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Humidity —

Part 3: Guide to the measurement of humidity

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Contents

Foreword

This British Standard was prepared by Technical Committee CPI/29.

This British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Summary of pages

This document consists of a front cover, an inside front cover, pages i and ii, pages 1 to 35 and a back cover.

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1 Scope

This British Standard gives guidance on the selection and use of instruments for the measurement of humidity. It introduces the main concepts and practical techniques involved in measuring humidity in air and other "inert" gases and provides an explanation of how to make valid and meaningful measurements. It also includes guidance on specifying or choosing appropriate equipment for a known application.

2 Normative references

The following normative documents are indispensible for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 1339-1*, Humidity — Part 1: Terms, definitions and formulae.*

BS 1339-2*, Humidity — Part 2: Humidity tables.*

3 Terms and definitions

For the purposes of this part of BS 1339, the terms and definitions given in BS 1339-1 apply.

4 Basic concepts of humidity

4.1 General

The word "humidity" denotes the presence of water or another 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 percent of the air around us. Hence, by far the most common application of humidity is the air–water vapour system. However, the concept is equally applicable to water vapour or any other vapour in any gas, e.g. a solvent vapour being dried from a pharmaceutical in a nitrogen atmosphere. Previous British Standards have concentrated entirely on the air–water system, as have the equivalent ASHRAE (American Society of Heating, Refrigeration and Air conditioning Engineers) standards. This new part of BS 1339 is the first to attempt a generalized statement suitable for all vapour–gas systems.

The term "vapour" usually applies to a gas which is below its critical temperature and can therefore become liquid if the pressure is increased, or if the vapour concentration in the gas becomes too high. In contrast, virtually all the components of air are above their critical temperature and will not liquefy under any normal conditions; air is therefore known as a permanent gas. In this Guide, where the word "gas" appears hereafter, it should be taken to mean a permanent gas.

4.2 Importance and relevance of humidity

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. For example, they are used in air conditioning, meteorology, horticulture, food processing, solids drying and general chemical engineering.

There are many different techniques for measuring humidity and the subject is complicated by the confusing variety of ways of expressing humidity.

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 in a typical laboratory by weighing 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 % of value.

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 should 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. This Guide is intended to assist you in this process.

4.3 Scientific fundamentals

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 (and 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 – will give off (or sometimes absorb or adsorb) water vapour. 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. Likewise, where any other liquid is present, its vapour will also be present in the surroundings to some extent, depending on the volatility of the liquid.

Air (or empty space, or any other gas) has a given capacity to hold water vapour. This capacity depends mainly on temperature. Generally speaking, the hotter the air, the more water vapour it can hold. At any particular temperature, air 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 mass of water vapour is actually present (irrespective of temperature or level of saturation). These include mole fraction, mixing ratio and volumetric humidity. The same principles can be applied to any vapour held in any gas, but the capacity to hold vapour depends on the identity of the vapour and, to a lesser extent, the gas.

If unsaturated air is cooled without changing the mass of water vapour present (i.e. at constant mole fraction or mixing ratio) it will reach a temperature at which it is saturated, and liquid water will then appear as condensation; this temperature is the “dew point”. Below 0 °C, the water will tend to appear as ice, and this is known as the “frost point”.

If water is allowed to evaporate into unsaturated air, the air will cool down and the mass of water present in the gas will also increase. It will again reach saturation, but at a higher temperature and mass fraction than the dew point temperature. Under ideal conditions with no heat losses, the final temperature is known as the “adiabatic saturation temperature”. It is closely related to the “wet bulb temperature”, which is the temperature reached by a liquid surface in contact with a flowing gas – see **4.7**.

4.4 Alternative humidity terminology

Table 1 summarizes the terms and formulae used in BS 1339 and compares them with other terminology in widespread use. For detailed definitions of these terms and expressions of the formulae, refer to BS 1339-1.

Table 1 — Alternative humidity terms

BS 1339 term	ASHRAE (1997) term	Alternative terms and synonyms	BS 1339 symbol	Units (SI)	Formula
Volumetric humidity	Absolute humidity	Water-vapour density, vapour concentration	d_v	kg/m^3	$d_v = m_v/V$
Mixing ratio	Humidity ratio	Absolute humidity, mass ratio, moisture content (dry basis)	Y	kg/kg	$Y = m_v/m_g$
Specific humidity	Specific humidity	Wet-basis humidity	Y_W	kg/kg	$Y_W = m_v/(m_g + m_v)$
Mole fraction		Volume fraction[a]	y	mol/mol	
Vapour pressure	Vapour pressure	Partial pressure	p	Pa	
Total pressure	Total pressure	Atmospheric pressure	P	Pa	
Saturation vapour pressure	Water vapour saturation pressure		p_s	Pa	
Saturation mixing ratio	Saturation humidity ratio	Saturation humidity	Y_s	kg/kg	
Relative humidity	Relative humidity		ψ, rh	%, % rh	$\psi = p/p_s$
Percentage saturation	Degree of saturation	Mass-ratio relative saturation	μ	%	$\mu = Y/Y_s$
Adiabatic saturation temperature	Thermodynamic wet-bulb temperature		t_{as}	°C	
Wet-bulb temperature	Wet-bulb temperature		t_{wb}	°C	
dew point temperature	dew point temperature		t_{dp}	°C	
Frost-point temperature	Frost point temperature	dew point temperature[a]	t_{fp}	°C	
Humid volume	Specific volume		v	m^3/kg	$v = V/m_g$
Volume (of mixture)	Volume		V	m^3	
Gas density	Density		ρ	kg/m^3	$\rho = (m_g + m_v)/V$

NOTE Numbers expressed as percentages may also be expressed as dimensionless fractions.

[a] Term is not an exact equivalent, although commonly used.

4.5 Problems of terminology

The widespread use of humidity in a broad range of industries can give rise to problems, as the traditional practices and common terminology often differ between these different industries.

For example, for many applications, it is convenient to state humidity as a volumetric concentration in grams per cubic metre, and this is often called "absolute humidity". This presents no real problems for conditions close to atmospheric pressure and ambient temperature. However, this expression is totally unsuitable for chemical engineering applications, as temperature will often vary greatly during the drying process, and gas volume varies with it. Instead, it is necessary to use the ratio of mass of vapour to mass of dry gas, and this is also known as absolute humidity in chemical engineering applications. The use of the same term for two quantities which are not even dimensionally equivalent can create confusion, and BS 1339-1 recommends that the term "volumetric humidity" is used for the first form (concentration) and that "mixing ratio" is used for the second form (mass ratio). However, it should be recognized that the term "absolute humidity", in both forms, is deeply entrenched in industry and is unlikely to be eliminated in the foreseeable future.

Below the normal freezing point of a liquid, vapour normally condenses out as ice, and the temperature at which this occurs is the frost-point temperature. However, under certain circumstances, the vapour can appear as supercooled liquid. This occurs at the supercooled liquid dew point temperature, which is slightly lower than the frost-point. For example, the difference is about 1 °C for water vapour at –10 °C, and about 4 °C at –50 °C. The term "dew point" is often used in a general way to refer to the scale encompassing both dew point and frost-point temperatures. Below 0 °C, the term "frost-point" is used to specifically indicate ice. To refer specifically to the liquid form below the normal freezing point, the term "supercooled" is used, e.g. supercooled water dew point.

Another quantity causing confusion is the equilibrium relative humidity (ERH), or water activity, of a substance. This is a property of the substance itself, and denotes the relative humidity of a vapour–gas mixture in equilibrium with the substance at its given composition (including liquid moisture content). Hygroscopic materials have low ERH values, tending to absorb water vapour from the air unless the latter is very dry. The ERH should not be confused with the relative humidity itself, which is a property of the vapour–gas mixture.

4.6 Invariant and variable parameters

It is useful to note the parameters of a vapour–gas mixture that do not vary with pressure and (dry-bulb) temperature for a given composition. These tend to be based on mass or the amount of substance (moles) rather than volume. They include:

— mixing ratio and specific humidity;
— mole fraction (or volume fraction of gases or vapours);
— molecular weight;
— mass or mass flowrate.

A near-fundamental quantity is the pure saturation vapour pressure, which is a function only of temperature. It is linked to the actual saturation vapour pressure in a gas mixture by the enhancement factor, which is a function of total pressure, but the correction is generally less than 0.5 % at atmospheric pressure.

Derived quantities, which tend to vary with temperature, pressure or composition, include:

— volumetric humidity;
— adiabatic saturation temperature and wet bulb temperature;
— gas density and specific (humid) volume;
— saturation vapour pressure in a gas mixture;
— partial pressure of the vapour in an unsaturated gas mixture;
— relative humidity.

4.7 Systems other than air–water

Some common assumptions for the air–water system do not apply to other solvent–gas systems. In particular, the wet-bulb temperature is not identical to the so-called thermodynamic wet-bulb temperature (correctly entitled the adiabatic saturation temperature). The adiabatic saturation temperature is based on an enthalpy balance (i.e. equilibrium conditions) and is easy to calculate but difficult to measure; the wet-bulb temperature is based on heat and mass transfer rates (i.e. kinetically controlled) and is difficult to calculate but easily measured. For the air–water system, they are coincidentally and conveniently almost equal (well within 1 ºC at near-ambient temperatures). Hence, calculation equations and measurements for one quantity can be used to give approximate values for the other. However, for other solvents, they can be markedly different, and more rigorous forms of calculation are needed.

4.8 Units used in the formulae

4.8.1 *General*

The formulae in BS 1339 parts 1 and 2 (and the accompanying program) are generally in SI units. These do not always coincide with standard engineering practice and some common pitfalls are noted in **4.8.2** to **4.8.5**. The most frequent problem is confusion between true SI and common engineering units, leading to an error by a factor of 1 000.

4.8.2 *Molal mass (molecular weight)*

In the original metric system, these were quoted as $g \cdot mol^{-1}$, so that, for example, the molal mass of water was approximately 18 and that of dry air about 29. When the SI unit of mass was changed to the kg, the unit for “amount of substance” was somewhat illogically left as the mole (gram molecular weight). Hence one mole of carbon-12 contains 12 g of carbon, or 0.012 kg. As a result, molal masses of air and water, quoted in strict SI units, become 0.029 and 0.018 respectively. For engineering purposes, it is often more convenient to use the kilomole (kmol; 1 kmol of C-12 contains 12 kg of carbon) but unfortunately this is not a recognized base SI unit. The formulae in BS 1339-1 use molal mass in $kg \cdot mol^{-1}$.

4.8.3 *Universal gas constant R*

This is quoted in molal units and is approximately 8.314 $J \cdot mol^{-1} \cdot K^{-1}$. In the formula for vapour pressure, if pressure is quoted in pascals and molecular weights in $kg \cdot mol^{-1}$, R is as given above. If molecular weights are quoted as $kg \cdot kmol^{-1}$or $g \cdot mol^{-1}$, the value required in the formula will be 8 314 $J \cdot kmol^{-1} \cdot K^{-1}$.

4.8.4 *Specific heat capacity C_P, humid heat C_s and enthalpy h.*

The SI unit for heat is the joule, and this gives the specific heat for dry air as being just over 1 000 $J \cdot kg^{-1} 1 \cdot K^{-1}$, and the enthalpy of dry air at 20 °C on this basis will be about 20 000 $J \cdot kg^{-1}$, while the latent heat of evaporation of water is 2 500 000 $J \cdot kg^{-1}$. For engineering purposes, the kilojoule (kJ) is a more convenient unit. All specific heat capacities and enthalpies (including latent heat) should be quoted in the same energy units. For the formulae in BS 1339, kilojoules are used, so that the specific heat for dry air is about 1 $kJ \cdot kg^{-1} \cdot K^{-1}$, the enthalpy of dry air at 20 °C is about 20 $kJ \cdot kg^{-1}$, and the latent heat of evaporation of water at 0 °C is 2 500.8 $kJ \cdot kg^{-1}$.

When handling engineering data, care should be taken to check whether energies are quoted in joules, kilojoules or calories. If calories are quoted, they may be based on the quantity of heat required to raise the temperature of 1 g or 1 kg of water by 1 ºC; the latter unit is more properly termed the kilocalorie. Likewise, enthalpies and specific heats may be quoted per unit mass or per mole, and it is important to check whether grams, kilograms, moles or kilomoles are the base unit.

4.8.5 *Mixing ratio Y and specific humidity Y_W.*

The mixing ratio is the mass of vapour divided by the mass of dry gas; specific humidity is the mass of vapour divided by the mass of moist gas. The SI unit, and the practice in the formulae, is to quote Y and Y_W in $kg \cdot kg^{-1}$, so that typical values for ambient air are about 0.002 to 0.02. However, it is common to see figures quoted in $g \cdot kg^{-1}$, so that ambient humidities would be in the range 2 to 20.

4.9 Main humidity parameters and their calculation

4.9.1 *Mixing ratios, mass and mole fractions*

The mixing ratio Y, mole ratio z, mole fraction y and specific humidity Y_W are all absolute, invariant values for a gas–vapour mixture of a given composition, as explained in **4.6**; they do not change with applied temperature or pressure. They are linked to each other directly. The formulae for converting between Y and Y_W, or between y and z, are the same for any combination of vapour and gas. However, the identity of the vapour and gas affects the interconversion between mass and mole units, which depends on their molecular weights (molal masses). The complete set of interconversion formulae for the air–water system is given in Table 2 (from **3.2.18** of part 1, which gives the corresponding formulae for other vapour–gas systems).

4.9.2 *Vapour pressure p and relative humidity ψ*

The partial pressure of vapour in a gas–vapour mixture, p', is linked directly to the mole fraction y by the total applied pressure P; it does not vary with temperature. Again, this makes conversion to other mass- and mole-based invariant humidity terms easy, as shown in Table 2.

The relative humidity ψ (%rh) is the ratio of the partial pressure to the saturation vapour pressure p_s (described below); it thus expresses, as a percentage, how close the mixture is to saturation. It varies with temperature and pressure as well as composition.

The distinction between pure vapour pressure p and actual vapour pressure p' is explained in **4.9.3**.

Table 2 — Interconversion formulae for air–water system, to three significant figures

Convert to:	Y (or ppm$_w$)[a]	z (or ppm$_v$)[a]	Y_W	y	p'	d_v
Convert from:						
Mixing ratio[a] Y (kg·kg^{-1})	1	$z = 1.6078Y$	$Y_w = \frac{Y}{1+Y}$	$y = \frac{Y}{(0.622+Y)}$	$p' = \frac{PY}{(0.622+Y)}$	$d_v = \frac{0.002167PY}{(0.622+Y)T}$
Mole ratio[a] z (mol·mol^{-1})	$Y = 0.622\ z$	1	$Y_w = \frac{z}{1.6078+z}$	$y = \frac{z}{1+z}$	$p' = \frac{z}{1+z}P$	$d_v = \frac{0.002167zP}{(1+z)T}$
Specific humidity Y_w (kg·kg^{-1})	$Y = \frac{Y_w}{1-Y_w}$	$z = \frac{1.6078Y_w}{(1-Y_w)}$	1	$y = \frac{Y_w}{(0.622+0.378Y_w)}$	$p' = \frac{PY_w}{(0.622+0.378Y_w)}$	$d_v = \frac{0.002167PY_w}{(0.622+0.378Y_w)T}$
Mole fraction y (mol·mol^{-1})	$Y = \frac{0.622Y}{(1-Y)}$	$z = \frac{y}{1-y}$	$Y_w = \frac{0.622y}{1-0.378y}$	1	$p' = yP$	$d_v = \frac{0.002167yP}{T}$
Vapour pressure p' (Pa)	$Y = \frac{0.622p'}{(P-p')}$	$z = \frac{p'}{(P-p')}$	$Y_w = \frac{0.622p'}{P-0.378p'}$	$y = \frac{p'}{P}$	1	$d_v = \frac{0.002167p'}{T}$
Volumetric humidity d_v (kg·m^{-3})	$Y = \frac{0.622}{\frac{0.002167P}{d_vT}-1}$	$z = \frac{1}{\frac{0.002167P}{d_vT}-1}$	$Y_w = \frac{0.622}{\frac{0.002167P}{d_vT}-0.378}$	$y = \frac{461.5d_vT}{P}$	$p' = 461.5d_vT$	1

[a] Multiply Y by 10^6 to obtain ppm$_w$; multiply z by 10^6 to obtain ppm$_v$

4.9.3 *Saturation vapour pressure p_s*

The saturation vapour pressure of a pure liquid varies with temperature. For accurate calculation of saturation vapour pressure of water, the formula given by Sonntag (1990) should be used (equation (1)) [1]. With p_s in Pascals ($N \cdot m^{-2}$) at absolute temperature T,

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

A similar formula applies for saturation vapour pressure over ice – see BS 1339-1. However, simpler (but less accurate) formulae exist, such as the Antoine equation. This is easier to use, especially as it is directly reversible to give T in terms of p_s:

$$\ln p_s = C_0 - \frac{C_1}{T - C_2} \qquad T = \frac{C_1}{C_0 - \ln p_s} + C_2 \tag{2}$$

The Antoine equation, with its commonly quoted values for coefficients C_0, C_1 and C_2, gives results within 0.1 % of steam tables and the Sonntag equation (1) over the range 50 °C to 100 °C, but shows a significant error at lower values (nearly 3 % at 0 °C). By slightly changing the coefficients to give a close fit at 0 °C and 100 °C, an alternative fit can be obtained with an error of less than 1.2 % over the complete range 0 °C to–100 °C, although of course the errors at higher temperatures will be greater than with the original coefficients. The coefficients are shown in Table 3.

Table 3 — Antoine equation coefficients for air–water system

		C_0	C_1	C_2 K		C_0	C_1	C_2 K
Standard values	***p*** (Pa)	23.196 3	3 816.44	46.13	***p*** (mm Hg)	18.303 6	3 816.44	46.13
New values	***p*** (Pa)	23.19	3 830	44.83	***p*** (mm Hg)	18.3	3 830	44.87

For vapours other than water, the Sonntag equation cannot be used, but coefficients are available for the Antoine equation for a wide variety of vapours in the book "The Properties of Gases and Liquids" [2].

Another commonly used alternative form is the Magnus equation. Like the Antoine equation, this is easily reversible:

$$\text{Over water:} \quad \ln p_s = \ln 611.2 + \frac{17.62 t_{dp}}{t_{dp} + 243.12} \qquad t_{dp} = \frac{243.12 \ln\left(p_s / 611.2\right)}{17.62 - \ln\left(p_s / 611.2\right)} \tag{3}$$

$$\text{Over ice:} \quad \ln p_s = \ln 611.2 + \frac{22.46 t_{fp}}{t_{fp} + 272.62} \qquad t_{fp} = \frac{272.62 \ln\left(p_s / 611.2\right)}{22.46 - \ln\left(p_s / 611.2\right)} \tag{4}$$

The Sonntag equation strictly only applies to water vapour with no other gases present (i.e. in a partial vacuum). The actual saturation vapour pressure p_s' of a gas mixture, e.g. water vapour in air, is given by multiplying the pure saturation vapour pressure p_s by an enhancement factor f, for which various equations are given in part 1. Likewise, the enhancement factor can be applied to convert pure vapour pressure p for unsaturated mixtures to actual vapour pressure p'. For water vapour in air at one atmosphere, 101 325 Pa, $f \approx 1.004\,7$. Hence, for most purposes, the correction is negligible, and except for accurate calculations, p_s and p_s' are interchangeable, as are p and p'. Alternatively, f can often be applied simply by taking it to be constant at a given total pressure, as temperature has only a weak effect on f at near-ambient conditions. However, f is strongly dependent on pressure, and should always be included for calculations at elevated pressure; for example, $f \approx 1.03$ at 10 bar and $f \approx 1.3$ at 100 bar.

4.9.4 *Volumetric humidity d_v and density of humid gas ρ_g*

The volumetric humidity (sometimes called absolute humidity) is a mass concentration of vapour in a given volume of gas. It therefore varies substantially with temperature and pressure even for a fixed mixture composition. For this reason, it is inconvenient and not recommended for chemical engineering calculations, though it is adequate for approximate calculations close to normal atmospheric temperatures and pressures, e.g. in meteorology and air-conditioning. The volumetric humidity is linked to the specific humidity Y_W by the density of the humid gas ρ_g, which itself varies significantly with temperature, applied pressure and the vapour content of the mixture. The governing equation is:

$$d_v = Y_W \rho_g = \frac{Y}{(1+Y)} \rho_g \tag{5}$$

Humid volume, v, is another commonly used term, but is conventionally defined as the volume of air per unit mass of dry gas, not moist gas. Hence, the humid volume is not the reciprocal of the gas density, except for completely dry gas.

4.9.5 *Wet bulb and adiabatic saturation conditions*

Study of previously published standards shows significant confusion between the adiabatic saturation temperature T_{as} (based on a heat balance) and the wet bulb temperature T_{wb} (based on rate effects or kinetics). By coincidence, they are almost equal for the air–water system at ambient conditions; they differ by less than 1°C for dry-bulb temperatures between 0 °C and 100 °C with humidity below 0.1 $\mathrm{kg \cdot kg^{-1}}$. For other solvent–gas systems, they differ considerably; wet-bulb temperature and humidity are almost invariably higher than the adiabatic saturation values. The confusion is not helped by the use of the term “thermodynamic wet-bulb temperature” for adiabatic saturation temperature, e.g. by others.

In industry, the most commonly quoted method to obtain wet bulb conditions is the psychrometer equation, which is a simple linear formula that gives vapour pressure directly:

$$p = p_{wb} - AP\left(T - T_{wb}\right) \tag{6}$$

A is entitled the psychrometer constant or coefficient; quoted values of A range between 6.4×10^{-4} and $6.8 \times 10^{-4}\ \mathrm{^\circ C^{-1}}$ for the air–water system at near-ambient temperature and pressure for various types of psychrometer. A commonly used value has been $6.66 \times 10^{-4}\ \mathrm{^\circ C^{-1}}$. Sonntag (1990) [1] gave a formula for Assmann psychrometers based on experimental data, valid for t_{wb} up to 50 °C:

$$A = 6.53 \times 10^{-4}\ (1+0.000\ 944 t_{wb}) \tag{7}$$

This formula assumes that enhancement factor has been applied to the vapour pressures p and p_{wb}; if pure vapour pressures have been used for both, the first term becomes 6.50×10^{-4}.

From the theory of psychrometrics, a formula for A can be derived, which allows its dependence with temperature to be predicted and also allows it to be extended to non air–water systems:

$$A = \frac{M_g C_s}{M_y \beta \lambda_{wb}} \tag{8}$$

Conduction and radiation have a significant effect in actual psychrometers, with 5 % to 10 % additional heat transfer altering the value of A by up to 2 %. Thus the psychrometric coefficient β is evaluated as about 1.1 based on physical properties and pure convection, but for all practical purposes it should be taken as 1, allowing for conduction and radiation. Also, the psychrometer formula breaks down at high humidities and wet-bulb temperatures approaching the boiling point, and A tends to zero. However, in this region, large errors in A have little effect on the calculated wet-bulb temperature t_{wb} as it is close to the dry-bulb temperature t.

4.9.6 *Psychrometric charts*

Psychrometric charts are plots of a number of useful psychrometric quantities, including temperature, mixing ratio, saturation humidity, relative humidity, enthalpy and adiabatic saturation temperature. They provide a simple and visual way of making a rough estimate of these parameters. Charts are specific to a given vapour–gas system and to a particular total pressure; most published charts are for air–water at one atmosphere. For accurate calculations, it is now more convenient to use computer programs such as that supplied as BS 1339-2.

4.10 Some common humidity calculations

Table 4 gives the steps required to perform the most common humidity calculations. These calculations may be performed automatically using the spreadsheet supplied with BS 1339-2.

Table 4 — Calculation methods for various humidity parameters

	Known	Required	Method
i.	T, T_{wb}	Y	Find saturation vapour pressure p_{wb} at wet bulb temperature T_{wb} from Sonntag (equation 1). Find actual vapour pressure p at dry bulb temperature T from psychrometer equation (6). Find mixing ratio Y by conversion from p (Table 2).
ii.	T, T_{wb}	T_{dp}, d_v	Find p if necessary by method (i) above. Find dew point T_{dp} from Sonntag [1] by calculating the T corresponding to p (iteration required; Antoine equation (2) gives a first estimate). Calculate volumetric humidity d_v using equation (5).
iii.	T, T_{wb}	%rh (ψ)	Use method (i) to find p. Find saturation vapour pressure p_s at T from Sonntag [1]. Now %rh = $100p/p_s$.
iv.	T, %rh	Y, d_v	Find saturation vapour pressure p_s at T from Sonntag (1). Actual vapour pressure $p = p_s$(%rh/100). Convert to Y (Table 2). Find d_v from equation (5).
v.	T, %rh	T_{wb}	Use method (iv) to find p and Y. For air–water system, estimate T_{wb} initially by finding adiabatic saturation temperature T_{as} using the formulae in Part 1 or a psychrometric chart. Find p_{wb} from psychrometer equation (6). Calculate new value of T_{wb} corresponding to p_{wb} by reversing equation (1). Repeat last two steps to solve iteratively for T_{wb} (computer program is preferable method).
vi.	T, T_{dp}	Y, %rh	Find saturation vapour pressure at dew point T_{dp} from equation (1); this is the actual vapour pressure p. Find Y from Table 2. Find saturation vapour pressure p_s at dry-bulb temperature T from (1). Now %rh = $100p/p_s$.
vii.	T, Y	T_{dp}, d_v, %rh, T_{wb}	Find p by conversion from Y (Table 2). Then use methods (ii), (iii) or (v) as appropriate.
viii.	T, d_v	Y	Find specific humidity Y_W from equation (5). Convert to mixing ratio Y using formula in Table 2.
ix.	T_{dp} at P_1 (elevated)	T_{dp} at P_2 (ambient)	Find vapour pressure p_1 at T_{dp} and P_1 from equation (1), ensuring that the enhancement factor is applied. Convert to vapour pressure p_2 at new pressure P_2 by the formula $p_2 = p_1P_2/P_1$. Find new dew point T_{dp} from (1) by calculating the T corresponding to p_2 (iteration required as in (ii)).

KEY

T = dry bulb temperature
T_{wb} = wet bulb temperature
T_{dp} = dew point temperature
Y = mixing ratio
d_v = volumetric humidity
%rh = ψ = relative humidity

Methods (i) to (iii) are used to find the humidity and dew point from temperature readings in a wet-and-dry-bulb psychrometer.

Methods (iv) and (v) are used to find the humidity, dew point and wet-bulb temperature from a relative humidity measurement at a given temperature.

Method (vi) gives the absolute and relative humidity from a dew point measurement.

Method (vii) allows the calculation of all the main parameters if the mixing ratio is known, e.g. from a mass balance on a process plant.

Method (viii) converts the volumetric form of absolute humidity to the mass form (mixing ratio).

Method (ix) allows the dew point measured in a compressed air duct to be converted to the dew point at atmospheric pressure, from which the humidity can be calculated. The basis is that the mole fraction $y = p/P$ is the same for a given mixture composition at all values of total pressure P. It is necessary to check that the temperature change associated with compression or expansion does not bring the dry-bulb temperature to a point where condensation can occur.

5 Significance of temperature and pressure for humidity measurement

5.1 The effects of temperature on humidity measurement

The effect of temperature on relative 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. It is therefore very important to consider the temperature effects carefully when relative humidity is the parameter of interest. See **A.1** for examples of effects of temperature on humidity measurements. Volumetric humidity is also affected significantly by temperature.

5.2 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 can have an effect on the measured humidity. Throughout this British Standard, the values of pressure are given in absolute terms (atmospheric pressure being 101 325 Pa, or 1 013 mbar), and not in "gauge" pressures (where atmospheric pressure would have a value of zero). See **A.2** for examples of effects of pressure on humidity measurements.

6 Introduction to methods for measuring humidity

6.1 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). The method of calculation and tables of figures are given in BS 1339-2.

6.2 Operating principles of various hygrometers

6.2.1 *General*

Humidity influences a vast range of physical, chemical and biological processes. It follows from this that there are many kinds of humidity-related effects that can be exploited to indicate changes in humidity. Descriptions of some of the most important methods for measuring humidity are given in **6.2.2** to **6.2.9**.

6.2.2 *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.

6.2.3 *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 and a set of look-up tables are given in BS 1339-2. 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 airflow over the thermometers should be used for this measurement. Other approaches, such as Mason's (non-aspirated) psychrometers and whirling (hand-aspirated) psychrometers, are less successful realizations of this principle and are prone to errors, as are "home-made" psychrometers.

6.2.4 *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, although response times are faster without this protection. Impedance hygrometers are usually also fitted with a temperature sensor. Readings on impedance hygrometers 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.

a) 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 can shift as a result.

b) 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 that use electrolysis as the sensing mechanism (see **6.2.7**).

c) Dew point type impedance sensors are a special case of impedance hygrometer, used to measure in absolute units rather than relative humidity. Following a 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.

6.2.5 *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.

6.2.6 *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.

6.2.7 *Electrolytic (phosphorus 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" (**6.2.4**b)) for another sensing method known by this description.)

6.2.8 *Spectroscopic*

In general, a spectroscopic technique is one where the composition of a material 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 infra-red 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 infra-red absorbance. Water absorbs infra-red 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 ionization mass spectrometry), FT-IR (Fourier-transform infra-red spectroscopy), and TDLAS (tunable diode laser absorption spectroscopy).

6.2.9 *Colour change*

Certain humidity indicators 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 that change colour according to the humidity of the gas.

6.2.10 *Others*

The list above is far from exhaustive. Other methods that 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 ultraviolet 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 sub-clause also lend themselves to measurement of moisture content in solids and liquids.

Table 5 gives a simplified overview of some of the features of the main hygrometer types. It gives broad indications of the properties of different measuring methods. The notes in brackets give additional information, or list features, that 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 can perform a little better than suggested here. In other cases, they can 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 Clause **7**.

Table 5 — 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[b] (bracketed ratings after cleaning)	Sampling, configuration	Guideline best humidity uncertainty in use[c] (±)
		Humidity	Temperature[a]				
Mechanical	R	20 %rh to 80 %rh	Near room temperature	%rh	* * *	Whole immersion	5 % rh to 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 %rh to 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% rh to 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 %rh to 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 °C to 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 °C to 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 °C to 4 °C
Electrolytic (phosphorous pentoxide)	A	Below 1 ppm_V to 1 000 ppm_V	Near room temperature	ppm_v, or vapour pressure	*	Sample gas flow	3 to 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 to 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 %rh to 20 %rh

[a] 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.

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

[c] 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 **9.4** for more information on uncertainty of measurement.

7 Selection of a type of hygrometer

7.1 Identifying measurement needs

7.1.1 *General*

To ensure fitness for purpose, it should be clear first of all what is the purpose is. 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 issues indicated in Clause **7** and then consult Table 5, which is intended to help with selection.

7.1.2 *Measurements required*

7.1.2.1 *What is to be measured*

Which unit or scale of measurement is required? 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 that 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.

7.1.2.2 *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 might have to be applied to the results if the pressure varies.

7.1.2.3 *Performance*

It is worth deciding if any performance characteristics are particularly important for the application in question. There might be a need to set criteria for sensitivity, stability (in terms of repeatability or reproducibility), uncertainty, response time, resolution, linearity or hysteresis).

7.1.2.4 *Output, readout*

The humidity result might simply be shown as a number on a digital display, or on a numbered scale. It might be given as an electrical voltage or current signal (analogue output) or as a digital signal (serial communication) for data transmission to another site. Several parameters or units of humidity might be shown or transmitted, including temperature. Data might be given continuously or at intervals. The instrument might record data in an internal or external data logger or, less frequently now, on a paper chart. Alternatively, humidity values might need to be hand-calculated from indirect results such as temperature readings. These alternatives might need to be considered when selecting an instrument.

7.1.3 *Instrument format and usage*

7.1.3.1 *General*

It is advisable to consider technical properties of an instrument, such as configuration, method of sampling, carrier gas to be used, materials of construction, ease of use, intrinsic error detection and any need to use the instrument for process control, or in hazardous areas, bearing in mind some of the following features.

7.1.3.2 *Configuration*

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

7.1.3.3 *Sampling*

Sampling is an important issue in all humidity measurement and is discussed in some detail in **8.1.2**. The sampling approach might be that of immersion, where the instrument sits wholly or partly in the environment to be measured; or the gas might be sampled by extracting a sample of it into 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 should be taken with certain types of hygrometer that can themselves affect the environment, by giving off either water or heat. Indeed any instrument introduced at the wrong temperature will influence its environment, thus affecting the measurement result. Conversely, moisture and heat from the operator's body can affect measurements using hand-held hygrometers.

7.1.3.4 *Type of gas*

In gases other than air, chemical compatibility can be an issue. Calibration specific to the gas in question might be required.

7.1.3.5 *Materials of construction*

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

7.1.3.6 *Ease of use*

Some hygrometers are straightforward to use. Others require some skill.

7.1.3.7 *Error detection*

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

7.1.3.8 *Use for control or monitoring*

In some cases the user simply needs to measure humidity. In other cases, 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.

7.1.3.9 *Hazardous areas*

In areas where there is some hazard, such as an explosive atmosphere, suitable precautions should be taken. For example, extraction of sample gas to remote probes might 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 reference to EU Directive 94/9/EC [4] should be made.

7.1.3.10 *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 might give no more than a very indirect indication of the actual moisture content, though equilibrium relative humidity (ERH) and water activity are proper indications in a different way of the condition or equilibrium of materials with the environment.

7.1.4 *Cost and upkeep*

7.1.4.1 *General*

It may be advisable to consider the following practical issues relating to cost, calibration, robustness, quality reliability and lifespan, versatility, interchangeability, need for maintenance availability of spare parts, and after-sales service.

7.1.4.2 *Cost*

Some methods of measurement are more expensive than others, and the most expensive method might not be the best for a particular application. When comparing different prices for the same type of instrument, variations in price might reflect the provision of special features, or might 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.

7.1.4.3 *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. See also **9.4.5**.

7.1.4.4 *Robustness*

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

7.1.4.5 *Quality, reliability, lifespan*

Quality is not always easy to judge. Aside from general impressions, compliance with a quality accreditation standard such as one of the BS EN ISO/IEC 17025 series may be some indication. Recommendations from other users might be a good guide to hygrometer selection. Some types of hygrometer tend to have a long lifespan; others less so.

7.1.4.6 *Versatility*

If more than one application is envisaged, the adaptability of the hygrometer should be borne in mind.

7.1.4.7 *Interchangeability*

It has been the custom for the sensor and the processing electronics, often called the secondary electronics, to be separate components; each being independently replaceable. It should be considered how interchangeable the instruments or components really are. Interchangeability is best checked by calibration against a consistent reference. However, replacing a key component of an instrument might invalidate its previous calibration.

It is increasingly the practice for humidity instruments to be a single unit so that the calibration issues are simplified.

7.1.4.8 *Maintenance*

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

7.1.4.9 *Availability of spares*

The local and speedy availability of spare parts should be checked, and whether they can be fitted by the user. Any consumable supplies, such as charts, should be available and clearly coded or identified, as they are not always interchangeable.

7.1.4.10 *After-sales service*

The availability of a warranty, or of a good maintenance or service contract can be a factor in the decision.

7.2 British and International Standard specifications

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

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

— BS 2842:1992, *Specification for whirling hygrometer*.
— BS 5248:1990, *Specification for aspirated hygrometer*.

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.)

8 Recommended practices in humidity measurement

8.1 General practical recommendations

8.1.1 *Humidity measurement*

The following should be considered.

a) 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.

b) Establish the measurement requirements at the selection stage in order to have the right hygrometer for the job.

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

d) Follow the manufacturer's care instructions for the hygrometer. Some hygrometers 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.

e) Seek traceable calibrations through laboratories accredited to UKAS or equivalent schemes.

f) 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, airflow, etc.

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

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

i) 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, for example ordinary urban pollution.

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

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

8.1.2 *Sampling*

The following should be considered.

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

b) 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 should be taken to where measurements are made in order to obtain a representative result.

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

d) Hygroscopic materials should be avoided in the construction of sampling systems. 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.

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

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

g) 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.

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

i) 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.

j) 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.

8.1.3 *dew point*

The measuring environment and all parts of the sampling pathway should 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 should 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.

8.1.4 *Relative humidity*

Due care should be taken of temperature. See **5.1** and other guidance throughout this part of BS 1339.

Care should 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

8.2.1 *Ambient humidities*

Avoid using hygrometers near the operator's body, which is a source of heat and moisture. Do not breathe so close to the measurement apparatus that it affects the measurement.

8.2.2 *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 and care should be taken with cold spots and breaks in the insulation.

8.2.3 *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. 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. Polytetrafluorethylene (PTFE) is only slightly permeable and will usually be satisfactory for dew points above –20 °C, and sometimes below this level. Materials such as polyvinylchloride (PVC) and rubber are relatively permeable and so are 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, such as analytical reagent (AR) quality solvents for oil-based contaminants, and purified water (distilled or deionized) 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 minimized by using the narrowest tubing that the flow conditions will permit.

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

Adequate flow of the gas sample should be ensured, to minimize 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 minimized, 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.

9 Performance and calibration

9.1 Uncertainty of measurement

There is always some uncertainty associated with any measurement result. The uncertainty of a measurement is defined as the parameter characterizing 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 that should be estimated.

Further reading is recommended in "*A Beginners Guide to Uncertainty of Measurement*" NPL, [5], in the ISO "*Guide to the expression of uncertainty in measurement*" [6], and in other of the references listed in the Bibliography.

9.2 Calibrations and traceability

Some humidity parameters (e.g. dew point) are realized 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 recognized conversions or tables (See BS 1339-2). On the basis of traceable measurements of dew point and temperature, values of relative humidity can 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. It should be recognized that the results of the equations in BS 1339 Parts 1 and 2 are theoretical and will be compared with data from instruments and calibration procedures which will depart from ideal in some way. Calibration procedures and instruments will be affected by heat flows that will arise from a mixture of conduction, convection and radiation. In practice, this means that practical instruments used in industry should be calibrated for the intended function.

9.3 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 on site, where they are to be used. 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 and non-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.

9.4 Practical methods of laboratory calibration

9.4.1 *General*

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.

9.4.2 *Humidity generation*

The main methods of humidity generation are as follows.

a) *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 close to the temperature of the saturator.

b) *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.

c) *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.

d) *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.

e) *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 **9.4.3** on salt solutions.)

f) *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.

g) *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.

h) *Diffusion and permeation tubes*. Water vapour diffusing at a constant rate through a membrane or an orifice can be combined with flowing (dry) gas to produce a defined value of moisture content.

Used appropriately, any of the these methods can provide a stable humidity for use in comparing one hygrometer with another (calibrated) one. This might 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.

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.

9.4.3 *Calibration using salt solutions*

Salt solutions generate characteristic values of relative humidity that 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, and hence a constant relative humidity, is maintained, 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 UKAS 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 **9.4.2**). Values of humidity generated over saturated solutions of various salts are shown in the following Table 6.

The values listed in Table 6 are taken from papers by Greenspan (1976) [7], O'Brien (1948) [8], Wexler (1954) [9] and Young (1967) [10]. 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 can 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.

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. Stabilization after a change in temperature may take an hour, or many hours, depending on the size of the change. For freshly mixed solutions, full stabilization 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, can provide only very approximate values of humidity, and can degrade quickly. Unsaturated solutions also generate atmospheres of relative humidity, but since their concentration gradually changes with repeated use, so does the generated humidity. However, unsaturated solutions have the significant advantage that they can be used to produce any desired relative humidity whereas saturated salt solutions are confined to a single, often inconvenient, fixed value.

Table 6 — 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 % rh										
Potassium sulfate	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 sulfate	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

9.4.4 *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 characterized 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, airflow, 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. This is because the ratio of molecular masses of water and air, for instance, is about 0.62, whereas the ratio for water and 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.

9.4.5 *Calibration intervals*

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

a) type of instrument;

b) manufacturer's advice;

c) required accuracy in use;

d) severity of conditions of use;

e) history of past stability or drift;

f) frequency of checks against other hygrometers (preferably stable ones);

g) maintenance in between calibrations;

h) cost of calibrations;

i) importance of avoiding incorrect results.

Until a record of performance has been built up, initial choice of calibration intervals may be based on a) to d) in this 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: six to 12 months after first calibration and thereafter every one to two years, depending on requirements;

— moderately stable hygrometer types, e.g. electrical relative humidity instruments, perhaps six months after first calibration. Thereafter, every six to 12 months, depending on requirements.

— Less stable hygrometer types e.g. aluminium oxide hygrometers, every six 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 irrespective of the frequency of calibrations.

Annex A of BS EN 30012-1:1994 discusses confirmation intervals in more depth.

9.5 Other issues

9.5.1 *International recognition and acceptability*

National standards for humidity, and national measurement accreditation schemes, exist in many countries. 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 formalized through the body EA (European cooperation for Accreditation).

9.5.2 *Bypassing traceability: fundamental measurements*

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

9.5.3 *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 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 might be acceptable for the extreme part of the range. In this situation, the associated uncertainties might 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 recognized documented procedure might 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 might 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.

9.5.4 *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 %rh 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 should be remembered that compliance with a specification means that the reading together with the uncertainty in the measurement should fall within the specified band (not just the reading itself).

In some cases, compliance with a specification can be established unambiguously, when the result together with its uncertainty (at a given level of confidence) lie entirely within a specified band or range of values. In other cases, failure to comply may be clear, when the result together with its uncertainty lie entirely outside a specified band. However, there can intermediate cases where the uncertainty partly overlaps the specified band. In this situation, there is no clear "pass" or "fail" outcome, but some probability of compliance, depending broadly on the degree of overlap.

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.

Annex A (informative)
Examples of the effects of temperature and pressure on humidity measurement

A.1 Temperature and instruments

A.1.1 *General*

All hygrometers have some temperature dependence. In some instruments (such as well-designed psychrometers and condensation hygrometers) the effects can be small, but this is not always true. In instruments that 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.

A.1.2 *Temperature and condensation*

One common cause of error in humidity measurement is the occurrence of unwanted condensation. Condensation can occur at cold spots that 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 ought to be kept at a temperature above the maximum dew point, by heating them if necessary.

A.1.3 *Temperature and absorption or desorption of water*

Many materials contain moisture as part of their structure; particularly organic materials, salts, and anything that 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.

A.1.4 *Temperature and saturation vapour pressure of water*

The saturation vapour pressure of water depends strongly on temperature. Near room temperature, the capacity of the air to hold water vapour doubles for every 10 °C increase in temperature. This capacity 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. Comprehensive figures are given in BS 1339-2.

A.1.5 *Temperature and relative humidity*

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

$$\psi = \frac{100p}{p_\mathrm{s}} \tag{1}$$

where

ψ is the relative humidity, expressed as a percentage (%);

p is the water vapour pressure;

p_s is the saturation vapour pressure at the prevailing ambient temperature.

At room temperature, a change in dew point of 1 °C corresponds approximately to a change in relative humidity of 6 % 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.

Similarly, a change of 1 °C in the measurement of the ambient temperature has almost exactly the same significance. The magnitude of the effect under different conditions is illustrated in Table A.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 A.1 — Approximate effect of a temperature change of ±1 °C on relative humidity at various existing temperatures and relative humidity levels

Existing relative humidity	Change in relative humidity				
	At 10 °C	At 20 °C	At 30 °C	At 50 °C	At 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
NOTE The change in the relative humidity levels is not symmetric, i.e. an increase or decrease in temperature give opposite but not exactly equal changes in relative humidity.					

A.1.6 *Temperature measurement in air*

A thermometer indicates its own temperature. It is important to be aware of this because a thermometer might not always be at the same temperature as its surroundings. The temperatures of other objects near to the thermometer can influence the measurement indicated by it. Thermometers can also suffer from time lags, and self-heating errors can affect electrical resistance thermometers. This is particularly true when a measurement is undertaken in air, as opposed to 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 in Table A.1.

A.2 The effects of pressure on humidity measurement

A.2.1 *General*

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:

$$P_{\text{total}} = p_{\text{nitrogen}} + p_{\text{oxygen}} + p_{\text{water}} + p_{\text{others}} \tag{2}$$

where

p is the partial pressure

It therefore follows that if any of the partial pressures of the component gases varies, then the total pressure P_{total} will vary accordingly. Also, if the total system pressure is changed either by compression or expansion, each of the component partial pressures will change 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. Some simple examples showing the effect of pressure change are given in **A.2.2** to **A.2.5**.

A.2.2 *Effect of doubling pressure on a relative humidity of 40 %rh*

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 same rule applies for other measures of concentration in terms of mass per unit volume, such as absolute humidity ($\text{g}\cdot\text{m}^{-3}$).

A.2.3 *Effect of doubling system pressure on mixing ratio*

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 the same 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.

A.2.4 *Effect of doubling system pressure on dew point temperature*

The dew point temperature of a system is directly related to the water vapour pressure of that system. From equation (2) in **A.2.1** it can be seen that a doubling of total pressure P_{total} will yield a doubling of the water vapour pressure, p_{water}.

For example, for a system of pure water vapour with a dew point of +10 °C, the water vapour pressure is about 1 228 Pa. If the system pressure is doubled, the resultant water vapour pressure will be $2\times 1\,228 = 2\,456$ Pa, which equates to a dew point temperature of about +20.8 °C (see BS 1339-2).

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 **A.2.5**).

A.2.5 *Water vapour enhancement factor*

The examples in **A.2.2** to **A.2.4** assume that all the component gases exhibit “ideal gas” behaviour. In practice a small, pressure-dependent correction might be required, which is called 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.

Tables or equations giving the saturation vapour pressure of water are usually valid 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.

Bibliography

This Part of BS 1339 is based on *A Guide to the Measurement of Humidity* published by the Institute of Measurement and Control, produced by the National Physical Laboratory and sponsored by the DTI's National Measurement System Policy Unit.

Standards publications referenced in the text

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

BS 2842:1992, *Specification for whirling hygrometer*.

BS 5248:1990, *Specification for aspirated hygrometer*.

BS EN 30012-1:1994, *Quality assurance requirements for measuring equipment — Part 1: Metrological confirmation system for measuring equipment*.

BS EN ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*.

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

Other publications referenced in the text

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[10] YOUNG, J.F. Humidity control in the laboratory using salt solutions – a review. *Journal of Applied Chemistry* 1967, **17**, 241-245.

Background reading

The background reading lists below are categorized 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. The texts listed are recommended starting points and these, in turn, carry references to much other useful reading material.

Many organizations 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.

Standards publications

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*.

BS 2842:1992, *Specification for whirling hygrometer*.

BS 5248:1990, *Specification for aspirated hygrometer*.

BS 5844:1980 (1987), *Methods of measurement of fluid flow: estimation of uncertainty of a flow-rate measurement*. [ISO 5168:1978]

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

BS EN ISO 17025:2000, *General requirements for the competence of testing and calibration laboratories*.

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

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

BS 5781-1:1992, *Quality assurance requirements for measuring equipment — Part 1: Metrological confirmation system for measuring equipment* [ISO 10012-1:1992].

General (easy) reading on humidity measurement

A Guide to the Measurement of Humidity. The Institute of Measurement & Control. ISBN 0-904457-24-9.

PRAGNELL, R.F. Measuring humidity in normal ambient environments. Proceedings of *Electronic environmental monitoring in museums*. National Museum of Wales. Edited by R.E. CHILD. 1992.

METEOROLOGICAL OFFICE. *Handbook of Meteorological Instruments*. Vol 3, *Measurement of humidity*. 2nd ed. London: TSO. 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

SONNTAG, D. Advancements in the field of hygrometry. *Meteorologische Zeitschrift, N.F.* April 1994, **3**, 51-66. (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, ISA. ISBN 0-87664-865-0 (Over 100 technical papers covering developments in all aspects of humidity measurement.)

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

In-depth reading

Particular humidity techniques or applications:

DADACHANJI, F. Humidity measurement at elevated temperatures, *Measurement and Control*. March 1992, **25**.

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

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

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

Sources of reference data

1993 and 1997 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*. 16th ed. Harlow: Longman. ISBN 0 582 22629 5. (Sections 2.1.4 and 3.4.1. cover humidity.)

GREENSPAN, L. Humidity fixed points of binary saturated aqueous solutions. *Journal of Research of the National Bureau of Standards*. 1977, **81A**(1). 89-96.

HARDY, R. *ITS-90 Formulations for Vapor Pressure, Frostpoint Temperature, Dewpoint Temperature and Enhancement Factors in the range – 100 °C to + 100 °C*. Proceedings of 3rd International Symposium on Humidity and Moisture, Teddington, England: April 1998.

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)

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.

KERLIN, T.W. and SHEPHERD, R.L. *Industrial temperature measurement. Instrument Society of America, 1982.* (Strong industrial flavour, good treatment of thermocouples, and response times of thermometers.)

McGEE, T.D. *Principles and methods of temperature measurement*. Chichester: Wiley, 1988.

MICHALSKI, L., ECKERSDORF, K. and McGHEE, J. *Temperature Measurement*. Chichester: Wiley, 1991. ISBN 0 471 93803 3.

NICHOLAS, J.V. and WHITE. D.R. *Traceable Temperatures: An Introduction to Temperature Measurement and Calibration.* Chichester: Wiley, 1994.

Temperature, its Measurement and Control in Science and Industry. Vol 7, 2002. Vol 6, 1992. American Institute of Physics, New York, (Collections of research papers, proceedings of ten-yearly international symposia, important reference for thermometry, covering all aspects from theory to everyday practice)

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

UKAS publication LAB 7. *Traceability of temperature: Platinum resistance thermometers, thermocouples, liquid-in-glass thermometers and radiation thermometers.*

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: TSO. (Practical emphasis, though technology is outdated, and discussions of accuracy optimistic by modern standards.)

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

Useful reading not specific to humidity

BELL, R.J., ed. SI: *The International System of Units* (SI) *(Official English Translation of the International Bureau of Weights and Measures (BIPM) text*. Le systeme international d'unites). 7th edition, 1998.

CHATFIELD, C. *Statistics for technology*. 3rd ed. (1983) London:Chapman and Hall, 1983. (General textbook on statistics.)

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *International vocabulary of basic and general terms in metrology*. 2nd ed., Geneva: ISO, 1993. (Geneva: International Organization for Standardization). ISBN 92-67-01075-1. (International definitive text on terms used in measurement.)

UKAS Publication NIS 3003. *The Expression of Uncertainty and Confidence in Measurement* Edition 1, 1977.

Useful addresses

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

European Cooperation for Accreditation of Laboratories (EA), 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), 21–47 High St., Feltham, Middlesex TW13 4UN.

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