or from the solution. Ready-made capsules are commercially available for a variety of relative humidity "fixed points". Such capsules are designed to seal over the end of relative humidity probes, providing a small enclosed atmosphere of defined relative humidity. Certain of these, if in the form of solution with solid salt present, are re-useable, and can be calibrated to assign a traceable value to the reference humidity they provide.

Other humidity calibration systems employing salt solutions exist; for example, in the form of single-use ampoules of solution. These are used to soak a pad in a housing designed for exposing a sensor to the humidity generated. These ampoules, too, may be supplied with a traceable calibration, on the basis of tests of samples from batches of ampoules.

As for any other calibration, traceability through a laboratory with NAMAS or equivalent accreditation provides the best assurance of a reliable measurement.

Salt solutions can also be used in various ways to provide nominal (uncalibrated) values of humidity. Used in conjunction with a calibrated hygrometer, such nominal humidity environments can also be useful for calibration (see humidity generation, above). Values of humidity generated over saturated solutions of various salts are listed in Table 9 in Section 10.

Just as it is for relative humidity in general, temperature stability is critical for calibration with salt solutions, particularly since the properties of the salt solutions change with temperature. Stabilisation after a change in temperature may take an hour, or many hours, depending on the size of the change. For freshly mixed solutions, full stabilisation may take days or weeks.

It is always vital to ensure that no salt contacts the sensing parts of the hygrometer, as this would cause errors in readings, and would destroy some sensors.

Any form of "salt check" offered for sale as a "kit" to be mixed into solution by the user, is not usually suitable for providing any kind of traceable calibration or reliable check by itself, except when used in conjunction with a calibrated hygrometer. Salts used in dry form, in particular, may provide only very approximate values of humidity, and may degrade quickly. Unsaturated solutions also generate atmospheres of relative humidity, but since their concentration gradually changes with repeated use, so does the generated humidity.

Some practical recommendations for the calibration of hygrometers

Hygrometers should be calibrated in terms of the quantity to be measured. For example, the performance of a wet- and dry-bulb hygrometer cannot be characterised by calibrating the thermometers alone; a humidity calibration of the hygrometer as a whole is needed.

Where a hygrometer consists of separate parts (e.g. probe and electronics) the pair should be calibrated together "as one item" and used together.

Wherever possible, calibrations should be performed under the intended conditions of use, i.e. at similar values of humidity and temperature, and preferably in similar conditions of pressure, air flow, etc.

Hygrometer readings in some units of measurement (such as grams per cubic metre) are specific to gas type. Therefore a calibration in these units is valid only for a selected gas.⁷ This is because the ratio of molecular masses of water and air, for instance, is about 0.62, whereas the ratio for methane is about 1.1. However, calibrations in terms of (say) parts per million by volume are not necessarily gas-specific, or only very slightly so (provided the instrument genuinely senses this quantity, and does not simply give a numerically converted result from some other parameter).

Before and after sending a hygrometer for calibration, it is wise to carry out measurement checks by comparing it against another hygrometer. This can show whether there is any damage or shift in performance due to transportation.

If a hygrometer has been exposed to contaminants, care should be taken that these contaminants are not carried with it to the calibration facility.

Calibration intervals

Choosing suitable intervals for recalibration of hygrometers depends on many factors including

- type of instrument
- manufacturer's advice
- required accuracy in use
- severity of conditions of use
- history of past stability or drift
- frequency of checks against other hygrometers (preferably stable ones)
- maintenance in between calibrations
- cost of calibrations
- importance of avoiding incorrect results

Until a record of performance has been built up, initial choice of intervals may be based on the first four in the list.

A very general guideline for the various types of hygrometers might be as follows:

Hygrometer types with relatively good stability e.g. condensation dew-point hygrometers, wet- and dry-bulb hygrometers - 6 to 12 months after first calibration. Thereafter every 1 to 2 years, depending on requirements.

Moderately stable hygrometer types e.g. electrical relative humidity instruments - perhaps 6 months after first calibration. Thereafter every 6 to 12 months, depending on requirements.

Less stable hygrometer types e.g. aluminium oxide hygrometers - every 6 months, or sooner if desired.

Where a choice of intervals is suggested above, the longer intervals would be for hygrometers confined to use in ordinary room or laboratory conditions; the shorter for those used in more varied conditions. If used in extreme conditions, or if accuracy were critical, then measurement checks of some kind at much shorter intervals would be recommended. Where hygrometers are strongly prone to drift, this will remain a significant source of uncertainty almost irrespective of the frequency of calibrations.

Annex A of BS 5781: 1992 Part 1 (ISO 10012-1: 1992) discusses confirmation intervals in more depth.

Checking

A measurement check is not the same thing as a calibration. A check is a test to confirm whether or not some condition is fulfilled (for example to confirm that the performance of an instrument has not drifted). The outcome of a check is not normally a certificate of calibration. However, checks of a measuring instrument against another (stable) instrument are often useful at intervals in between calibrations.

7.4 Uncertainty of measurement

There is always some uncertainty associated with any measurement result. The uncertainty of a measurement is defined as the parameter characterising the range in which the "true value" can be expected to lie. It defines a "margin of doubt" about a reading or estimated value.

The terms "uncertainty" and "error" are sometimes used interchangeably, leading to some confusion. In general, error is defined as the result of a measurement minus the true value. A known and constant or systematic error can be compensated by a correction of some sort, and need not necessarily be considered as an uncertainty. Unknown errors cannot simply be compensated, and these are then sources of uncertainty which must be estimated.

Below, sources of error are explained and discussed qualitatively. More rigorous definitions and discussions can be found in the ISO *Guide to the expression of uncertainty in measurement*, and in other of the references listed in Section 12.

"Random" and "systematic" uncertainties

Aside from "known" errors, which can be compensated, uncertainties (which are unknown) may be due to "random" or "systematic" errors. Figure 3 illustrates the nature of random and systematic contributions to uncertainty.

Random errors are those which give rise to variations in repeated readings, and may be termed as "noise", "short-term fluctuations" or "lack of repeatability". The uncertainty due to random errors can be reduced by taking the average of a large number of readings. This gives a better estimate of the true value than simply taking a single or "spot" reading.

A systematic error is one which has a single value, which may be unknown, and which may even change from time to time in the long term. Such an error may be termed as a "bias" or "offset" and may perhaps pass unnoticed. If a constant systematic error is intrinsic to an instrument its value can be found by calibration, and a correction may be applied. However if the systematic error is due to another influence such as the sampling

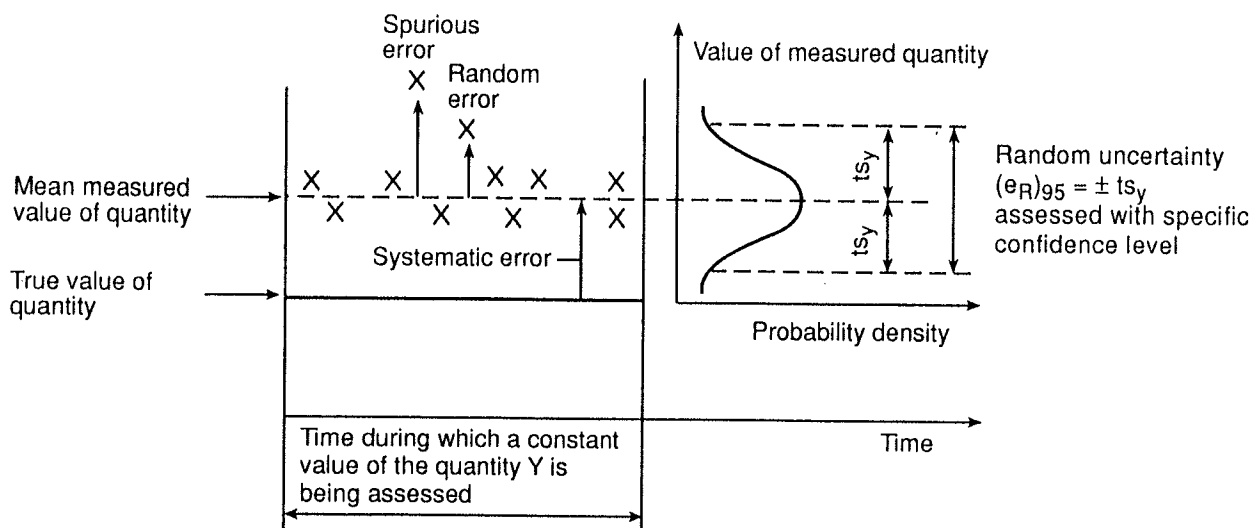


Figure 3. Illustration of random and systematic contributions to uncertainty of measurement, reproduced from BS 5844 : 1980 with the permission of BSI. (Complete editions of the standard can be obtained by post from BSI Customer Services, 389 Chiswick High Road, London W4 4AL.)

arrangement, or some aspect of the environment being measured, then the resulting uncertainty may have to be estimated, rather than eliminated by calibration.

Level of confidence of an uncertainty estimate

No statement of uncertainty is complete without defining the level of confidence attached to that statement. For example, a particular measurement might be said to have an uncertainty of " $\pm 3\%$ rh at the 95% confidence level". This would mean that one could be 95% certain that the instrument reading was within 3 %rh of the "true value". In some contexts the expression "a coverage factor of $k = 2$ " is used to mean approximately the same thing. A larger coverage factor indicates a higher level of confidence.

Use of the 95% level of confidence is the internationally agreed convention in most areas of measurement. If unspecified, the 95% confidence level is normally assumed. However, it also remains a common practice to state "total limits" equivalent to a level of confidence of about 99%.

Practical sources of error and uncertainty

For hygrometers, as for other instruments, practical sources of error include:

Short-term instability, or "noise" - Effects can be minimised by taking the average of a large number of measurements.

Long-term instability, or drift - Best dealt with by calibration or monitoring at intervals against a stable reference. Drift can then be forecast approximately, and if necessary offset from time to time by adjusting the instrument at the time of calibration. Keeping a history of calibrations, and of any adjustments to the instrument, allows estimates of drift to be made.

Offsets in the form of systematic bias, non-linearity, etc. - Best dealt with by calibration against an authoritative reference value (traceable to recognised or national standards, preferably through a calibration laboratory which is accredited, e.g. under NAMAS or equivalent schemes). Hence any bias can be compensated by applying a numerical correction, or, if necessary, by adjusting the instrument.

Although bias or systematic error in a measurement can be found by comparison against a better reference, this by itself is never enough to estimate the uncertainty in a measurement. It does not, for example, tell the user what errors might arise due to effects which cannot be directly measured, or are not constant.

As well as sources of error which are intrinsic to any instrument, errors arise due to real measurement situations. These include:

Unstable conditions of measurement - The instrument may never equilibrate with the environment being measured. Most methods of humidification are prone to fluctuations.

Sampling errors - The instrument may not encounter a representative sample of the gas to be measured. In the case of relative humidity, representative temperature is as important as moisture content itself. For very dry gases, careful sample handling is extremely important.

Interferences - Heat, contaminants, incorrect air flow, airborne droplets, etc. may interfere with proper measurement of humidity.

Breakdowns and operator mistakes - ... ! (examples of what are referred to as "spurious errors")

... and many others.

All possible significant errors that cannot be directly compensated must be treated as uncertainties.

Estimating uncertainty of measurement

For random aspects of uncertainty, the effect is quantified in terms of the spread or the standard deviation of a number of readings. For systematic effects, the size of the contribution may be found from measurements, calculations, or other kinds of information. The overall uncertainty in a particular measurement is the outcome of all the contributing uncertainties. The size of this combined effect has to be estimated.

If all possible sources of uncertainty could be estimated, the combined effect would probably be no worse than the sum of the individual effects. On the other hand, the various errors, known and unknown, would be unlikely to cancel one another out completely. The best estimate of overall uncertainty is usually lies somewhere between these two extremes. This is quantified in practice by combining the components "in quadrature" using the sum of the squares of contributing uncertainties, i.e.

$$\text{overall uncertainty} = \sqrt{(u_1)^2 + (u_2)^2 + (u_3)^2 + \dots} \quad (4)$$

where u_1 , u_2 , etc. are the individual estimated contributing uncertainties, all expressed at the same level of confidence.

Further details of how to calculate uncertainties are given in several of the references listed in Section 12, "Further reading", and an illustration is given in Example 11.4.

Propagation of errors

Traceability of measurement is achieved through a chain of calibrations. While this method provides the best estimate of the "true value" for any measurement, each step in the chain introduces some additional uncertainty. This is because each instrument in the chain will be subject to possible drift, limited resolution, sampling uncertainties at each step, and so on. The uncertainty for any measurement in the chain is the cumulative result of those errors that precede that point in the chain. To estimate the uncertainty in any real measurement, the user must consider what the uncertainty from the calibration chain is, and what the application adds.

Table 3. Illustration of how uncertainties propagate down the calibration chain

Step in the calibration chain	Uncertainty
National laboratory	Uncertainty in primary standard measurement
Calibration of NAMAS or equivalent lab's transfer standard against national (primary) standard	Imported uncertainty of standard ... together with uncertainty due to sampling during calibration, and resolution and performance of the instrument while being calibrated
Calibration of working instrument against NAMAS or equivalent lab's transfer standard	Imported calibration uncertainty ... together with transfer standard's long-term drift, resolution and performance as reference during calibration, sampling uncertainties, and resolution and performance of working instrument while being calibrated
Use of working instrument to make humidity measurements	Imported calibration uncertainty ... together with the working instrument's long-term drift, and resolution and performance during measurements, and uncertainties due to sampling and fluctuations in the condition being measured, etc.

The number of steps shown here is the minimum for most situations; sometimes more steps are involved. It can be seen how the uncertainty for any traceable measurement will be much greater than, for instance, that of the national standard or "state of the art". The actual uncertainty at each step is calculated by the approach of equation (3) and will depend on the exact circumstances. The uncertainty quoted on any certificate of calibration should include all the contributions from previous steps in the calibration chain. The uncertainty associated with any instrument may depend as much on the chain of calibration as on the intrinsic properties of the instrument itself.

From a calibration chain like this, starting with a primary realisation of dew point with uncertainty of ± 0.05 °C, measurements in practice might achieve dew-point uncertainties no better than ± 0.4 °C, and relative humidity uncertainties no better than perhaps ± 3 to ± 5 percent of value, at the 95% level of confidence. Hygrometers with less than perfect stability, and imperfect measuring conditions, could give an end result with many times this uncertainty.

This discussion of how uncertainties accumulate must not be taken as an argument against traceable calibration! The uncertainty in not adopting this approach is vastly greater.

Example 11.4 illustrates an analysis of the uncertainties in calibrating a humidity test chamber. Further reading on the analysis of uncertainties is listed in Section 12.

7.5 Other issues

International recognition and acceptability

National standards for humidity, and national measurement accreditation schemes, exist in many countries worldwide. National primary facilities for humidity are most often based on carefully validated humidity generators of the two-pressure or two-temperature type. A few national laboratories also employ gravimetric hygrometers, which provide the most fundamental definitive humidity measurements.

Often these national or accredited laboratories are signatories to agreements for mutual recognition of traceability. This is particularly true within Europe, where reciprocal agreements between accreditation schemes are formalised through the body EAL (European Cooperation for Accreditation of Laboratories).

Bypassing traceability: "fundamental" measurements

Claims are sometimes made for the "fundamental" nature of certain methods of measurement, suggesting that traceable calibration is therefore not required. However, even if governed by a "fundamental" principle, any measurement can suffer from errors in practice, and these may only be revealed by comparison with an authoritative reference standard.

What if traceability is not available?

For certain humidity measurements traceable calibrations cannot be obtained, due to extreme operating ranges or unusual operating conditions of instruments (e.g. high pressures) not covered by existing national standards. Where traceable calibration is really not available, other measures described below can give some confidence.

Where the humidity range of an instrument exceeds that of the national standard (e.g. at very low or very high humidities), reasoned extrapolation of calibration data may be acceptable for the extreme part of the range. In this situation the associated uncertainties may be very large. For instance, when extrapolating at very low humidities the uncertainties would escalate rapidly in line with falling vapour pressure. Thus, at a low absolute value of humidity, say 0.5 ppm_v (-80 °C in dew point), the estimated uncertainties would more than double for every 50% drop in moisture content (i.e. for every several degrees fall in dew point).

As an alternative to extrapolation, non-traceable referencing against a recognised documented procedure may at least provide an element of consistency, without providing accuracy in any absolute terms. Some benefit can also be gained by obtaining traceability for other aspects of the humidity measurement, for example for temperature or electrical aspects.

Where a device is for single use only (e.g. colour change tubes, or ampoules of salt solution for generating reference humidities) it may be possible to calibrate a batch by measuring a number of samples.

Whether or not the suggestions above can be followed, further information can be gained by comparison of the "uncalibrateable" instrument against one of a similar type. Comparison against an instrument of a different type is even better, offering some degree of independent confirmation. Where such measurements show disagreement, this can give some indication (but not the full extent) of the uncertainties involved.

Note on meeting humidity test specifications

Sometimes, the reason for seeking a particular level of performance from a hygrometer is to comply with documented specifications for humidity measurement or testing. These specifications vary. Many published standard test specifications set very tight humidity tolerances, some as low as ± 2 or ± 3 %rh. Compliance with such specifications is therefore very difficult, and sometimes impossible, when fluctuations in temperature and humidity and other uncertainties are taken into account. It must be remembered that compliance with a

specification means that the reading together with the uncertainty in the measurement must fall within the specified band (not just the reading itself).

When setting humidity tolerances, writers of specifications should consider the properties of the available humidity instruments, the calibration uncertainties, and the likely magnitude of other uncertainty contributions.

8. RECOMMENDED PRACTICES IN HUMIDITY MEASUREMENT

8.1 General practical recommendations

Use the appropriate method. Where relative humidity is of interest, a direct measurement of relative humidity is usually best. Where an absolute measure of humidity is needed, choose dew point, vapour pressure or similar measurements.

Establish the measurement requirements at the purchasing stage in order to have the right instrument for the job.

Allow hygrometers to equilibrate in any new environment. This is particularly necessary after changes in temperature due to transportation or storage. Depending on the instrument and on how great the change in conditions, this may require from only a few minutes to many hours.

Follow the manufacturer's care instructions for the instrument. Some instruments need routine cleaning or other maintenance. Before using any solvent cleaner, check (with the manufacturer, if necessary) that this will not harm the sensor or other materials of construction.

Seek traceable calibrations through laboratories accredited to NAMAS or equivalent schemes.

Wherever possible, ensure that hygrometers are calibrated under the conditions of use, i.e. at similar values of humidity and temperature, and (if relevant) in similar conditions of pressure, air flow, etc.

Keep a record of calibrations and any adjustments to the hygrometer. This will show the long-term stability of the instrument and allow the associated uncertainty to be assessed.

Check instruments, if possible, at intervals between calibrations, by comparison with another (stable) instrument, to monitor for long-term drift. Routine checks are also useful before and after subjecting an instrument to transportation or other stress which might lead to a shift in its performance. Where the check is against two (or more) instruments this is even better: not only does this add confidence, but in the event of one instrument drifting among a set of three, it can be seen which reading is most suspect.

Cleanliness of the environment will affect different hygrometers in different ways. Dust and airborne droplets should be avoided or filtered out if possible. Contaminants can come from the most surprising sources, ordinary urban pollution, for example.

The readings given by some types of hygrometer are sensitive to gas type. For any instrument which reads in terms of mass per unit volume, e.g. in grams per cubic metre, it must be confirmed whether the calibration is valid for the gas in use.

Avoid using instruments in direct sunlight or near any other source of heat, unless they are suitably shielded to prevent measurement errors.

Sampling in general

Relative humidity measurements should be carried out at a representative temperature. Failure to allow temperature equilibration will lead to a false indication of the relative humidity.

Variations in vapour pressure from place to place can occur where an environment is subject to any addition or removal of water. If so, care must be taken over where to make a measurement in order to obtain a representative result.

Sources and sinks of water vapour should be avoided in any sampling system. Invasion of stray water can be minimised by attention to leaks, hygroscopic materials, droplets and condensation. The lower the humidity, the more critical these precautions are.

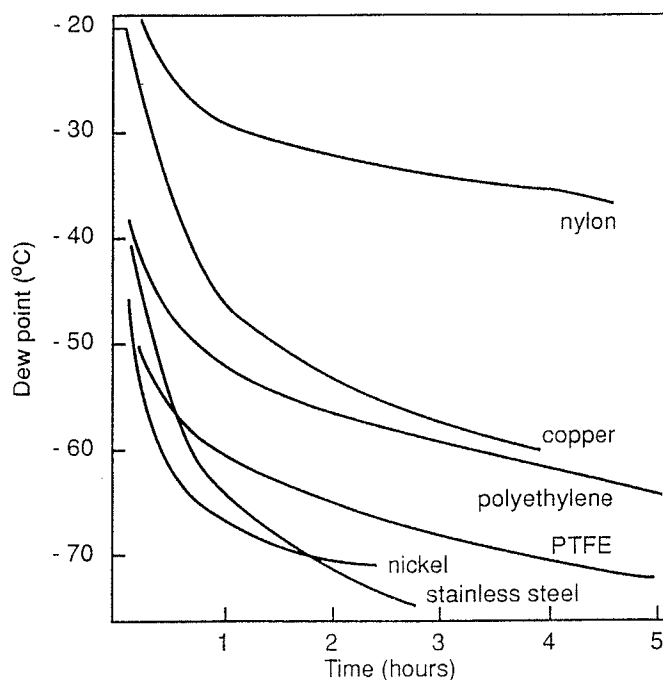


Figure 4. Illustration of the moisture given off by different tubing materials when flushed with very dry gas after being at ambient humidity.

Hygroscopic materials should be avoided. Many materials contain moisture as part of their structure, particularly organic materials (whether natural or synthetic), salts (or anything which contains them) and anything which has small pores. Temperature changes can increase the tendency of these materials to affect the humidity of the surrounding air.

Condensation in a sampling process can invalidate humidity measurements by reducing the water content of the gas being measured. What is more, condensed liquid may alter the humidity elsewhere by dripping or running to other locations and evaporating there. In these circumstances, measurement results may be misleading if hygrometer location is not considered carefully.

Water droplets or mist must be avoided. These can result in overestimates of the humidity of the air between the droplets. Such results may exceed 100 %rh, or may be impossible to interpret meaningfully. Droplets of liquid also damage some electrical types of humidity sensor. Filtering the air sample can eliminate droplets.

If pumps are used for sampling gas, these should be located after the hygrometer, to avoid contaminating the measurement environment. Where possible, oil free pumps should be used, or filters employed. Oscillations in pressure due to pumping can sometimes be reduced or buffered using a needle valve or a reservoir of large volume.

Special treatments such as filtration can change the amount of moisture in a gas. Some drying agents take out other gases, too.

When sealing any sensor or probe into a port or manifold in a duct or chamber, leaks through the probe or electrical cable should be considered. These are not always sealed against passage of ambient air.

Where sampling involves a step change in temperature, pressure or gas flow rate, relative to the process being sampled, results may need to be converted or interpreted. For example "pressure dew point" will differ from the value found after expanding the gas sample to atmospheric pressure. Care should be taken to distinguish between "gauge" and absolute values of pressure. Conversions are discussed in Sections 4, 10 and 11.

Dew point in general

The measuring environment and all parts of the sampling pathway must be kept above the dew point if condensation is to be avoided. Electrical trace heating or other heating methods should be used if necessary. An excess temperature of 10 °C above the dew point is usually a safe margin.

For measurements in the region below 0 °C it must be clear whether the condensate is dew or frost. Failure to distinguish between these can result in errors of about 1 °C for every 10 °C below zero.

Relative humidity in general

Due care must be taken of temperature. (See Section 4.1 and other advice throughout.)

Care must be taken when expressing uncertainties, changes or fractional differences in relative humidity. For example, the difference between 50 %rh and 52 %rh is 2 %rh. This can also be expressed as a difference of 4% of value. It is important to distinguish clearly between these two kinds of statement.

8.2 Recommendations specific to ranges of measurement

Ambient humidities

Avoid using hygrometers near the body, which is a source of heat and moisture. Do not breathe close to the measurement.

High humidities, above the ambient range

Sample lines should be maintained above the dew point of the gas being measured, to avoid condensation. Electrical trace heating is often the most practical method.

Low humidities, and very dry gases

If possible, prepare for measurements by flushing sample lines and hygrometers with dry gas, or by evacuating to low pressure. Drive off stray residual water by baking assemblies if possible (but not instruments - unless designed for this!). The lower the moisture content to be measured, the more dramatically the required drying time multiplies.

Avoid hygroscopic materials. At low humidities (anything much below a dew point of 0 °C) the amounts of water given off by organic and porous materials can dramatically affect the value of humidity. (See Figure 4.) The lower the level of moisture, the more significant the effects.

Choose impermeable materials, to avoid inward diffusion of moisture through sampling tubes and enclosures. Steel and other metals are practically impermeable. PTFE ("Teflon") is only slightly permeable and will usually be satisfactory for dew points above -20 °C, and sometimes below this level. Materials such as PVC and rubber are relatively permeable and so totally unsuitable at low humidities, and not really satisfactory in any humidity range.

Surface finish of pipework is important for very dry gases. Even the tiny quantities of water adsorbed on the surfaces of non-hygroscopic materials can have significant effect. Polished or electropolished steel is recommended for the best results.

Clean environments are always best for humidity measurements, but this is especially critical at very low humidities. Even fingerprints harbour water. High purity cleaning agents are recommended: Analytical Reagent (AR) quality solvents for oil-based contaminants, and purified water (distilled or deionised) for salts. Cleaning should be followed by thorough drying by a clean method.

Sample tubing should be as short in length as possible. The surface area should be minimised by using the narrowest tubing that the flow conditions will permit.

Avoid leaks. Minimising the number of connections (elbows, tees, valves, etc.) helps with this.

Adequate flow of the gas sample should be ensured, to minimise the influence of sources of stray water in the flow path.

"Dead ends" should be avoided, as they cannot easily be flushed.

Back-diffusion of moisture should be minimised, e.g. by fast flow rates of gas, long exhaust tubes after the sensor, or by valves which isolate the low-humidity region from ambient air.

8.3 Practical recommendations for specific types of hygrometer

The instruction manuals supplied with hygrometers are the first source of information for their use and care. However some general recommendations are given below.

Mechanical hygrometer

Calibration *in situ* is best, if possible, to avoid disturbances to mechanical linkages.

The correct recording chart for the model of instrument should be used, identifiable by a reference code or number. Charts should be of the correct range and properly fitted.

Further advice on use of mechanical hygrometers given in "Handbook of Meteorological Instruments, Volume 3, Measurement of Humidity" (HMSO) - out of print, but available through libraries. (See Section 12 "Further reading".)

Wet- and dry-bulb hygrometer (psychrometer)

The wicking used for the wet bulb should be that supplied for the instrument, and should be clean, close fitting and properly secured, correct in length, and absorbent.

Wicks should be cleaned before use by boiling for 10 minutes in water with a little detergent, then rinsed thoroughly in purified water. The water used for wetting the wick for measurements must also be highly pure (distilled or deionised). Wicks should not be handled except with clean tools (e.g. tweezers).

Contamination, whether soluble in water or not, interferes with proper evaporation and wetting of the wick. Even if not visibly dirty, wicks may need changing or cleaning on a daily or weekly basis, depending on the cleanliness of the environment. Visible contamination definitely requires a clean wick.

Psychrometers especially should be used away from sources of radiant heat. Where readings are taken visually, the observer should avoid warming the environment or breathing on the instrument. As these have greatest significance for the wet-bulb temperature, this should be read first, and the dry bulb second.

Air velocity past the thermometer bulbs should be 3 to 10 metres per second. For more compact sensors, such as thermocouples, a lower flow rate down to 1 m s⁻¹ is acceptable. If there is any doubt, the manufacturer should be consulted for the correct value.

Failure to provide any of these conditions can lead to incorrect results, with the hygrometer most probably over-reading.

Calibration of psychrometers should be in terms of humidity. Calibration of the thermometers alone is not sufficient. However, where possible, calibration of the thermometers first of all is also recommended, to minimise the calibration corrections which will subsequently be applicable to the humidity values.

The value of the constant A used to calculate humidity results from temperature readings (where readings and calculations are not automated) should be supplied to the calibrating laboratory, and should appear on the calibration certificate. (The psychrometric equation is detailed in Section 10.3.)

When using a psychrometer in a confined space, it should be remembered that evaporation at the wet bulb will raise the humidity of the air nearby; as will the presence of the observer, for visually read psychrometers.

Home-made or improvised psychrometers should be used only with the greatest of caution. Though commonly attempted, it is surprisingly difficult to obtain satisfactory performance from an improvised instrument. In order to identify and eliminate errors due to thermometer stem conduction, thermal radiation, and a host of other sources, a traceable calibration in terms of humidity is certainly needed. Commercially available psychrometers, while no less in need of calibration, are much more likely to provide reliable measurements.

See also the notes accompanying the psychrometric equation in Section 10.3.

Relative humidity (capacitive/resistive) sensor

Care should be taken to avoid mechanical shock (impact) or thermal shock (sudden temperature changes).

Sensors should be protected from steam or water sprays, and from direct sunlight.

Where a sensor is at risk of exposure to dust, droplets, or the occasional knock during handling, the appropriate guard or filters for the sensor head should be used.

Any temptation to breathe on the sensor, or to wave it over cups of tea, etc. should be resisted. Filters and saturation guarding may protect the sensor, but these actions carry a risk of damage by condensation or other contamination.

Protective filters can slow the response time of sensors. This can be avoided by removing any filter, but the benefit must be weighed against the risk of damage to the sensor.

Sensors should not normally be submerged in liquids. In the case of a resistive (electrolytic) sensor, water or other liquids would certainly damage the sensor beyond repair.

Salt solutions are especially commonly used for calibration of electrical sensors, and should be provided with traceability directly or via a calibrated hygrometer. Protection of sensors from direct contact with salt or solution is most important as contamination would destroy or seriously impair the sensing element.

Impedance dew-point hygrometer

Sensors constructed using aluminium oxide or other metal oxides, essentially respond to vapour pressure. They are often used at high pressure, or to sample gas originating from systems at high pressure. If so, care must be taken to ensure that the sample pressure is known, and a correction applied if necessary.

As for other electrical sensors, filtration should be used to protect from dust and droplets or mist.

Regular calibration is particularly important for metal oxide hygrometers. The calibration intervals may be dependent on usage.

Aluminium oxide sensors normally exhibit a temperature coefficient, which may be partially compensated within the instrument, but not totally. If the hygrometer must be used at a temperature other than that at which it was calibrated, ensure that any necessary correction to the reading is made, and that any resulting uncertainty is taken into account.

When using the sensors at low levels of moisture, the precautions listed above under "sampling" and "low humidities" should be observed.

Condensation hygrometer

A clean mirror is essential for proper operation. Deionised or distilled water should be used to remove soluble contaminants. If necessary, alcohol may first be used to remove oil-based contaminants.

A suitable method of cleaning is to steep a cotton bud in the purified water, then wiping the mirror gently, repeating if necessary. When the drop of water can be pulled away cleanly, the mirror is clean. In general, droplets which continue to stick to the mirror are a sign of dirt traces, and will leave tide marks on drying. These tide marks interfere with proper operation of the hygrometer, since they contain salts, which locally alter the vapour pressure, and hence the dew point. The region around the mirror should be cleaned similarly, but is less critical.

Frequency of cleaning the mirror depends on the environment and on the accuracy requirement. Even in relatively clean environments, cleaning at daily to weekly intervals is usually needed. Above all, there is no need to wait for visible contamination before cleaning.

During measurements, the mirror should be observed, if possible, using a viewing microscope if fitted. The phase of the condensate (water or ice) and the quality of the film on the mirror can thus be seen. The film should normally consist of small, uniformly distributed droplets or ice crystals. The droplets or crystals may be larger at the extremes of the measurement range. However, uneven films, large feathery crystals, or pools of water all cause measurement errors, and require cleaning, re-setting or other action.

Dew-point hygrometers should never be calibrated in terms of temperature alone. Only calibration in terms of humidity can characterise performance as a hygrometer.

9. QUALITY ASSURANCE OF HUMIDITY MEASUREMENTS

9.1. Measurement accreditation

Many organisations carry a recognised approval or accreditation for their activities. An accreditation means that certain aspects of their business have been independently assessed, and that they comply with given criteria of quality. An accreditation or certification may, for instance, cover an organisation's overall quality management system, e.g BS EN ISO 9000 series (equivalent to BS 5750).

However a generalised quality accreditation can not always address the details of specialised technical practices. For this reason, accreditation schemes specific to measurement have been developed. The UK Accreditation Service (UKAS) operates NAMAS (National Accreditation of Measurement and Sampling). NAMAS accreditation of a calibration or testing laboratory provides assurance that measurements are carried out to the highest standards of technical competence, traceable to recognised national or international standards, using agreed methods, and with realistic statements of uncertainty. The NAMAS regulations are based on international standards on the operation and accreditation of laboratories, such as EN 45000 and ISO Guide 25. NAMAS certificates are widely recognised and accepted throughout the UK and also worldwide.

Counterparts of NAMAS exist in many other countries, and in many cases are recognised as being exactly equivalent. Formal agreements provide for the mutual recognition of certificates from different national accreditation schemes. The European Cooperation for Accreditation of Laboratories (EAL) is the body which is the focus for multilateral recognition among national measurement accreditation schemes in Europe.

9.2. Competence in humidity measurement

What is assured when a laboratory or its personnel are said to be technically competent in humidity measurement? Well, reading this Guide does not in itself lead to competence! Practical skill and experience are also required. However, it can safely be said that if personnel are to be considered to be competent in humidity measurement, they should be familiar with much - if not all - of the information in the preceding chapters, for those kinds of instrument they use.

This document is a guideline, not a prescriptive specification or accreditation standard. However, it does summarise most of the widely accepted best practices in humidity measurement. Therefore, it is reasonable to expect that any humidity laboratory that has passed a NAMAS or equivalent assessment by an expert in the field will generally follow the practices described in this Guide. This does not mean, of course, that a competent laboratory need necessarily undertake all the types of measurement described here. Nor does it mean that they need use this document in order to be applying the good practices described here.

Broadly speaking, therefore, a competent laboratory (whether formally accredited or not) could be expected to implement most of the practices in Section 8 (Recommended practices) for those types of humidity measurement they undertake. Laboratory personnel competent in humidity measurement could be expected to be familiar with the instrument characteristics listed in Section 6.2 (Strengths and weaknesses of particular methods) for any instrument types they deal with.

10. TABLES, CHARTS AND FORMULAE

Below, some useful methods are given for converting between various parameters for humidity measurement. Those given in the form of charts or diagrams are for general indication only, and cannot be relied upon for exact values. Numerically correct conversions can be calculated using the formulae given below. The formulae have varying uncertainties associated with them (i.e. most of them are approximations, in some respect). For each, the associated uncertainty should be noted if accuracy is critical. The temperatures are expressed on the International Temperature Scale of 1990 (ITS-90).

10.1 Tables

Relative humidity

Values of relative humidity corresponding to a selection of dew points and temperatures are given. If this table is used to estimate relative humidities in between the values listed, the uncertainty may be up to ± 1 or ± 2 percent of value. Small differences in air pressure within the normal atmospheric range will affect these figures by less than 0.1 %rh.

Table 4. Values of relative humidity at a selection of temperatures and dew points

Temperature °C	0	5	10	15	20	25	30	35	40	50	60	70	80	90	100
Dew point °C	Relative humidity (%)														
0	100.0	70.1	49.8	35.8	26.1	19.3	14.4	10.9	8.3	4.9	3.1	2.0	1.3	<1	<1
5	-	100.0	71.1	51.1	37.3	27.5	20.5	15.5	11.8	7.1	4.4	2.8	1.8	1.2	<1
10	-	-	100.0	72.0	52.5	38.7	28.9	21.8	16.6	9.9	6.2	3.9	2.6	1.7	1.2
15	-	-	-	100.0	72.9	53.8	40.2	30.3	23.1	13.8	8.6	5.5	3.6	2.4	1.7
20	-	-	-	-	100.0	73.8	55.1	41.6	31.7	18.9	11.7	7.5	4.9	3.3	2.3
25	-	-	-	-	-	100.0	74.6	56.3	42.9	25.7	15.9	10.2	6.7	4.5	3.1
30	-	-	-	-	-	-	100.0	75.4	57.5	34.3	21.3	13.7	9.0	6.1	4.2
35	-	-	-	-	-	-	-	100.0	76.2	45.6	28.2	18.0	11.9	8.0	5.6
40	-	-	-	-	-	-	-	-	100.0	59.8	37.0	23.7	15.6	10.5	7.3
50	-	-	-	-	-	-	-	-	-	100.0	61.9	39.6	26.1	17.6	12.2
60	-	-	-	-	-	-	-	-	-	-	100.0	63.9	42.1	28.4	19.7
70	-	-	-	-	-	-	-	-	-	-	-	100.0	65.8	44.5	30.8
80	-	-	-	-	-	-	-	-	-	-	-	-	100.0	67.6	46.8
90	-	-	-	-	-	-	-	-	-	-	-	-	-	100.0	69.2

Absolute humidity

Table 5. Values of the mass of water vapour (in grams) contained in a cubic metre (m³) of saturated air at a total pressure of 101 325 Pa (1013.25 mbar).

Temperature °C	0	1	2	3	4	5	6	7	8	9
0	4.87	5.22	5.58	5.97	6.39	6.83	7.29	7.78	8.31	8.86
10	9.44	10.06	10.71	11.39	12.12	12.88	13.69	14.54	15.43	16.38
20	17.37	18.41	19.51	20.66	21.87	23.14	24.48	25.88	27.35	28.89
30	30.50	32.19	33.96	35.81	37.75	39.78	41.90	44.11	46.42	48.84

(The mass of 1 m³ of dry air at 20 °C is approximately 1.191 kg. The mass of 1 m³ of air saturated with water vapour at 20 °C is approximately 1.209 kg.)

Vapour pressure

Values of saturation vapour pressure with respect to water and ice are given below for a selection of temperatures. These values apply for pure vapour: the correct value in the presence of air is obtained by multiplying the vapour pressure values in the table by the appropriate water vapour enhancement factor. (This factor is also tabulated below, for a selection of overall (absolute) pressures and humidities.)

Table 6. Saturation vapour pressure in pascals (Pa) with respect to water for a range of temperatures, using equation (9) of Section 10.3, below. Values below 0 °C refer to supercooled water. 100 Pa = 1 mbar.

Temperature °C	0	1	2	3	4	5	6	7	8	9
100	101419	-	-	-	-	-	-	-	-	-
90	70182	72890	75685	78568	81542	84609	87771	91031	94391	97853
80	47416	49368	51388	53477	55636	57868	60174	62557	65017	67559
70	31202	32577	34002	35479	37010	38597	40240	41942	43704	45528
60	19948	20889	21868	22886	23944	25043	26184	27366	28600	29877
50	12353	12979	13632	14313	15023	15763	16534	17337	18173	19043
40	7385	7788	8210	8651	9113	9596	10100	10627	11178	11753
30	4247	4497	4760	5036	5325	5629	5948	6283	6633	7000
20	2339	2488	2645	2811	2986	3170	3364	3568	3783	4009
10	1228	1313	1403	1498	1599	1706	1819	1938	2068	2198
0	611.2	657.1	705.9	758.1	813.5	872.5	935.3	1002	1073	1148
-10	287	310	335	362	391	422	455	490	528	568
-20	126	137	149	162	176	191	207	225	244	264
-30	51.0	56.0	61.5	67.4	73.9	80.9	88.4	96.7	105	115
-40	19.0	21.1	23.4	25.8	28.6	31.5	34.8	38.3	42.2	46.4
-50	6.4	7.2	8.1	9.0	10.1	11.2	12.5	13.9	15.4	17.2

The uncertainties in these vapour pressures over water are estimated to be less than ± 0.01 percent of value at 0 °C and above, and less than ± 0.6 percent of value below 0 °C, at the 95% confidence level.

Table 7. Saturation vapour pressure in pascals (Pa) with respect to ice for a range of temperatures, using equation (10) of Section 10.3, below. 100 Pa = 1 mbar.

Temperature °C	0	1	2	3	4	5	6	7	8	9
0	611.2	-	-	-	-	-	-	-	-	-
-10	260	284	310	338	369	402	437	476	518	563
-20	103	114	125	137	151	165	181	199	217	238
-30	38.0	42.1	46.7	51.7	57.2	63.3	69.9	77.1	85.1	93.8
-40	12.8	14.4	16.1	17.9	20.0	22.3	24.9	27.7	30.8	34.2
-50	3.94	4.45	5.03	5.67	6.39	7.20	8.10	9.10	10.2	11.5
-60	1.08	1.24	1.41	1.61	1.84	2.09	2.38	2.70	3.07	3.48
-70	0.262	0.303	0.351	0.406	0.469	0.541	0.623	0.716	0.822	0.943
-80	0.055	0.064	0.076	0.089	0.104	0.122	0.143	0.166	0.194	0.225
-90	0.010	0.012	0.014	0.017	0.020	0.024	0.028	0.033	0.039	0.046
-100	0.001	0.002	0.002	0.003	0.003	0.004	0.005	0.006	0.007	0.008

The uncertainties at the 95% confidence level in these vapour pressures over ice are less than 1 percent of value, or are less than one digit in the last place shown - whichever is greater.

Water vapour enhancement factor

In the presence of air (or other gases), the saturation vapour pressure for pure water is multiplied by a correction factor which depends upon the gas species, the overall (absolute) pressure and the dew-point temperature. (See also Sections 4 and 10.3.)

Table 8. Water vapour enhancement factor in air at a selection of overall absolute pressures and dew-point temperatures. (0.1 MPa = 1000 mbar)

Temperature °C	-80	-60	-40	-20	0	20	40	60	80
0.1013 MPa	1.008	1.006	1.005	1.004	1.004	1.004	1.005	1.006	1.006
0.2 MPa	1.02	1.01	1.010	1.009	1.007	1.007	1.007	1.008	1.010
0.5 MPa	1.04	1.03	1.03	1.02	1.018	1.016	1.015	1.015	1.017
1 MPa	1.09	1.07	1.05	1.04	1.04	1.03	1.03	1.03	1.03

The uncertainties in these values of enhancement factor are less than or equal to ± 1 in the last digit shown, at the 95% confidence level.

Humidities over saturated salt solutions

Saturated solutions of various salts in water can be used to maintain particular values of relative humidity inside sealed enclosures at constant and uniform temperature.

Table 9. Equilibrium relative humidities generated over saturated solutions of a selection of salts.

Saturated salt solution	Temperature °C										
	0	5	10	15	20	25	30	35	40	50	60
	Relative humidity (%)										
Potassium sulphate	99	98	98	98	98	97	97	97	96	96	--
Potassium nitrate	96	96	96	95	95	94	92	91	89	85	--
Potassium chloride	89	88	87	86	85	84	84	83	82	81	80
Ammonium sulphate	82	82	82	82	81	81	81	80	80	79	--
Sodium chloride	76	76	76	76	75	75	75	75	75	74	75
Sodium nitrite	--	--	--	--	65	64	63	62	61	--	--
Ammonium nitrate	--	--	75	70	67	64	60	53	--	--	--
Sodium dichromate	61	59	57	57	55	54	53	51	50	49	47
Magnesium nitrate	60	59	57	56	54	53	51	50	48	45	--
Potassium carbonate	43	43	43	43	43	43	43	--	--	--	--
Magnesium chloride	34	34	33	33	33	33	32	32	32	31	29
Potassium acetate	--	--	23	23	23	23	22	--	--	--	--
Lithium chloride	11	11	11	11	11	11	11	11	11	11	11
Potassium hydroxide	--	14	12	11	9	8	7	7	6	6	5

The values listed in the table are taken from papers by Greenspan (1976), O'Brien (1948), Wexler (1954) and Young (1967). Where gaps are shown in the table, no reliable data are available.

The estimated uncertainties in the tabulated values range between ± 0.2 %rh and ± 3 %rh, and are detailed in OIML Recommendation 121. However, in practice, the humidity generated by a given salt may differ by several percent from the value in the table, due to influences such as slow equilibration, temperature variations, impurities and incomplete saturation. Stability is improved by the use of a slurry containing excess solid. For accurate results the value of humidity should be verified using a traceably calibrated hygrometer, or else traceably calibrated commercially-manufactured capsules or ampoules should be used.

Conversions between some humidity parameters

Table 10. Short summary of numerical relation between common humidity parameters in air at atmospheric pressure (101325 Pa)

Dew point (with respect to ice below 0 °C)	Saturation vapour pressure	Number of parts water vapour per million parts dry gas	Relative humidity at 100 °C	Relative humidity at 20 °C
°C	Pa	ppm _v	%rh	%rh
100	101419	∞	100	
80	47695	889334	47	
60	20065	246923	20	
40	7421	79028	7.3	
20	2349	23733	2.3	100
10	1233	12319		53
0	614	6097		26
-10	261	2583		11
-20	103	1018		4.4
-40	12.9	127		
-60	1.1	11		
-80	0.06	0.6		

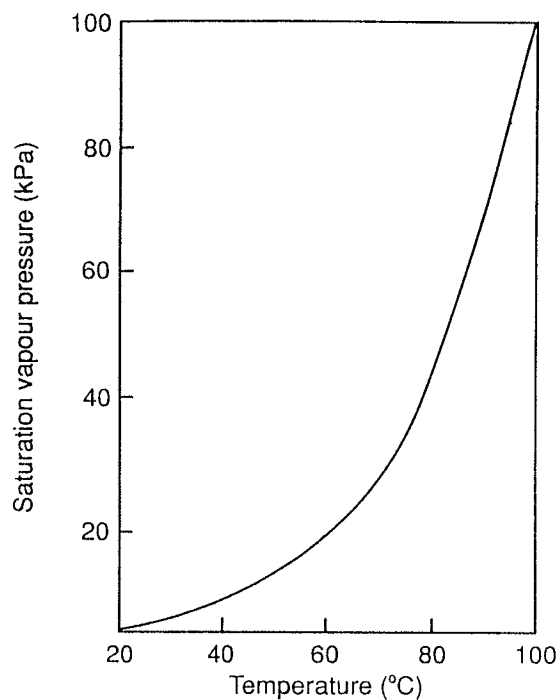
10.2 Charts

Some charts illustrating the relationships between different humidity parameters are shown below. These charts are for general indication only, and are not intended for accurate evaluations. Where exact values are required, these should be calculated, using the formulae given in Section 10.3 below.

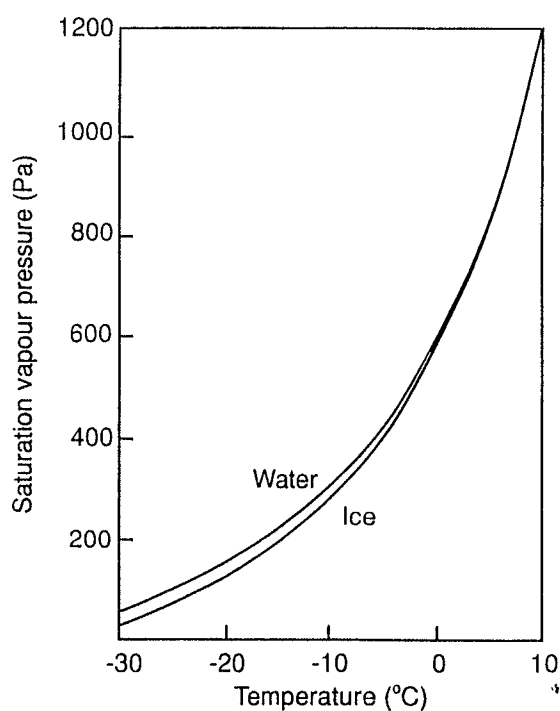
Illustrative graph of the vapour pressure curve of water

The vapour pressure of water is shown (a) for water and (b) for ice and supercooled water.

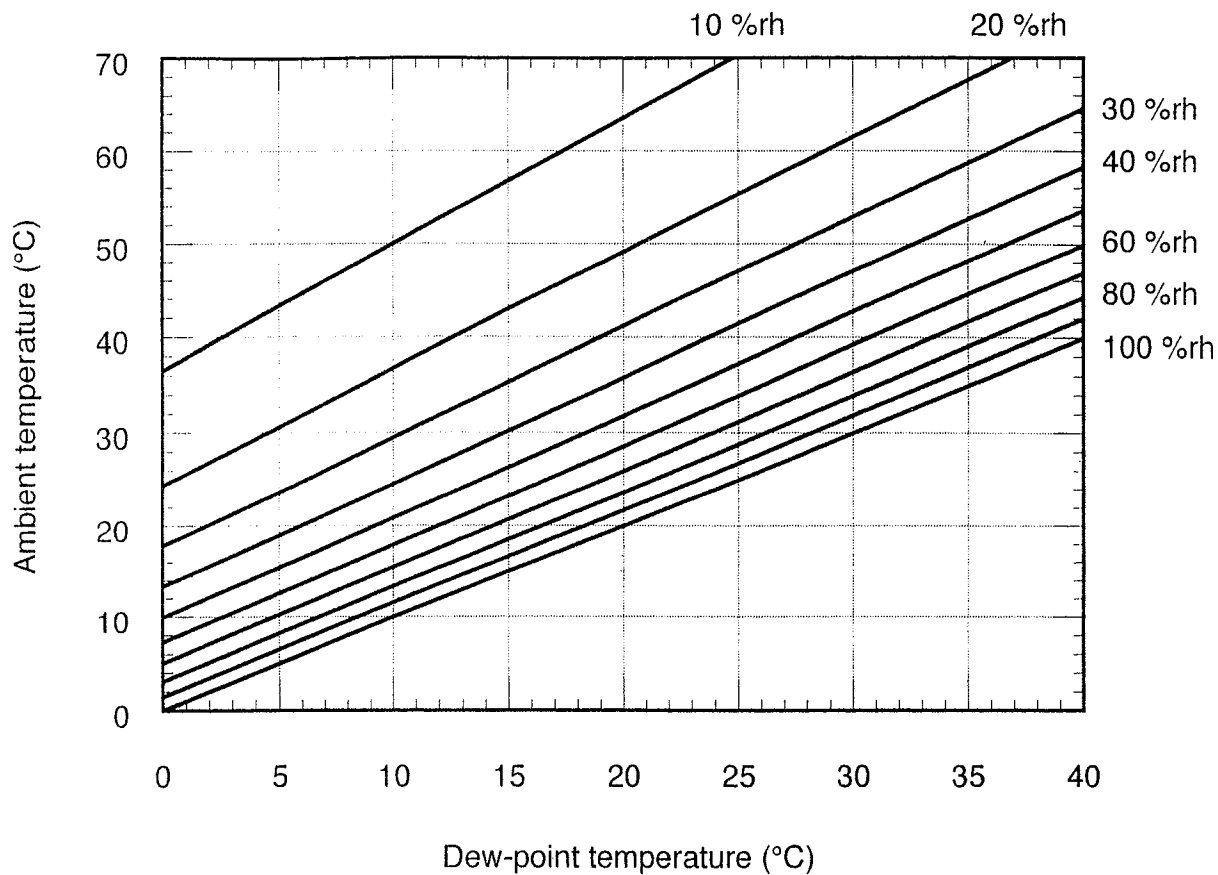
(a)



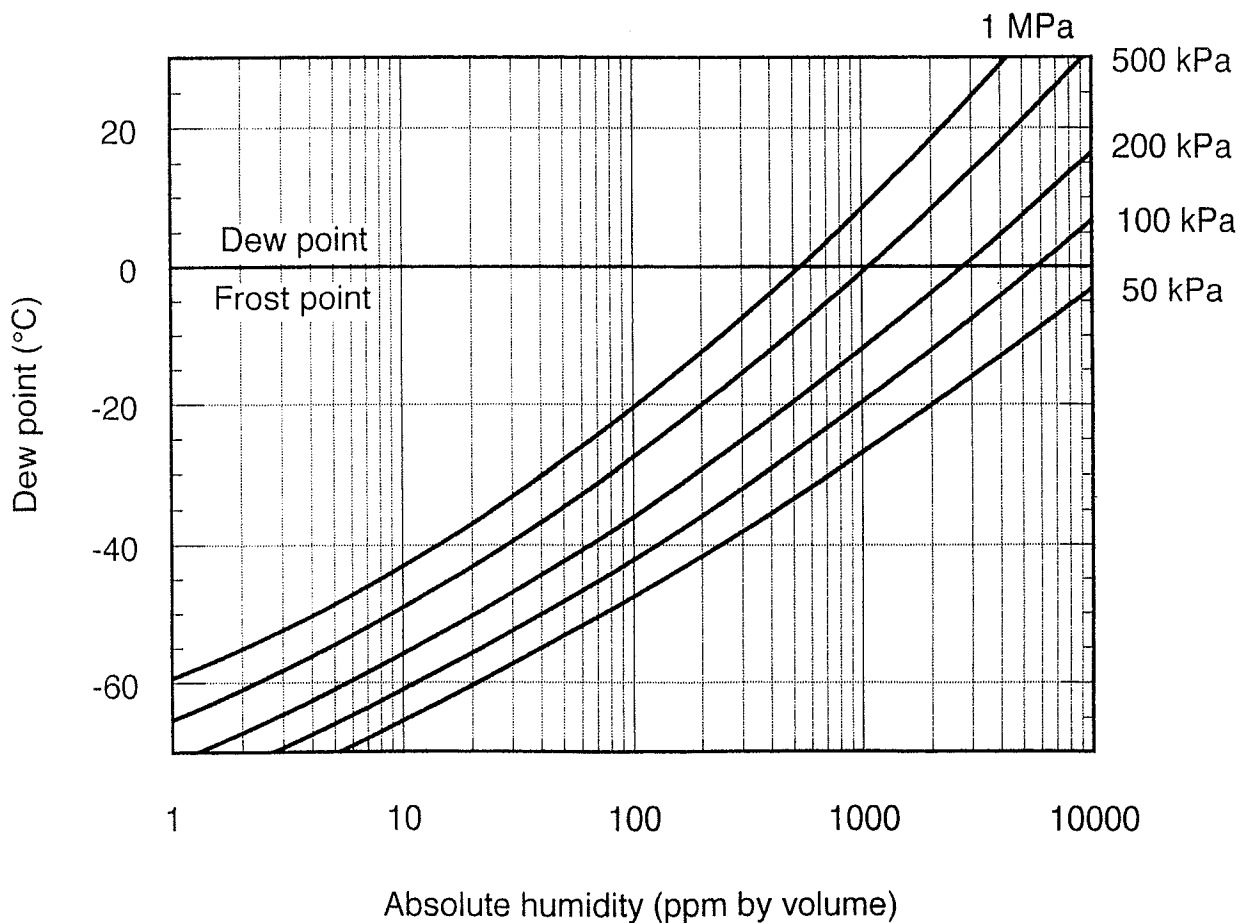
(b)



Relative humidity versus dew point and temperature



Conversions between dew point and absolute humidity (ppm_v) at different overall air pressures



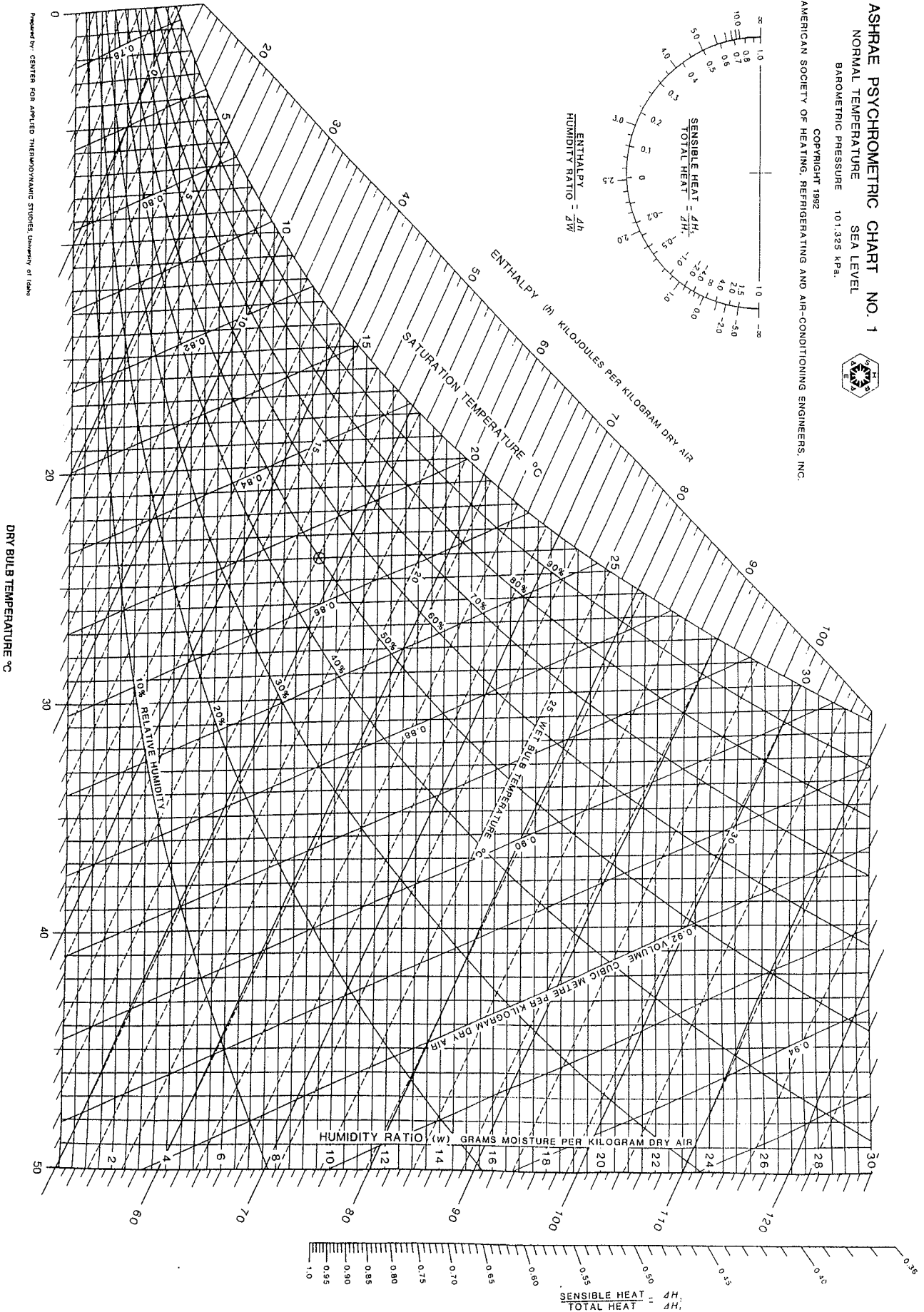
Psychrometric chart

ASHRAE PSYCHROMETRIC CHART NO. 1

NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa.



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10.3 Formulae

Relative humidity from vapour pressure

$$\text{Relative humidity (in \%)} = \frac{e}{e_s} \times 100 \quad (5)$$

where e is the actual vapour pressure of water and e_s is the saturation vapour pressure of water at the prevailing temperature and barometric pressure.

Psychrometer equation

Water vapour pressure e in air is found from the actual or dry-bulb temperature t and the wet-bulb temperature t_w using the equation

$$e = e' - AP(t - t_w) \quad (6)$$

where e' is the saturation vapour pressure of water at temperature t_w , P is the total barometric pressure (in the same units), and A is the established value of the *psychrometer coefficient*. Widely recognised values of A for t_w above 0 °C are:

$A = 6.66 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ for moving air as in the Assmann ventilated psychrometer

$A = 8.0 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ in a Stevenson screen as used by the Meteorological Office.

However, values of A other than those above may apply to certain psychrometers; the values for individual ventilated psychrometers are recognised to vary between $A = 6.4 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ and $A = 6.8 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$. The values of A given above yield approximate values of humidity, to which corrections can be added or subtracted, on the basis of a traceable humidity calibration. Alternatively, on the basis of a calibration of a given psychrometer, an individual value or formula for A may be assigned for that particular instrument. The use of a particular value of A is only valid if the correct conditions of air flow are provided for the instrument in question.

Pure vapour pressure from dew point

A simple equation relating saturation vapour pressure and dew point is the *Magnus formula*. At a temperature t (in °C), the saturation vapour pressure $e_w(t)$, in pascals, over liquid water, is

$$\ln e_w(t) = \ln 611.2 + \frac{17.62 t}{243.12 + t} \quad (7)$$

($e_w(t)$, is in pascals (Pa): 100 Pa = 1 millibar (mbar))

For the range -45 °C to +60 °C, values given by this equation have an uncertainty of less than ±0.6 percent of value, at the 95% confidence level.

Over ice, $e_i(t)$ is

$$\ln e_w(t) = \ln 611.2 + \frac{22.46 t}{272.62 + t} \quad (8)$$

For the range -65 °C to +0.01 °C, values given by this equation have an uncertainty of less than ±1.0 percent of value, at the 95% confidence level.

A more accurate but complex alternative formula for vapour pressure (in pascals) from dew point (in kelvin) is as follows for water

$$\begin{aligned} \ln e_w(T) = & -6096.9385 T^{-1} + 21.2409642 - 2.711193 \times 10^{-2} T \\ & + 1.673952 \times 10^{-5} T^2 + 2.433502 \ln T \end{aligned} \quad (9)$$

and for ice

$$\ln e_i(T) = -6024.5282 T^{-1} + 29.32707 + 1.0613868 \times 10^{-2} T - 1.3198825 \times 10^{-5} T^2 - 0.49382577 \ln T. \quad (10)$$

(Formulae due to Sonntag, 1990, updated from formulae given by Wexler, 1976 and 1977.)

The uncertainties associated with these equations are:

less than 0.01 percent of value, for water from 0 °C to +100 °C
less than 0.6 percent, for supercooled water below 0 °C down to -50 °C
less than 1.0 percent for ice down to -100 °C

at the 95% confidence level. For vapour pressures in the presence of air, the uncertainties for the formulae are only within these limits if the water vapour enhancement factor is taken into account (see below).

Dew point from pure vapour pressure

The Magnus formula given above can be re-stated in alternative form, to derive values of dew point from vapour pressure. For vapour pressure e_w , in Pa, over water, the dew point t_d , in °C, is given by

$$t_d = \frac{243.12 \ln (e_w/611.2)}{17.62 - \ln (e_w/611.2)}. \quad (11)$$

(100 Pa = 1 mbar.) The uncertainty in values of t_d given by this equation is less than ± 0.04 °C, in the range -45 °C to +60 °C.

For vapour pressure e_i over ice, the frost point t_i , in °C, is given by

$$t_i = \frac{272.62 \ln (e_i/611.2)}{22.46 - \ln (e_i/611.2)}. \quad (12)$$

The uncertainty in values of t_i given by this equation is less than ± 0.08 °C, in the range -65 °C to +0.01 °C. For dew points in the presence of air, the uncertainties for these formulae are only within these limits if the water vapour enhancement factor is taken into account (see below).

Water vapour enhancement factor

In the presence of additional gases or gas mixtures, such as air, the actual water vapour pressure e' is given by

$$e' = ef \quad (13)$$

where e is the pure vapour pressure of water (e.g. from the above formulae due to Magnus or Sonntag) and f is the water vapour enhancement factor.

Values of f in air are given for barometric (absolute) pressures P in the range 3 kPa to 110 kPa (30 mbar to 1100 mbar) by

$$f = 1.0016 + 3.15 \times 10^{-6} P - 0.074/P. \quad (14)$$

with uncertainty of less than ± 0.08 percent of value from -50 °C to +60 °C.

For pressures from atmospheric up to 2 MPa (20 atmospheres), f is given by

$$f = \exp \left[\alpha \left(1 - \frac{e_s}{P} \right) + \beta \left(\frac{P}{e_s} - 1 \right) \right] \quad (15)$$

where

$$\alpha = \sum_{i=1}^4 A_i t^{(i-1)} \quad \text{and} \quad \beta = \exp \sum_{i=1}^4 B_i t^{(i-1)} \quad (16)$$

and values of A_i and B_i are given in Table 11.

Table 11. Coefficients for f

	Water -50 °C to 0 °C	Water 0 °C to 100 °C	Ice -100 °C to 0 °C
A1	3.62183×10^{-4}	3.53624×10^{-4}	3.64449×10^{-4}
A2	2.60553×10^{-5}	2.93228×10^{-5}	2.93631×10^{-5}
A3	3.86501×10^{-7}	2.61474×10^{-7}	4.88635×10^{-7}
A4	3.82449×10^{-9}	8.57538×10^{-9}	4.36543×10^{-9}
B1	-10.7604	-10.7588	-10.7271
B2	6.39725×10^{-2}	6.32529×10^{-2}	7.61989×10^{-2}
B3	-2.63416×10^{-4}	-2.53591×10^{-4}	-1.74771×10^{-4}
B4	1.67254×10^{-6}	6.33784×10^{-7}	2.46721×10^{-6}

A selection of values of the water vapour enhancement factor are shown in Table 8 in Section 10.1.

Conversions between dew point and relative humidity

There is no simple direct formula for converting in either direction between dew point and relative humidity. Conversions between these two parameters must be carried out via the intermediate step of evaluating both the actual vapour pressure of water and the saturation vapour pressure at the prevailing temperature. Values of relative humidity or dew point can then be calculated using the appropriate formulae above. Table 4 in Section 10.1 shows values of relative humidity at a selection of temperatures and dew points.

10.4 Use of software

Software packages are available for computerised calculations and conversions for humidity, including (sometimes) the production of charts and tables.

Although commercially produced software should have been carefully validated prior to release, results can be checked by another method if there is any doubt. The origins of the formulae used should be stated (e.g. in the accompanying documentation). Values can be checked by referring to the source literature, and by carrying out calculations manually or using entirely separate software to check that the answers agree. It is wise to check that the formulae are not being used outside their range of validity, and to know the associated uncertainties. Check how the number of digits displayed relates to the uncertainty; it is easy to assume that values shown to many decimal places can be relied upon to that precision. This is not always the case.

Checking or validation of privately written computer programmes is, if anything, more important than for purchased software. Documentation is important if programmes are to be used by anyone other than the author. Ideally, programmes should be "locked" or made tamper-proof, e.g. by "password" protection. In writing software for calculating or converting between humidity parameters, some of the variables require evaluation to many significant figures. "Double precision" arithmetic may be needed to avoid rounding errors. The uncertainty of the results due to any rounding and due to the intrinsic uncertainty in the formulae should be borne in mind. Ideally uncertainties should be made clear in all output, by rounding the results to a meaningful level of precision, and by building uncertainty statements into the output information.

General precautions for any software include checking any received discs for viruses, retaining backup copies, and storage in a place safe against fire, magnetic fields, etc.

11. EXAMPLES AND CALCULATIONS

The following are a few worked examples and calculations illustrating how to approach some practical problems in humidity measurement.

11.1 Example 1: Relative humidity - ambient monitoring

It is important to remember just how great the effect of temperature is on relative humidity measurements. It is vital that the humidity sensor is in thermal equilibrium with the environment being measured. Even a small temperature difference causes an error.

If the temperature is 23 °C and the relative humidity is 50 %rh, what is the effect of a difference of 1 °C in temperature between the sensor and the air to be measured? (Corrections for the water vapour enhancement factor are negligible here.)

The effect of temperature can be seen from the following calculation. At 23 °C the saturation vapour pressure (e_s) over pure water is 2811 Pa (from Table 6 in Section 10 above). By definition, relative humidity is the ratio of the actual water vapour pressure (e) to the saturation vapour pressure (e_s) at the temperature of the gas.

$$\text{Relative humidity} = \left(\frac{e}{e_s} \right) \times 100\%$$

and we are told in this case that the relative humidity is 50 %rh.

Thus, at 50 %rh the water vapour pressure in the space being measured is

$$\frac{50}{100} \times 2811 = 1406 \text{ Pa} .$$

If the temperature changes by 1 °C, to 24 °C, the new relative humidity value will be found from e_s at 24 °C = 2986 Pa (from Table 6), and actual vapour pressure $e = 1406$ Pa, so that

$$\text{relative humidity} = \frac{1406}{2986} \times 100\% = 47.1 \text{ \%rh} .$$

Therefore, in this case, the error in relative humidity is almost 3 %rh, for a mismatch in temperature of 1 °C.

11.2 Example 2: Dew-point measurement with respect to water or ice

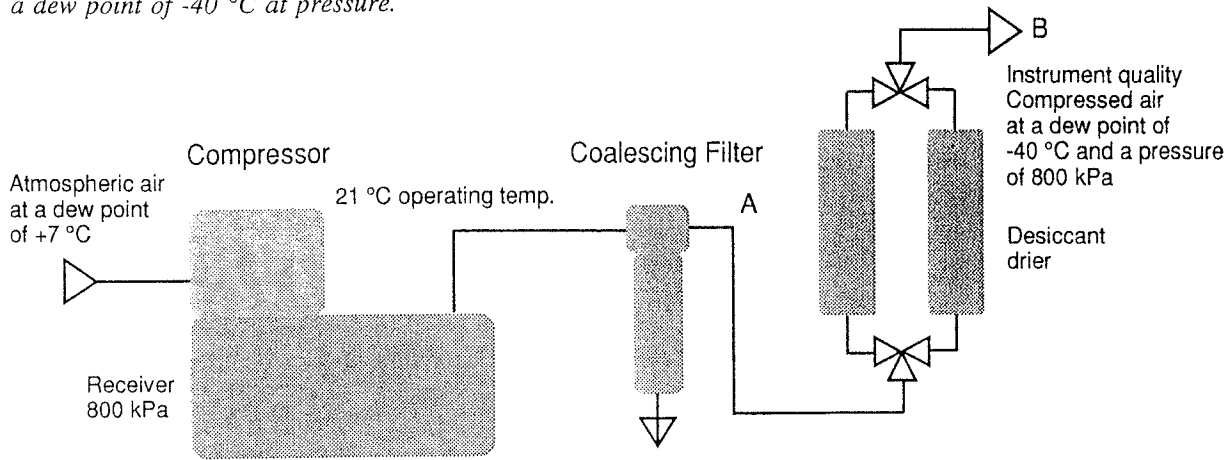
In the region below 0 °C, condensation can occur in the form of ice or supercooled water. For a given vapour pressure, the dew-point and frost-point temperatures differ. In measurements using the condensation principle, it is important to know which type of condensate is formed.

In a certain measurement with a condensation hygrometer, supercooled water is formed, indicating a dew point of -12 °C. How different would the reading be if ice were to form instead? (Corrections for the water vapour enhancement factor are negligible here.)

From Table 6 in Section 10, the saturation vapour pressure over pure water at -12 °C is 244 Pa. By looking this up in Table 7 relating to ice (frost point) we can see that a vapour pressure of 244 Pa relates to a temperature somewhere between -10 °C and -11 °C. To be more exact, by interpolating between the values of vapour pressure for -10 °C and -11 °C (or by calculation from equations (7) or (9) in Section 10), 244 Pa corresponds to about -10.7 °C. Thus, for a dew point of -12 °C (with respect to supercooled water), the corresponding frost point (with respect to ice) is -10.7 °C. Thus the liquid or solid phase of the condensate makes a difference of about 1.3 °C, in this part of the measurement range. The reading would be higher for ice than for water.

11.3 Example 3: Effects of pressure and temperature change on dew point

a) Atmospheric air with a dew point of +7 °C is being sucked into a compressor which pressurises the air into a receiver at 800 kPa (8 atmospheres). The air feeds from the receiver through a coalescing filter operating at an ambient temperature of 21 °C into a twin-column desiccant dryer which delivers instrument quality air at a dew point of -40 °C at pressure.



What is the dew point at position A after the coalescing filter? (Neglecting water vapour enhancement factor.)

In this example, the ambient air has a dew point of +7 °C, and so is saturated with respect to water vapour at +7 °C. Using tables of saturation water vapour pressures we obtain a partial pressure of water vapour of 1002 Pa. The total pressure of the gas at point A is increased to 800 kPa. This eight-fold increase in the total gas pressure will result in a similar rise in partial pressures, so the water vapour pressure rises to 8016 Pa. Looking back at the tables, this equates to a dew point of +41.6 °C. However, as the operating temperature of the receiver and filter is only +21 °C we can assume that condensation is occurring within the receiver and filter vessels, and that air at position A is saturated at +21 °C and therefore has a dew point of +21 °C.

How much moisture is present at position A, in absolute humidity (parts per million by volume (ppm_v))?

From the tables, the partial pressure of water vapour, e , for a gas of +21 °C dew point is 2488 Pa. The total pressure at A is 800 kPa. The fraction of the total gas volume made up of water vapour can be found from:

$$\frac{e}{P_{tot}} = \frac{2488}{800 \times 10^3} \times 10^6 = 3110 \text{ ppm}_v$$

What is the remaining fraction of water in the gas after the dryer at point B?

A dew-point temperature of -40 °C with respect to ice corresponds to a partial pressure of water vapour of 12.8 Pa. So, again using the formula:

$$\frac{e}{P_{tot}} = \frac{12.8}{800 \times 10^3} \times 10^6 = 16 \text{ ppm}_v$$

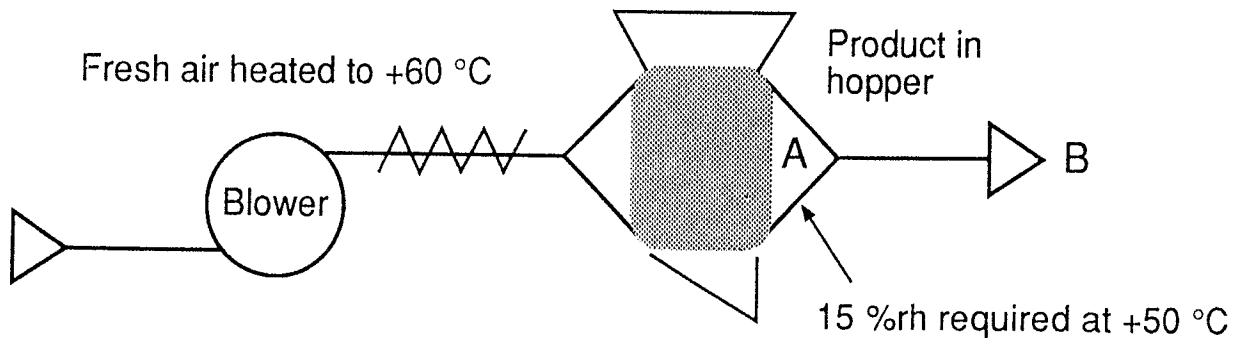
If the pressure of the air at point B is reduced to atmospheric, what is the effect on the dew-point temperature and on the number of parts per million by volume?

An eightfold decrease in total pressure will result in a corresponding decrease in partial pressures so the water vapour pressure is reduced from 12.8 Pa to 1.6 Pa. Referring back to the tables we see that the dew point is thus reduced to approximately -57 °C.

Calculating the number of parts per million by volume, we find that the value remains the same irrespective of changes in pressure, i.e.

$$\frac{e}{P_{tot}} = \frac{1.6}{100 \times 10^3} \times 10^6 = 16 \text{ ppm}_v .$$

b) A hopper load of a food product is being dried prior to packaging by blowing through fresh air which is heated to +60 °C. The dew point of the exhaust air is being measured. During the drying process moisture is carried out of the product and at the same time the product temperature gradually increases. To ensure good storage life of the product when packaged, the requirement is to dry the product until the exhaust air is less than 15 %rh at the product temperature which measures +50 °C towards the end of a drying cycle.



What is the equivalent dew point measured at position A at the end of a drying cycle?

Relative humidity is the ratio, expressed as a percentage, of actual water vapour pressure at the measured dew point to saturation water vapour pressure at the gas temperature. Rearranging the formula for calculating relative humidity we obtain:

$$e = \frac{e_s \times \text{relative humidity}}{100} .$$

The saturation water vapour pressure e_s at 50 °C is 12 353 Pa, so

$$e = \frac{12\,353 \times 15}{100} = 1853 \text{ Pa} .$$

From tables we can deduce that a water vapour pressure of 1853 Pa equates to a dew point of about +16.3 °C.

At the end of a drying cycle, what is the relative humidity of the exhaust air at position B where the air temperature cools to an ambient value of 21 °C?

$$\text{Relative humidity} = \frac{e}{e_s} \times 100 = \frac{1853}{2488} \times 100\% = 74 \text{ \%rh} .$$

At the mid point in the drying cycle, the relative humidity reaches 100 %rh at a temperature of +40 °C. Why would it be impossible to measure this condition using a humidity sensor installed at point B?

As the air passing through the hopper at this stage is totally saturated at the operating temperature of +40 °C, the dew point is +40 °C. However, the temperature at the exhaust vent point B is only 21 °C. As a result the air flow will no longer be wholly gaseous as water vapour will condense to form mist droplets, so a measurement at this point would not be valid.

11.4 Example 4: Calibration of a humidity test chamber

The following example considers the uncertainties in calibration of an environmental chamber. The techniques of uncertainty combination and the source of the contributions mentioned are also applicable to test, measurement and process rooms where there is a humidity specification to be met. Questions are:

- a) What are the main sources of uncertainty in calibrating a humidity chamber?*
- b) How can we estimate them?*
- c) How can we find the combined effect, i.e. an overall uncertainty in calibrating the chamber?*
- d) What might be the uncertainty in using the chamber subsequently?*

a) What are the main sources of uncertainty in calibrating a humidity chamber?

Sources of uncertainty in calibrating and using a humidity chamber arise from the calibration of the measurement system and additionally from the control system. In calibrating a chamber, the uncertainties of main concern are:

1. Uncertainty of the reference measuring equipment
2. Uncertainty associated with the measurement of a fluctuating condition
3. Uncertainty in humidity distribution from place to place in the chamber

b) How can we estimate the uncertainties connected with each aspect?

The following paragraphs detail some of the major sources of uncertainty.

Uncertainty of the reference measuring equipment:

This comprises not only the uncertainty in the calibration of the reference instrument of the calibrating authority, but also the following contributions. (This list may not be exhaustive.)

- Resolution of the instrument
- An allowance for stability or drift consistent with the observed variation between consecutive calibration results
- An allowance for the uncertainty which results from any assumption of the linearity of the reference between calibration points (the greater the number of calibration points the smaller the assumption and the smaller the contribution)
- Any known errors for which the user chooses not to correct

Once a value has been assigned to the uncertainty in using the reference instrument, this value is combined with all of the other chamber calibration contributions.

This uncertainty does not include "correctable systematic errors" for which corrections are applied (for example, the corrections given on the calibration certificate for the reference instrument).

Uncertainty associated with the measurement of a fluctuating condition:

Ideally, calibrations are carried out in a stable environment. However, in the calibration of chambers the conditions are constantly fluctuating. As well as fluctuations in the humidity generating mechanism of the chamber, there will also be fluctuations in temperature. The latter may equal or exceed the former in the end effects on relative humidity, since this is so strongly affected by temperature.

Response times Since the conditions are fluctuating the "standard" sensor may never be in equilibrium with the environment. In fact the largest deviations may never be indicated. The magnitude of these errors cannot easily be ascertained since it will be dependent upon the response of the standard and the rate of fluctuation of the chamber. (Note that chambers with spray type humidification often exhibit rapid fluctuations.)

Fluctuation If the standard continuously records the humidity, all fluctuations should at least be observed even if their magnitude is reported incorrectly (see Response times, above). Also the mean value can be estimated. If the standard records measurements at intervals only (discrete measurements) then the peaks of the fluctuations may not be seen at all. The discontinuous data must then be statistically analysed to calculate the mean and peak values. (This approach is not ideal in this case, since the formula used for standard deviation assumes a normal distribution, and in the case of chamber control this is unlikely. In fact the most extreme peak in humidity is likely to be greater than the value returned by statistical techniques.)

The errors due to response times and the maximum observed or calculated fluctuations should be estimated and included in the overall uncertainty for calibrating the chamber humidity.

Humidity distribution in the chamber:

Ideally the humidity calibration would involve the simultaneous continuous measurement of many points in the working space of the chamber. However, in most practical cases the humidity of a chamber is measured at a single point in the centre of the chamber and the response in the remainder of the working space is estimated.

Estimation of the humidity distribution of a chamber based on a central point calibration and a temperature gradient/fluctuation calibration Any temperature gradient across a chamber which exists permanently or occurs as a result of temperature fluctuations, causes a corresponding change in the relative humidity. The temperature gradient between the position of the hygrometer and the "worst" position in the working space should be measured and the effect on the humidity calculated (assuming a uniform vapour pressure, which may be a simplification but is probably the best approximation). In this situation other unknowns may also have to be estimated.

c) How can we find the combined effect of the individual uncertainties, i.e. an overall uncertainty in calibrating the chamber?

Suppose the measurement data for this value of humidity are:

Source of Contribution	Contribution at 95% level of confidence
<u>Standard</u> Uncertainty assigned to the reference hygrometer after consideration of the most recent calibration certificates	± 4 %rh
<u>Humidity fluctuation in the centre of the chamber</u> With a set condition of 25°C, 60 %rh, the following levels were measured in the centre of the chamber: 61.6 %rh, 62.7 %rh, 62.6 %rh, 63.6 %rh and 62.0 %rh. Mean value 62.5% (i.e. 2.5 %rh high). Standard deviation of unknown population 0.76 %rh, estimated statistically. (See Note below)	
From the above, fluctuation estimated statistically to be ± 1 %rh at 95 percent confidence level.	± 1 %rh
<u>Humidity distribution error caused by temperature gradients</u> In the working space of interest, the worst temperature deviation from the chamber's centre was 1.4 °C. This equates to a humidity error of approximately 5 %rh at 60 %rh (treated here as a 95% confidence estimate)	± 5 %rh

Combination of contributions will be in the general form

$$\left[\left(\begin{array}{c} \text{Uncertainty} \\ \text{of} \\ \text{standard} \end{array} \right)^2 + \left(\begin{array}{c} \text{Fluctuation} \\ \text{at central} \\ \text{position} \end{array} \right)^2 + \left(\begin{array}{c} \text{Humidity} \\ \text{distribution} \end{array} \right)^2 \right]^{\frac{1}{2}}$$

Hence the total uncertainty will be:

$$[(4)^2 + (1)^2 + (2)^2]^{\frac{1}{2}} = 6.5 \text{ \%rh}$$

The above will give an estimate of the uncertainty of calibration of the chamber in this example. In other cases, and at other temperatures and humidities, there could be further contributions which, depending upon the chamber design, might be significant.

NOTE. Statistical treatment of data and analysis of uncertainties are not covered in depth here, but recommendations for further reading on these subjects are given in Section 12 below.

d) What might be the uncertainty in using the chamber subsequently?

In using the chamber, other uncertainties will certainly need to be taken into account in addition to the calibration uncertainty. For example, previous calibrations of the chamber should be consulted and some additional allowance made for drift between calibrations. When in use, the effects of any load in the chamber should also be considered as this can be expected to affect the humidity and temperature in the working space. If the chamber is used to provide changing values of humidity or temperature (a "cycle" or "ramp"), it is most likely that the humidity values will have a worse uncertainty during periods of change than during the relatively stable conditions of the calibration.

In this case the calibration of the chamber at the given set point shows it to disagree from the reference hygrometer by 2.5 %rh. How will this affect the use of the chamber?

If the appropriate correction of -2.5 %rh is applied when using the chamber, no further uncertainty is implied.

On the other hand, if the user does not apply this calibration correction to the chamber value of humidity, the result will be wrong by 2.5 %rh. In this situation, the figure of 2.5 %rh must at the very least be included with the other uncertainties, increasing the overall uncertainty in using the chamber.

The figures in the example above realistically illustrate the practical measurement capabilities in many working laboratories, leading in this case to an uncertainty for using the chamber of at least ± 6.5 percent of value, at 50 %rh. However, some published test specifications have tolerances of ± 5 %rh, and tolerances of ± 2.5 %rh are not unknown. Compliance with such specifications is therefore very difficult, and sometimes impossible. Writers of specifications should consider the uncertainty of available humidity standards and the likely magnitude of other uncertainty contributions when setting humidity tolerances in specifications.

12. FURTHER READING

The reading lists below are categorised according to the different aspects of the subject. It should be possible to obtain any of these texts from a library by supplying the full reference details shown below. The texts listed are recommended starting points, and these in turn carry references to much other useful reading material.

Many organisations involved in humidity measurement produce their own booklets giving general information about humidity. Some of these are excellent, and their exclusion from the list below is not meant to suggest that they are not useful. However, the list below includes only information that is available in the public domain and which is commercially neutral.

When reading about "state-of-the-art" technology, the date of the text should be borne in mind. It should also be noted that not all the texts below are completely consistent with this Guide in their usage of terms and symbols.

General (easy) reading on humidity measurement

"Measuring Humidity in Normal Ambient Environments" R.F. Pragnell *Proceedings of "Electronic Environmental Monitoring in Museums"*, National Museum of Wales. (1992) Ed. R.E. Child.

Meteorological Office "Handbook of Meteorological Instruments, Volume 3, Measurement of humidity, Second Edition, (London:HMSO). ISBN 0 11 400325 4. (*Out of print. Particularly detailed for wet- and dry-bulb and mechanical hygrometers, for weather monitoring.*)

General (more advanced) reading on humidity measurement

1993 ASHRAE Handbook - Fundamentals - SI Edition. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta, USA. ISBN 0 910110 97 2. (*Chapter 6, Psychrometrics.*)

"Advancements in the field of hygrometry" D. Sonntag *Meteorologische Zeitschrift, N.F.* Volume 3, pp 51-66 (April 1994). (*Review article*)

Moisture and Humidity Measurement and Control in Science and Industry *Proceedings of the 1985 International Symposium on Moisture and Humidity, Washington D.C. April 15-18 1985.* (North Carolina, USA). ISBN 0-87664-865-0 (*Over 100 technical papers covering developments in all aspects of humidity measurement*)

"Moisture sensors in process control" K.G. Carr-Brion (Elsevier Science Publishers Ltd, UK) 1986. (*Covers measurement in liquids and solids, as well as in gases.*)

In-depth reading

Particular humidity techniques or applications:

"Dew and frost formation on the condensation dew point hygrometer" R.F. Pragnell *Measurement and Control*, Volume 26, April 1993.

"Humidity measurement at elevated temperatures" F.Dadachanji *Measurement and Control*, Volume 25, March 1992.

"Recording humidity: no need to lose your hair" R.F. Pragnell *Environmental Engineering*, September 1990.

"The modern condensation dew point hygrometer" R.F. Pragnell *Measurement and Control*, Volume 22, April 1989.

Sources of reference data:

1993 ASHRAE Handbook - Fundamentals - SI Edition. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta, USA. ISBN 0 910110 97 2. (*Chapter 6, Psychrometrics, Chapter 19.2, Sorbents and Desiccants.*)

CRC Handbook of Chemistry and Physics (*also known as the "Rubber handbook" or "Rubber Bible"*) 76th Edition. (London: CRC Press). ISBN 0-8493-0476-8. (*Sections 6.10, 6.15-6, 6.113 and 15.22-3 cover humidity*)

Kaye and Laby Tables of Physical and Chemical Constants, Sixteenth Edition. (Harlow: Longman). ISBN 0 582 22629 5. (*Sections 2.1.4 and 3.4.1. cover humidity.*)

"Functional Equations for the Enhancement Factors for CO₂-Free Moist Air." L. Greenspan, (1976). *Journal of Research of the National Bureau of Standards*, Volume 80A, pp 41-44.

"Important new values of the physical constants of 1986, vapour pressure formulations based on the ITS-90, and psychrometer formulae" D. Sonntag, (1990). *Zeitschrift fur Meteorologie* Volume 40, (5), pp 340-344.

"Humidity Fixed Points of Binary Saturated Aqueous Solutions" L. Greenspan, (1977). *Journal of Research of the National Bureau of Standards*, Volume 81A, (1) pp 89-96

"The control of humidity by saturated salt solutions" F.E.M. O'Brien, (1948). *Journal of Scientific Instruments* Volume 25, pp 73-76.

"Relative humidity-temperature relationships of some saturated salt solutions in the temperature range 0 °C to 50 °C" A. Wexler and S. Hasegawa, (1954). *Journal of Research of the National Bureau of Standards* Volume 53, No. 1, pp 19-26.

"Humidity control in the laboratory using salt solutions - a review" J.F. Young, (1967). *Journal of Applied Chemistry* Volume 17, pp 241-245.

OIML Recommendation 121 - The scale of relative humidity of air certified against saturated salt solutions. Organisation Internationale de Metrologie Legale, France.

Physics of humidity:

Humidity and Moisture Measurement and Control in Science and Industry *Proceedings of the 1965 International Symposium on Moisture and Humidity*. (New York: Reinhold). Volume 3 Chapter 1 " Fundamentals Concepts and Definitions Relating to Humidity" L.P. Harrison. (*Comprehensive introduction to the theory relating to humid gases. Out of print*)

International and British standard specification documents relating to humidity:

Below are listed only a partial selection of the standards specifically concerned with humidity. Many others address humidity as part of their subject matter.

ANSI/ASHRAE Standard 41.6-1994, Method for measurement of moist air properties.

ASTM E 104 - 85 (Re-approved 1991), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions

BS 1339: 1965 (1981), Definitions, formulae and constants relating to the humidity of the air. (*Under revision in 1996*)

BS 2842: 1992, British Standard Specification for Whirling Hygrometer.

BS 4833: 1986 (1992), Hygrometric tables for use in the testing and operation of environmental enclosures.

A guide to the measurement of humidity

BS 5248: 1990, British Standard Specification for Aspirated Hygrometer.

ISO 4677/1-1985, Atmospheres for conditioning and testing - Determination of relative humidity - Part 1: Aspirated psychrometer method, Part 2: Whirling psychrometer method.

OIML Recommendation 121 - The scale of relative humidity of air certified against saturated salt solutions".

Temperature measurement

The following texts provide guidance for temperature measurement in general. The first three are general texts with at least some advice on the special concerns which relate to measurement of temperature in air.

"Temperature Measurement" L. Michalski, K. Eckersdorf and J. McGhee. (Chichester: Wiley) (1991) ISBN 0 471 93803 3.

"Traceable Temperatures: An Introduction to Temperature Measurement and Calibration" J.V. Nicholas and D.R. White. (Chichester: Wiley) (1994)

"Principles and Methods of Temperature Measurement" T.D. McGee (Chichester: Wiley) (1988)

"Industrial Temperature Measurement" T.W. Kerlin and R.L. Shepherd. Instrument Society of America, 1982. (*Strong industrial flavour, good treatment of thermocouples, and response times of thermometers.*)

"Temperature, its Measurement and Control in Science and Industry" American Institute of Physics, New York, Vol 5 (1982), Vol 6 (1992). (*Collections of research papers, proceedings of ten-yearly international symposia, important reference for thermometry, covering all aspects from theory to everyday practice*)

NAMAS Information Sheet NIS 7 Traceability: Thermometers, Thermocouples and PRTs (Liquid-in-glass Thermometers, Thermocouples, Platinum Resistance Thermometers and Radiation Thermometers)

"The International Temperature Scale of 1990, ITS-90 (English version of the official French text)" National Physical Laboratory (London: HMSO). ISBN 0 11 480059 6

Classic texts on humidity now out of print

Humidity and Moisture Measurement and Control in Science and Industry *Proceedings of the 1965 International Symposium on Moisture and Humidity*. (New York: Reinhold). Volume One, Principles and Methods of Measuring Humidity in Gases. Volume Two, Applications. Volume Three, Fundamentals and Standards. Volume Four, Principles and Methods of Measuring Moisture in Liquids and Solids.

NPL Notes on Applied Science No 4 - Measurement of Humidity. (London: HMSO) (*Practical emphasis, though technology outdated, and discussions of accuracy optimistic by modern standards*)

"Humidity" - Institute of Physics Monograph. H.L. Penman, (1957). (*Concise handbook. Useful discussions of humidity physics and phenomena. Discussions of technology outdated.*)

Useful reading not specific to humidity

"Guide to the expression of uncertainty in measurement". (Geneva: International Organization for Standardization). ISBN 92-67-10188-9. (*International definitive text on uncertainty analysis, for the advanced reader*)

"International vocabulary of basic and general terms in metrology". Second Edition, 1993. (Geneva: International Organization for Standardization). ISBN 92-67-01075-1. (*International definitive text on terms used in measurement*)

NAMAS leaflet P3 "What's so special about a NAMAS laboratory report or certificate?"

NAMAS leaflet M1 - "Introducing NAMAS".

NAMAS information Sheet NIS 3003 "The Expression of Uncertainty and Confidence in Measurement for Calibrations" (*Simplification of the ISO uncertainties document above*)

"SI: The International System of Units" (Translation of International Bureau of Weights and Measures publication "Le système international d'unités") edited by R.J. Bell, 1993 (Sixth edition).

"Statistics for technology" C. Chatfield. Third Edition. (1983) (London:Chapman and Hall) (*General textbook on statistics*)

BS 5844 : 1980 (1987) (ISO 5168 - 1978) Methods of Measurement of Fluid Flow: estimation of uncertainty of a flow-rate measurement.

BS EN ISO 9000 : 1994, Quality systems - model for quality assurance in design, development, production, installation and servicing.

EN 45000 (BS 7501 : 1989), General Criteria for the Operation of Testing Laboratories.

ISO 10012-1 : 1992 (BS 5781 : Part 1 : 1992), Quality assurance requirements for measuring equipment.

ISO Guide 25 : 1990, General requirements for the competence of calibration and testing laboratories.

Useful addresses

British Standards Institution (BSI), 389 Chiswick High Road, London W4 4AL

European Cooperation for Accreditation of Laboratories (EAL), PO Box 29152, 3001 GD Rotterdam, Netherlands

Institute of Measurement and Control (InstMC), 87 Gower Street, London WC1E 6AA

International Organization for Standardization (ISO), Case Postale 56, CH-1211 Geneve 20, Switzerland

National Physical Laboratory (NPL), Queens Road, Teddington, Middlesex TW11 0LW

United Kingdom Accreditation Service (UKAS), Queens Road, Teddington, Middlesex TW11 0NA

INDEX

- Abbreviations 7
- Absolute humidity 7, 46, 51
 - see also mixing ratio 8
- Absolute measures of humidity 6, 7
- Absorption 6, 10
- Accreditation 24, 30, 37, 45
- Accuracy 5, 26
- Acoustic hygrometer 16
- Adaptability 20
- Adiabatic expansion hygrometer 16
- Adjustment 27, 29, 39
- Adsorption 6
- After-sales service 21
- Aluminium oxide hygrometer 15, 22
- Analogue output 19
- APIMS (atmospheric pressure ionisation mass spectrometry) 16, 23
- Aspirated psychrometer
 - see wet- and dry-bulb hygrometer 14
- Assmann psychrometer 53
- Bench-top calibration 31
- Bottled gas 31
- British and international standard specifications . . . 7, 14, 24, 28
- Buying a hygrometer 24
- Cable length 19
- Calculations 53-61
- Calibration 20, 24, 29-37, 39, 59, 60
- Calibration chain 36
- Calibration curve 26
- Calibration intervals 32
- Capacitive hygrometer 14, 15, 18, 22
- Care of instruments 39
- Certification 45
- Charts 49-52
- Checking hygrometers 27, 32, 33, 39
- Chemical compatibility 20
- Cleaning 21, 39
- Colour change hygrometer 16, 18, 24
- Competence 45
- Condensate 6
- Condensation 5, 10, 40, 41, 43
- Condensation hygrometer 15, 18, 22
- Confidence level 26, 34
- Configuration 18, 19
- Consumable supplies 21
- Contamination 18, 39
- Control of humidity 20, 27
- Conversions 46, 49, 51, 53-55
- Cost 20
- Coverage factor 34
- Data sheets 25
- Datum point 8
- Definitions 5-7
- Demonstrations 24
- Desiccant 6
- Desorption 6, 10, 39, 41
- Dew point 7, 46, 51, 53-55
 - effect of pressure 12, 57, 58
- Dew-point generator 30
- Dew-point impedance sensors 15, 18
- Display 19
- Drift 34
 - see also stability 27
- Dry bulb 6
 - see also wet- and dry-bulb hygrometer 6
- Drying
 - see desiccant 6
- EAL (European Cooperation for Accreditation of Laboratories) 37, 45
- Ease of use 20
- Electrical impedance hygrometer 14
 - electrolytic 15
- Electrical output 6
- Electrolytic
 - see also resistive sensor 15
- Electrolytic (phosphorous pentoxide) hygrometer 15, 18, 23
- End use 20
- Energy 8, 9
- Enhancement factor 13, 48, 54
- Enthalpy 8
- Equilibration 39
- Equilibrium relative humidity 8, 20
- ERH
 - see equilibrium relative humidity 8
- Error 33, 34
- Error detection 20
- Evaporation 5, 7, 14
- Examples 56-61
- Exhibitions 24
- Extrapolation 37
- Field calibration 20, 30
- Finding suppliers 24
- Fitness for purpose 19, 24
- Fixed points 31
- Flow rate 19
- Flow-mixing generator 31
- Format of instrument 19
- Formulae 53, 54
- Frost point 8
- FT-IR (Fourier-transform infrared spectroscopy) 16, 23
- Fundamental measurements 37
- Further reading 62-65
- Gas type 20, 32, 39
- Generation of humidity 30
- Getting help 24
- Goldbeater's skin 14
- Gravimetric hygrometer 16

A guide to the measurement of humidity

Hair hygrometer		
see mechanical	14	
Hand aspirated psychrometer	14	
Harmonisation	28	
Hazardous areas	20	
Humidity	6	
Humidity chamber	31, 59-61	
Humidity concepts	5	
Humidity generation	30	
Humidity ratio		
see mixing ratio	8	
Hygrometer	6	
acoustic	16	
adiabatic expansion	16	
capacitive	14, 15, 18, 22	
colour change	16, 18, 24	
condensation	15, 18, 22	
electrical impedance	14, 22	
electrolytic (phosphorous pentoxide)	15, 18, 23	
gravimetric	16	
impedance	18	
lithium chloride	15, 18, 23	
Lyman-alpha	16	
mechanical	14, 18, 21	
optical fibre	16	
optical refractive index	16	
piezoelectric (quartz oscillator)	16	
pneumatic bridge	16	
resistive	14, 15, 18, 22	
spectroscopic	16, 18, 23	
table of main features	18	
thermal conductivity	16	
thermal rise	16	
typical ranges	18	
wet- and dry-bulb	14, 18, 21, 28, 53	
zirconia	16	
Hygrometry	6	
Hygroscopic	6	
Hysteresis	19, 20, 27	
Impedance hygrometer	18, 22	
Impedance sensors	15	
In-situ calibration	20	
Inert gas	6	
Infrared hygrometer	16, 23	
Instrument format	19	
Instruments		
temperature effects	10	
Interchangeability	21	
International recognition	37, 45	
Interpretation of data sheets	25	
Intrinsic safety	20	
Introduction	5	
Latent heat	8	
Level of confidence	26, 34	
Lifespan	20	
Linearity	19	
see non-linearity	26	
Lithium chloride hygrometer	15, 18, 23	
Lyman-alpha hygrometer	16	
Magnus formula	53	
Maintenance	21, 39	
Maintenance cost	20	
Mason's psychrometer	14	
Mass concentration		
see absolute humidity	7	
Materials	20	
Measured quantities	7-9	
Measurement ranges	18, 19	
Mechanical hygrometer	14, 18, 21	
Metal oxide sensors	15, 22, 43	
Methods for measuring humidity	14-17	
Mixed-flow generator	31	
Mixing ratio	8	
see also parts per million by weight	9	
Moisture	6	
Moisture content	8	
Moisture content by volume		
see absolute humidity	7	
Mole	8	
Mole fraction	8	
see also parts per million by volume	9	
Monitoring humidity	20	
Mounting	19	
NAMAS	24, 29, 30, 45	
National Physical Laboratory	29	
National standards	29, 37	
Non-aspirated psychrometer	14	
Non-linearity	26	
Operating principles of hygrometers	14-17	
Optical dew-point hygrometer	15, 22	
Optical fibre hygrometer	16	
Optical refractive index hygrometer	16	
Orientation	19	
Output	19	
Partial pressure	8, 12	
Parts per million by mass		
see parts per million by weight	9	
Parts per million by volume	9	
Parts per million by weight	9	
Percentage saturation	9	
Performance	19, 29	
Phosphorous pentoxide hygrometer	15	
Piezoelectric (quartz oscillator) hygrometer	16	
Pneumatic bridge hygrometer	16	
Pressure	19, 51	
effect on dew point	12, 57	
effect on relative humidity	12, 58	
units	8	
water vapour enhancement factor	13	
Pressure, partial	8	
Primary standard	29	
Probe	6, 14, 19, 21	

A guide to the measurement of humidity

Psychrometer		
see wet- and dry-bulb		
hygrometer	14	
Psychrometer equation	53	
Psychrometric chart	52	
Quality	20, 24, 45	
Quartz oscillator		
see piezoelectric	16	
Random error	33, 35	
Range of operation	25	
Ranges of measurement	18, 19, 25	
Readout	19	
Recommended practices	39, 41-44	
Records	39	
Regeneration	21	
Relative humidity	6, 9, 10, 46, 51, 53, 55, 56	
effect of pressure	12	
Reliability	20	
Repeatability	19, 26, 33	
Replacement of parts	21	
Reproducibility	19, 26	
Resistive hygrometer	14, 15, 18, 22	
electrolytic	15	
Resolution	19, 25	
Response time	19, 20, 27	
Robustness	20	
Salt ampoule	31	
Salt capsule	31	
Salt solution	30, 31, 48	
Sampling	18, 19, 35, 39	
Saturation	5, 7, 8	
Saturation vapour pressure	5, 9, 10, 47, 53	
Selection of a hygrometer	19	
Sensible heat	8, 9	
Sensitivity	19	
Sensor	6	
Serial output	19	
Silicon hygrometer	22	
Silicon sensor	15	
Site calibration	30	
Software	55	
Sources of information	24, 62-65	
Spares	21	
Specific humidity	9	
see also parts per million by		
weight	9	
Specification	19, 24, 25, 28, 29	
Spectroscopic hygrometer	16, 18, 23	
Stability	19, 27	
Stevenson screen	53	
Stored energy	8	
Strengths and weaknesses of methods	21	
Systematic error	33, 35	
Table of hygrometer features	18	
Tables	11, 18, 46-48	
TDLAS (tunable diode laser absorption		
spectroscopy)	16, 23	
Temperature		
and absorption or desorption	10	
and condensation	10	
and salt solutions	31	
and sampling	10	
and saturation vapour pressure of		
water	10	
dew-point	7	
dry-bulb	6	
effect on instruments	10	
effects on humidity		
measurement	10, 58	
frost-point	8	
wet-bulb	7	
Temperature coefficient	28	
Temperature measurement	11	
Temperature sensor	14	
Terms	5-7	
Test reports	25	
Test specifications	37	
Thermal conductivity hygrometer	16	
Thermal rise hygrometer	16	
Tolerances	37	
Traceability	29, 35-37	
Transfer standard	29	
Transmitter	6	
Two-pressure generator	31	
Two-temperature generator	31	
Type of gas	20, 32, 39	
Typical ranges of hygrometers	18	
UKAS	45	
Ultraviolet hygrometer	16	
Uncertainty	5, 18, 19, 21, 22, 25, 26, 29, 33-36, 59-61	
Units of measurement	7, 8, 19	
Upkeep	20	
Usage of terms	7-9	
Vapour concentration		
see absolute humidity	7	
Vapour density		
see absolute humidity	7	
Vapour pressure	9, 12, 47, 50, 53, 54	
Versatility	20	
Vocabulary	6	
Volumetric absolute humidity		
see absolute humidity	7	
Warranty	21	
Water activity	9, 20	
Water vapour	5	
Water vapour enhancement factor	13, 48, 54	
Weather house hygrometer	14	
Wet bulb	7	
see also wet- and dry-bulb		
hygrometer	7	
Wet sock	14	
Wet- and dry-bulb hygrometer	14, 18, 21, 28, 53	
Whirling psychrometer	14	
Wick	7, 14	
Zirconia hygrometer	16	