

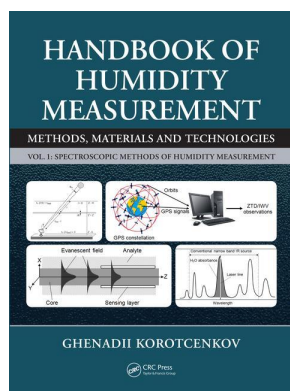
This article was downloaded by: 10.2.97.136

On: 03 Dec 2023

Access details: *subscription number*

Publisher: *CRC Press*

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: 5 Howick Place, London SW1P 1WG, UK



## **Handbook of Humidity Measurement Methods, Materials and Technologies: Spectroscopic Methods of Humidity Measurement**

Ghenadii Korotcenkov

### **Water, Water Vapors, and Humidity**

Publication details

<https://test.routledgehandbooks.com/doi/10.1201/b22369-1>

Ghenadii Korotcenkov

**Published online on: 26 Mar 2018**

**How to cite :-** Ghenadii Korotcenkov. 26 Mar 2018, *Water, Water Vapors, and Humidity from: Handbook of Humidity Measurement, Methods, Materials and Technologies: Spectroscopic Methods of Humidity Measurement* CRC Press

Accessed on: 03 Dec 2023

<https://test.routledgehandbooks.com/doi/10.1201/b22369-1>

**PLEASE SCROLL DOWN FOR DOCUMENT**

Full terms and conditions of use: <https://test.routledgehandbooks.com/legal-notices/terms>

This Document PDF may be used for research, teaching and private study purposes. Any substantial or systematic reproductions, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The publisher shall not be liable for an loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

---

# 1 Water, Water Vapors, and Humidity

## 1.1 WATER AND WATER VAPORS

Water is a special substance (Cracolice and Edward 2006; Petrucci et al. 2017). Water makes the Earth unique. Water covers 71% of the Earth's surface. It is vital for all known forms of life. Life, the climate, and the weather all exist as they do because gaseous, liquid, and solid forms of water can coexist on the planet. Water is a transparent and nearly colorless chemical substance that is the main constituent of Earth's streams, lakes, and oceans, and the fluids of most living organisms. Its chemical formula is  $H_2O$ , meaning that its molecule contains one oxygen and two hydrogen atoms, that are connected by covalent bonds. Figure 1.1 shows the schematic of water molecule, whereas Table 1.1 shows some of its properties. As the water molecule is not linear and the oxygen atom has a higher electronegativity than hydrogen atoms, it is a polar molecule, with an electrical dipole moment: the oxygen atom carries a slight negative charge, whereas the hydrogen atoms are slightly positive. On account of its polarity, a molecule of water in the liquid or solid state can form up to four hydrogen bonds with neighboring molecules. This attraction explains many of the properties of water, such as solvent action (Campbell and Farrell 2007).

Although hydrogen bonding is a relatively weak attraction compared to the covalent bonds within the water molecule itself, it is responsible for a number of water's physical properties (Cracolice and Edward 2006; Petrucci et al. 2017). These properties include its relatively high melting and boiling point temperatures: more energy is required to break the hydrogen bonds between water molecules. In contrast, hydrogen sulfide ( $H_2S$ ) has much weaker hydrogen bonding because of sulfur's lower electronegativity.  $H_2S$  is a gas at room temperature, in spite of  $H_2S$  having nearly twice the molar mass of water. Water is one of the few known substances whose solid form is less dense than the liquid. The extra bonding between water molecules also gives liquid water a large specific heat capacity. This high heat capacity makes water a good heat storage medium (coolant) and heat shield. On account of their polarity, water molecules are strongly attracted to one another, which

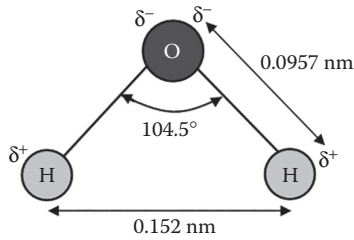
gives water a high surface tension. The molecules at the surface of the water *stick together* to form a type of *skin* on the water, strong enough to support very light objects. Insects that walk on water are taking advantage of this surface tension. Surface tension causes water to clump in drops rather than spreading out in a thin layer. It also allows water to move through plant roots and stems and the smallest blood vessels in your body—as one molecule moves up the tree root or through the capillary, it *pulls* the others with it. Water also has an exceptionally high heat of vaporization. Water's heat of vaporization is 41 kJ/mol.

Pure water containing no exogenous ions is an excellent insulator, but not even *deionized* water is completely free of ions. Water undergoes autoionization in the liquid state, when two water molecules form one hydroxide anion ( $OH^-$ ) and one hydronium cation ( $H_3O^+$ ). As water is such a good solvent, it almost always has some solute dissolved in it, often a salt. If water has even a tiny amount of such an impurity, then it can conduct electricity far more readily.

It is important that the air around us always has some content of water vapor and this content can be varied in wide range (Wexler 1965). For example, atmospheric humidity ranges from nearly 0% to more than 4% of the mass of air, making it the third most common atmospheric constituent. Other gases presented in atmosphere are listed in Table 1.2. However, it is necessary to take into account that since air is seldom totally without water vapor, the above-mentioned percentages change depending on the amount of water vapor that is mixed with other gases.

Like other gases, water vapor can be considered to behave as an ideal gas, except its behavior near saturation. However, in average environmental conditions, water can also be presented in the liquid and solid phases. Therefore, usually we speak of water vapor instead of water gas.

Whether one likes it or not, water and water vapor can be found everywhere (Visscher 1999). On account of the asymmetrical distribution of their electric charge, water molecules are easily adsorbed on almost any surface, where they are present as a mono- or multimolecular



**FIGURE 1.1** Schematic of the  $\text{H}_2\text{O}$  molecule. (Reprinted from *Sens. Actuators A*, 233, Sikarwar, S. and Yadav, B.C., Opto-electronic humidity sensor: A review, 54–70, Copyright 2015, with permission from Elsevier.)

**TABLE 1.1**  
**Some Properties of  $\text{H}_2\text{O}$  Molecule**

Property	Value
H–O–H angle	104.5°
OH–bond length	0.957 Å
Molar weight	18.01528
Molecule size	~2.8 Å
OH–dissociation energy	498 kJ/mol (5.18 eV)
Dipole moment	$6.17 \times 10^{-30}$ C·m (1.85 D)

**TABLE 1.2**  
**Gases Present in Standard Amounts in a Dry Atmosphere**

Constituent	Volume Ratio (%)	Parts per Million
Nitrogen, $\text{N}_2$	78.084	780,840
Oxygen, $\text{O}_2$	20.946	209,460
Argon, Ar	0.934	9340
Carbon dioxide, $\text{CO}_2$	0.0314	314.0
Neon, Ne	0.001818	18.18
Helium, He	0.000524	5.24
Methane, $\text{CH}_4$	0.00016	1.6
Krypton, Kr	0.000114	1.14
Hydrogen	0.00005	0.5
Nitrous oxide, $\text{N}_2\text{O}^a$	0.00005	0.5

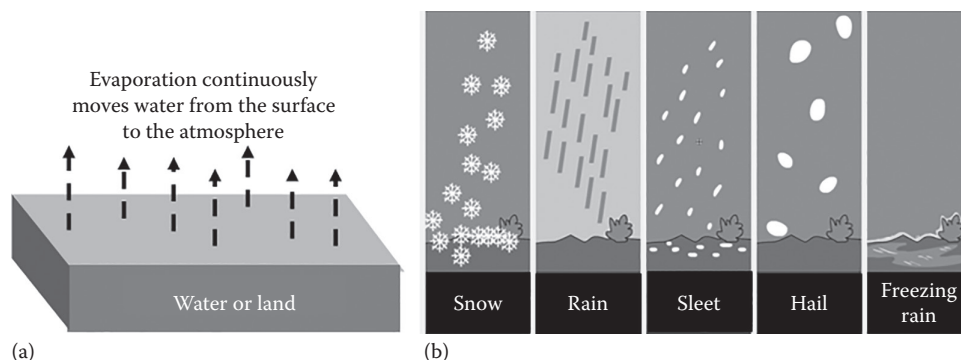
Source: Smith, F.G. (Ed.), *Atmospheric Propagation of Radiation*. Volume 2 of *The Infrared & Electro-Optical Systems Handbook*, J.S. Accetta, D.L. Shumaker (Eds.), Infrared Information Analysis Center, Ann Arbor, MI; SPIE Optical Engineering Press, Bellingham, Washington, DC, 1993.

<sup>a</sup> Has varying concentration in polluted air.

layer of molecules. Therefore, the American Heritage Dictionary defines humidity as: dampness, especially of air. Usually, water vapor in the air or any other gas is called humidity, in liquids and solids; it is generally designated as moisture.

Water and water vapor in the environment are constantly involved in various processes such as evaporation (Figure 1.2a), sublimation, condensation, and deposition. Whenever a water molecule leaves a surface and diffuses into a surrounding gas, it is said to have evaporated. Each individual water molecule, which transitions between a more associated (liquid) and a less associated (vapor/gas) state does so through the absorption or release of kinetic energy. The aggregate measurement of this kinetic energy transfer is defined as thermal energy and occurs only when there is differential in the temperature of the water molecules. Liquid water that becomes water vapor takes a parcel of heat with it, in a process called evaporative cooling. The amount of water vapor in the air determines how fast each molecule will return to the surface. When a net evaporation occurs, the body of water will undergo a net cooling directly related to the loss of water. Sublimation is another form of evaporation; water molecules become gaseous directly, leaving the surface of ice without first becoming liquid water. Sublimation accounts for the slow mid-winter disappearance of ice and snow at temperatures too low to cause melting. Condensation is the reverse process of evaporation. Water vapor will only condense onto another surface when that surface is cooler than the dew point temperature (Section 1.2), or when the water vapor equilibrium in air has been exceeded. When water vapor condenses onto a surface, a net warming occurs on that surface. The water molecule brings heat energy with it. In turn, the temperature of the atmosphere drops slightly. In the atmosphere, condensation produces clouds, fog, and precipitation (Figure 1.2b). Fog and clouds form through condensation around cloud condensation nuclei. In the absence of nuclei, condensation will only occur at much lower temperatures. Deposition is a phase transition separate from condensation, which leads to the direct formation of ice from water vapor. Frost and snow are examples of deposition. Water vapor is totally invisible. If you see a cloud, fog, or mist, these are all liquid water, not water vapor.

The number of variables that interact and affect the humidity levels in the environment are myriad. Changes in the water vapor content in the atmosphere not only varies with the time of day and latitude but also is affected by seasonal changes. The amount of water vapor in air depends also on the temperature of



**FIGURE 1.2** (a) Water evaporation and (b) forms of precipitation. Precipitation can be in the form of rain, snow, sleet, and hail. When water vapor is frozen directly into a solid without first forming a liquid, it forms tiny ice crystals called snow. Sleet is a frozen rain that forms when rain droplets encounter a cold air and freezes into ice before falling from the sky. Hail is the rounded lumps of ice that falls from the sky, whereas rain consists of droplets of liquid water that falls from the sky.

the air. At lower temperatures, very little water vapor can be held in air. At higher temperatures, the amount of water vapor in air increases. At the boiling point of water, the air has reached the maximum water vapor that it can hold, and the excess is condensed into water and seen as steam. This means that air humidity is not a constant value and can significantly change in a short time.

As it will be shown in [Chapter 2](#), water vapor has a significant effect on the properties of the materials. The water molecules presented in air change the length of organic materials, the conductivity and weight of hygroscopic materials and chemical absorbents, and, in general, the impedance of almost any materials. Water absorbs infrared (IR) and ultraviolet radiation. It changes the color of chemicals, the refractive index (RI) of air and liquids, the velocity of sound in air or electromagnetic radiation in solids, and the thermal conductivity of gases and that of liquids and solids. It is probably difficult to find a material that is inert to water molecules and with which it would be impossible, with some physical method to measure the presence of water (Visscher 1999).

In addition, water vapor is key agent in both weather and climate. As it is known, water vapor is the most abundant of all greenhouse gases. Water vapor, like a green lens that allows green light to pass through it but absorbs red light, is a *selective absorber*. Along with other greenhouse gases, water vapor is transparent to most solar energy, as you can literally see. But it absorbs the IR energy emitted (radiated) upward by the Earth's surface, which is the reason that humid areas experience very little nocturnal cooling but dry desert regions cool considerably at night.

As shown by observations and research ([Chapter 2](#)), air humidity affects our security, our living conditions,

our quality of life, and efficiency of industrial production. A huge variety of manufacturing, storage, and testing processes are humidity-critical. All this means that the measurement of humidity and constant monitoring of its change when using various sensors becomes mandatory for meteorological observations and industrial control (Nitta 1981; Fleming 1981a, b; Spomer and Tibbitts 1997; Wiederhold 1997; Rittersma 2002; Srivastava 2012). It should be noted that people began to realize the significance of this process many years ago. Even in the fifteenth century, Leonardo da Vinci built the first device for the air humidity measurement. According to other data, the first hydrometer was invented in the same fifteenth century by German Nicolaus de Cusa. It was a wool gravimetric hygrometer. There is also evidence that the accurate measurement of relative humidity (RH) was a very important activity in ancient China, and that there were dire consequences to those who got their weather predictions wrong. The death penalty was reportedly very easily imposed if it rained during a major ceremonial event! In Japan, the Beard Plant was used in the Edo era to give an indication of RH conditions to maintain product quality in the silkworm industry (Hattingh 2001).

## 1.2 THE MAIN GAS LAWS OF PHYSICS

Before starting discussions concerning humidity, the main ideal gas laws, helping to understand how a humidity level shifts, depending on the environment, will be presented ([Table 1.3](#)). The ideal gas law is the equation of state of a hypothetical ideal gas. It is a good approximation of the behavior of many gases under many conditions.

In [Table 1.3](#),  $P$  is the pressure of the gas;  $V$  is the volume of the gas;  $n$  is the amount of substance of

**TABLE 1.3**  
**The Gas Laws**

Name	Definition	Law
Boyle–Mariotte’s law	“The absolute pressure exerted by a given mass of an ideal gas is inversely proportional to the volume it occupies if the temperature and amount of gas remain unchanged within a closed system” or “At constant temperature, the product of the volume and pressure of a given amount of gas is a constant”	$P = \frac{k}{V}$ or $P \cdot V = k = \text{const.}$
Charles’s law	“When the pressure on a sample of a dry gas is held constant, the Kelvin temperature and the volume will be directly related” or “At constant pressure, the volume of a given quantity of gas is proportional to absolute temperature ( $^{\circ}\text{K}$ ). Or at constant volume, the pressure of a given quantity of gas is proportional to absolute temperature”	$V = q \cdot T$ or $P = j \cdot T$
Dalton’s law of partial pressures	“The total pressure of a mixture of gases is equal to the sum of the pressures that each gas would exert if it were present alone”	$P_t = P_1 + P_2 + P_3 + \dots$
Avogadro’s law	“Equal volumes of gases at the same temperature and pressure contain equal numbers of molecules” <i>Example:</i> one liter of any ideal gas at a temperature of $0^{\circ}\text{C}$ and a pressure of 101.3 kPa, contains $2.688 \times 10^{22}$ molecules	
Volume of a mole of gas at STP	As one liter of gas at STP contains $2.688 \times 10^{22}$ molecules (or atoms in the case of a mono atomic gas), it follows that a mole of gas ( $6.022 \times 10^{23}$ molecules) occupies a volume of 22.4 l at STP	
Ideal gas law	The product of volume and pressure of a given amount of gas is proportional to absolute temperature	$P \cdot V = nRT$
Van der Waals equation	The van der Waals equation (or van der Waals equation of state) is an equation relating the density of gases to the pressure ( $p$ ), volume ( $V$ ), and temperature ( $T$ ) conditions ( <i>i.e.</i> , it is a thermodynamic equation of state). It can be viewed as an adjustment to the ideal gas law that takes into account the nonzero volume of gas molecules, which are subject to an interparticle attraction	$\left(p + \frac{n^2 a}{V^2}\right)(V - nb) = nRT$

gas (also known as number of moles);  $R$  is the ideal, or universal, gas constant, equal to the product of the Boltzmann constant and the Avogadro constant;  $T$  is the absolute temperature of the gas; STP is standard conditions of temperature and pressure;  $a$  is a measure of the average attraction between particles; and  $b$  is the volume excluded by a mole of particles.

While summarizing the data presented in Table 1.3, it turns out that Boyle’s law states that the pressure–volume product is constant, Charles’s law shows that the volume is proportional to the absolute temperature, Gay-Lussac’s law says that the pressure is proportional to the absolute temperature, and Dalton’s law states that all gases make contribution to a total pressure in proportion to their content. Knowledge of these laws is important because the water vapor is one

of several gases that makes up air, and in most cases it behaves as an ideal gas. This means that the water vapors such as nitrogen, oxygen, and other trace gases contribute to the total pressure of the air. The portion that water vapors contribute to the total pressure of the air is called the partial pressure of water vapor. Further it will be shown that the partial pressure of water vapor is a key metric, found as a component in the formulas that define all other humidity parameters. It is important to note that the change in the total pressure of a gas mixture, at constant composition, results in the same change in the partial pressure of each component.

At the end of this section, some important physical thermodynamic constants will be presented. These constants are displayed in Table 1.4.



**TABLE 1.4**  
**Some Physical Constants in Thermodynamics**

Physical Value	Symbol	Unit	Numerical Value
Absolute temperature (IPTS-68)	$T_{68}$	K	$273.15 + T_{68}$
Physical standard temperature	$T_0$	K	273.15
Triple point of water	$T_{tp}$	K	273.16
Physical standard pressure	$p_0$	Pa	101325
Molar standard volume of ideal gas	$V_m = R \cdot T_0 / p_0$	m <sup>3</sup> /mol	0.02241383
Universal molar or ideal gas constant	$R$	J/K·mol	8.3144598
Gas constant of water vapor	$R_w = R/M_v$	J/Kg	0.461520
Molar molecular mass of water	$M_v$	g/mol	18.01528
Gas constant of dry air	$R_a = R/M_a$	J/Kg	0.287055
Molar molecular mass of dry air	$M_a$	g/mol	28.9645
Relation of molecular mass	$\gamma = M_v/M_a$		0.62198
Mass of water molecules	$m_{H_2O} = M_v = N_A$	g	$2.991555 \cdot 10^{-23}$
Avogadro constant	$N_A$	mol <sup>-1</sup>	$6.022045 \cdot 10^{23}$
Loschmidt constant	$N_L = N_A/V_m$	m <sup>-3</sup>	$2.686754 \cdot 10^{25}$
Saturated vapor pressure by triple point	$P_{sw}(T_{tp})$	Pa	611.657

Source: Wernecke, R. and Wernecke, J., *Industrial Moisture and Humidity Measurement: A Practical Guide*, Wiley-VCH, Weinheim, Germany, 2014.

### 1.3 UNITS FOR HUMIDITY MEASUREMENT

Humidity measurement determines the amount of water vapor presents in a gas that can be a mixture, such as air, or a pure gas, such as nitrogen or argon. There are many different ways to express humidity. On the basis of measurement techniques, the most commonly used units for humidity measurement are RH, dew/frost point

(D/F PT), and parts per million (ppm) (Spomer and Tibbitts 1997; Wiederhold 1997; Chen and Lu 2005). Other parameters that can be used to indicate moisture levels are tabulated in [Table 1.5](#).

It should be noted that the humidity can be fully described with a single parameter (any of them) if the gas pressure and temperature are known, but many national

**TABLE 1.5**  
**Terms Relevant to Moisture**

Term	Definition	Unit
Absolute humidity	Ratio of vapor mass to the volume occupied by the air	g/m <sup>3</sup>
Volumetric concentration	Ratio of vapor volume $\times 10^6$ to the volume of the dry gas	ppmv
	Ratio of vapor weight $\times 10^6$ to the weight of the dry gas	ppmw
Saturated water vapor pressure (above water and ice)		Pa, kPa
Partial water pressure		kPa
Mixing ratio or mass ratio	Ratio of water vapor mass to the mass of dry gas	%, g/kg
Relative humidity	Ratio of vapor mass to the mass of saturated vapor or ratio of actual vapor pressure to saturation vapor pressure	% RH
Specific humidity	Ratio of vapor mass to total mass of the gas	%, g/kg
Dew point	Temperature (above 0°C) at which the water vapor in a gas condenses to liquid water	°C
Frost point	Temperature (below 0°C) at which the water vapor in a gas condenses to ice	°C
Volume ratio	Ratio of vapor partial pressure to partial pressure of dry gas	% by volume

Note: ppm—parts per million.

humidity laboratories have chosen the dew point temperature as the primary humidity parameter for practical reasons: the realization of a dew point temperature scale provides a simple source of traceability in a wide range of humidity at a good uncertainty level.

D/F PT is the temperature (above 0°C) at which the water vapor in a gas condenses to liquid water. At this temperature, water is either evaporated to a gas, or is condensed from gas to water. Frost point is the temperature (below 0°C) at which the vapor condenses to ice. D/F PT is a function of the pressure of the gas but is independent of temperature and is therefore defined as absolute humidity measurement. An increase in pressure will also increase the dew point. Harrison (1965) defined the dew point temperature of moist air as follows: the thermodynamic dew point temperature  $t_d$  of moist air at pressure  $P$  and with mixing ratio  $r$  is the temperature at which moist air, saturated with respect to water at the given pressure, has a saturation mixing ratio  $r_w$  equal to the mixing ratio  $r$ . Here,  $r_w = r_w(P, t_d)$  is the mixing ratio of moist air saturated with respect to a plane surface of clean liquid water when the system consisting of the water and moist air is at a uniform temperature  $t_d$ , and the system is at a pressure  $P$  equal to that which exists in the given sample of moist air having the mixing ratio  $r$ . In addition, any plane surface that are below the dew or frost point temperature will acquire a dew or frost layer.

The vapor concentration or absolute humidity of a mixture of water vapor and dry air is defined as the ratio of the mass of water vapor  $M_w$  to the volume  $V$  occupied by the mixture:

$$D_V = \frac{M_w}{V}, \text{ expressed in g/m}^3, \quad (1.1)$$

where:

$M_w = n_w \cdot m_w$ ,  $n_w$  is a number of moles of water vapor present in the volume  $V$

$m_w$  is the molecular mass of water

As an example, Table 1.6 shows the approximate mass of water (in grams) contained in a cubic meter (m<sup>3</sup>)

**TABLE 1.6**  
**Mass of Water Vapor per Cubic Meter of Saturated Air**

Temperature, °C	0	5	10	15	20	25	30	35
Water vapor, g/m <sup>3</sup>	4.9	6.8	9.4	12.9	17.4	23.1	30.5	39.8

Source: Bell, S., A beginner's guide to humidity measurement, National Physical Laboratory, Teddington, Middlesex, UK, TW11 OLW, <http://www.npl.co.uk>; <http://www.rottronic.com/>, 2012.

of saturated air at a total pressure of 101325 Pa (1013.25 mbar). As shown in Table 1.6, 1 m<sup>3</sup> of air at 20°C (100% saturated) contains about 17 g water. If it is warmed to 37°C, the absolute humidity remains the same but the RH is only 39% because at 37°C, 1 m<sup>3</sup> of air contains 44 g water vapor when fully saturated and the ratio of 17–44 gives a value of 39%.

Specific humidity is the ratio of the mass  $M_w$  of water vapor to the mass ( $M_w + M_a$ ) of moist air:

$$Q = \frac{M_w}{(M_w + M_a)}, \text{ expressed in \% or g/kg} \quad (1.2)$$

The mixing ratio  $r$  of moist air is the ratio of the mass  $M_w$  of water vapor to the mass  $M_a$  of dry air with which the water vapor is associated:

$$r = \frac{M_w}{M_a} \quad (1.3)$$

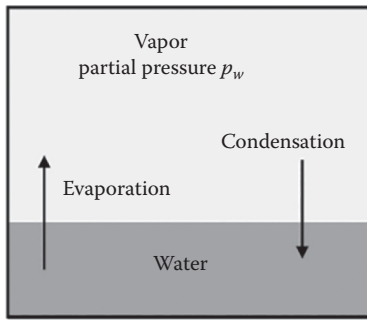
One should note that except in solid physics, volumetric units are rarely used.

PPM represents water vapor content by volume fraction (ppmv) or, if multiplied by the ratio of the molecular weight of water to that of air, as ppmw. PPM is also an absolute measurement. Although this measurement unit is more difficult to conceive, it has extensive applications in industry especially for trace moisture measurement. The vapor pressure of water is the pressure at which water vapor is in thermodynamic equilibrium with its condensed state. At higher pressures water would condense.

RH is the ratio of the partial pressure of water vapor ( $p_w$ ) presented in a gas to the saturation vapor pressure ( $p_{ws}$ ) in the gas at a given temperature. The value of RH is very sensitive to temperature, and thus it is a relative measurement. The RH measurement is expressed as a percentage. It is important to know that the RH in the closed chamber of Figure 1.3 is exactly 100% RH when equilibrium is achieved. In this situation, air contains a well-defined maximum quantity of water vapor. When this saturation vapor pressure is reached, any further addition of water vapor results in condensation.

$$\text{RH (in \%)} = \frac{p_w}{p_{ws}} \cdot 100 \quad (1.4)$$

The expression equilibrium relative humidity (ERH) refers to a condition where there is no net exchange of water vapor between a moisture-containing material (paper, medicines, foodstuffs, tobacco, seeds, etc.) and its environment. It is equivalent for water activity,  $a_w$ , used in the field of biology or food technology, generally



**FIGURE 1.3** Closed chamber with liquid water and gaseous water particles (vapor). In equilibrium, the number of water particles leaving the surface of the liquid water is equal to the number rejoining it. The gaseous water particles exert a pressure  $p_w$  to the wall.

expressed as a ratio rather than a percentage (i.e., 0.6 instead of 60%).

In some cases, for the humidity characterization it is being used the heat index (HI), which indicates how the human body feels temperature. Therefore the result is also known as the *felt air temperature* or *apparent temperature*. For example, when the temperature is 32°C with 70% RH, the HI is 41°C. If RH is low, human body cools itself by perspiration, dissipating heat from the body. At higher RH, the evaporation rate from the human skin is lower. In that case, the body cannot dissipate heat as easily as it is the case in dry air. The HI is based on subjective measurements and is only meaningful above 25°C and 40% RH. The most popular definition of the HI is the one of the National Weather Service and Weather Forecast Office of the National Oceanic and Atmospheric Administration (NOAA). The HI in °C is given by the Equation 1.5 with the coefficients listed in Table 1.7.

**TABLE 1.7**  
**Coefficients for Heat Index Formula**

Coefficient	Value
$c_{00}$	-8.7847
$C_{10}$	1.6114
$c_{01}$	2.3385
$C_{11}$	-0.1461
$C_{20}$	-0.0123
$c_{02}$	-0.0164
$C_{21}$	$2.2117 \cdot 10^{-3}$
$C_{12}$	$7.2546 \cdot 10^{-4}$
$C_{22}$	$-3.5820 \cdot 10^{-6}$

Source: Data extracted from <http://www.sensirion.com>.

$$HI = c_{00} + c_{10}T + c_{01}U_w + c_{11}TU_w + c_{20}T^2 + c_{02}U_w^2 + c_{21}T^2U_w + c_{12}TU_w^2 + c_{22}T^2U_w^2 \quad (1.5)$$

where:

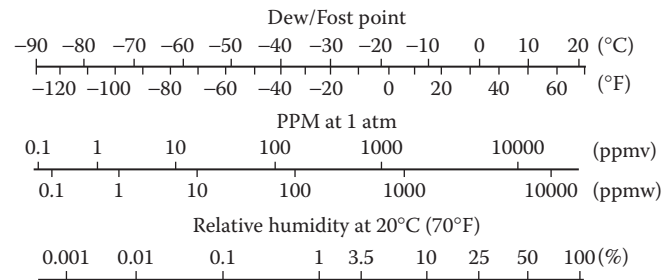
$U_w$  is RH

$T$  is temperature in °C

Figure 1.4 and Table 1.8 show the correlation among RH, ppmv, and the D/F PT. At present there are different approximations, which can be used for description of these correlations. However, many of them are complicated. As a result, conversions between the different parameters used to be cumbersome. However, they are now becoming standard operation since the introduction of the microprocessors.

As a rule, the conversions include the intermediate step of calculating the actual vapor pressure of water and the saturated vapor pressure of water at the temperature of interest. For example, absolute humidity, which is defined by the mass of water vapor  $m_{H_2O}$  per humid air volume  $V$  and can be expressed as  $d_V = m_{H_2O}/V$ , specific humidity ( $Q$ ), mixing ratio ( $r$ ), and ppmv can be calculated as follows:

$$d_V = 2.167 \cdot \left( \frac{p_w}{273.15 + T} \right), [g/m^3] \quad (1.6)$$



**FIGURE 1.4** Correlation among humidity units: relative humidity (RH), dew/frost point (D/F PT), and parts per million by volume fraction (ppmv). (From Chen, Z., and Lu, C., *Sensor Lett.*, 3, 274–295, 2005.)

**TABLE 1.8**  
**Relations between Psychrometric Parameters**

Dew Point, °C	Relative Humidity at 20°C, %	Water Content in Air, ppmv
-75	0.002	~1
-45	0.3	70
-20	4.5	$10^3$
0	25	$6.1 \cdot 10^3$
10	50	$1.3 \cdot 10^3$
20	100	$2.3 \cdot 10^4$



$$Q = \frac{1000p_w}{(1.6078P_{\text{total}} - 0.6078p_w)}, [\text{g/kg}] \quad (1.7)$$

$$r = 621.97 \cdot \frac{p_w}{P_{\text{total}} - p_w}, [\text{g/kg}] \quad (1.8)$$

$$\text{PPMV} = 10^6 \cdot \frac{p_w}{P_{\text{total}} - p_w} \quad (1.9)$$

where:

$P_{\text{total}}$  is total or barometric pressure in Pa

$p_w$  is water vapor partial pressure in Pa

$T$  is in °C

As it is known (Dalton's law), total pressure can be expressed as sum of partial pressures of gases presented in air:

$$P_{\text{total}} = p_{\text{N}_2} + p_{\text{O}_2} + p_{\text{H}_2\text{O}} + p_{\text{other}} \quad (1.10)$$

A relatively simple equation for the calculation of the saturation vapor pressure  $p_{ws}(T)$  in the pure phase with respect to water is the Magnus formula (WMO 2008):

$$p_{ws}(T) = 6.112 \cdot \exp\left(\frac{17.62 \cdot T}{243.12 + T}\right) \quad (1.11)$$

Saturation vapor pressure over ice can be calculated using the equation (WMO 2008):

$$p_{IS}(T) = 6.112 \cdot \exp\left(\frac{22.46 \cdot T}{272.62 + T}\right) \quad (1.12)$$

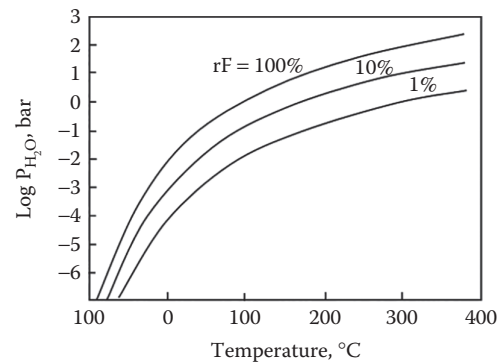
In these equations,  $p_w(T)$  and  $p_{IS}(T)$  are kPa and  $T$  in °C. Uncertainty of these calculations does not exceed 0.6%–1% of value. Saturation water vapor pressures calculated in the temperature range from 0°C to 100°C are listed in Table 1.9. The change of the water vapor pressure over the wider temperature range from –100°C to +400°C is shown in Figure 1.5. The whole of this range is used in industry. Vapor pressures to be measured thus span about 10 orders of magnitude.

When water freezes, the molecules assume a structure that permits the maximum number of hydrogen-bonding interactions between molecules.

**TABLE 1.9**  
Saturation Vapor Pressure of Water (0°C–100°C)

Temperature		Vapor Pressure			
$T, ^\circ\text{C}$	$T, ^\circ\text{F}$	$P, \text{kPa}$	$P, \text{mbar}$	$P, \text{torr}$	$P, \text{atm}$
0	32	0.6113	6.113	4.5851	0.0060
5	41	0.8726	8.726	6.5450	0.0086
10	50	1.2281	12.281	9.2115	0.0121
15	59	1.7056	17.056	12.7931	0.0168
20	68	2.3388	23.388	17.5424	0.0231
25	77	3.1690	31.690	23.7695	0.0313
30	86	4.2455	42.455	31.8439	0.0419
35	95	5.6267	56.267	42.2037	0.0555
40	104	7.3814	73.814	55.3651	0.0728
45	113	9.5898	95.898	71.9294	0.0946
50	122	12.3440	123.440	92.5876	0.1218
55	131	15.7520	157.520	118.1497	0.1555
60	140	19.9320	199.320	149.5023	0.1967
65	149	25.0220	250.220	187.6804	0.2469
70	158	31.1760	311.760	233.8392	0.3077
75	167	38.5630	385.630	289.2463	0.3806
80	176	47.3730	473.730	355.3267	0.4675
85	185	57.8150	578.150	433.6482	0.5706
90	194	70.1170	701.170	525.9208	0.6920
95	203	84.5290	845.290	634.0196	0.8342
100	212	101.3200	1013.200	759.9625	1.0000

Source: Lide, D.R. (Ed.), *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, FL, 2005.



**FIGURE 1.5** Water vapor pressure versus temperature  $rF = 100\%$  is the saturation/dewpoint curve, 10% and 1% show the pressures at the respective relative humidity. (Reprinted from *Sens. Actuators A*, 12, Heber, K.V., Humidity measurement at high temperatures, 145–157, Copyright 1987, with permission from Elsevier.)

As hydrogen-bonding is stronger in ice than in liquid water, it follows that intermolecular attraction forces are the strongest in ice. For that reason, vapor pressure above ice is less than the vapor pressure above liquid water (Table 1.10).

**TABLE 1.10**  
**Comparison of Vapor Pressure Under Water and Ice**

Temperature (°C)	Vapor Pressure Liquid (kPa)	Vapor Pressure Ice (kPa)	Ratio Ice/Liquid
0	0.611	0.611	1.00
-5	0.422	0.402	0.95
-10	0.287	0.260	0.91
-15	0.191	0.165	0.86
-20	0.126	0.103	0.82
-25	0.081	0.064	0.78
-30	0.049	0.037	0.75

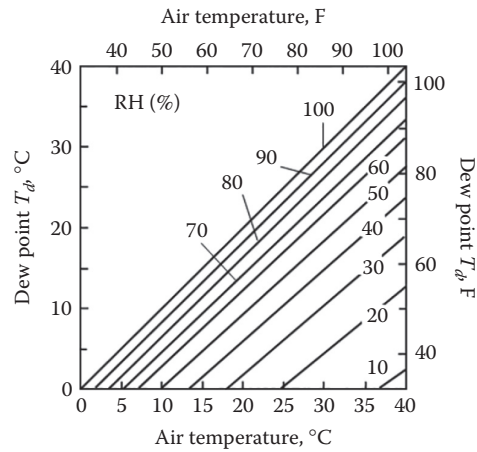
It is important to know that the saturation vapor pressure depends only on temperature. There is no effect of total pressure and there is no difference between the situation in an open space and that in a closed container. From the above it follows that

1. In an open space, at constant moisture level and temperature, % RH is directly proportional to the total pressure. However, the value of % RH is limited to 100% as  $P_w$  cannot be greater than  $P_{sw}$ .
2. In an open space, at constant moisture level and pressure, % RH decreases strongly as temperature increases.
3. In a closed container of fixed volume, % RH decreases as temperature increases, however not quite as strongly as in the situation of the open space.

As regards the relationship of the water vapor pressure with a dew point temperature ( $T_d$ ), at standard pressure  $p_N$ , and a gas temperature  $T$  from  $-3^\circ\text{C}$  to  $70^\circ\text{C}$ , the  $T_d$  can be determined by

$$T_d = 241.2^\circ\text{C} \cdot \left[ 17.5043 \cdot \left( \ln \frac{e_w}{6.11213 hPa} \right)^{-1} - 1 \right]^{-1} \quad (1.13)$$

where  $hPa = \text{mbar}$  ( $e_w = p_w$ ). In deriving this formula it was taken into account that the  $T_d$  of a gas is the temperature at complete saturation with water vapor. This means that in this point a water vapor pressure  $p_w$  is equal to the saturated water vapor pressure  $p_{sw}$ . Consequently, with the further addition of water vapor, dewing or wetting will occur. An equivalent statement is that a gas must be cooled to the  $T_d$  to achieve dewing or wetting. The results of these calculations for different humidity levels make it possible to establish a correlation between the air temperature, dew point, and RH. This correlation is shown in Figure 1.6.



**FIGURE 1.6** The chart illustrating correlation between the air temperature, dew point, and RH. (Data extracted from <http://www.asge-online.com>.)

There is also a very simple approximation that allows conversion between the dew point, temperature, and RH. This approach is accurate to within about  $\pm 1^\circ\text{C}$  as long as the RH is above 50%:

$$T_{dp} \cong T - \frac{100 - \text{RH}}{5} \quad (1.14)$$

and

$$\text{RH} \cong 100 - 5(T - T_{dp}) \quad (1.15)$$

This can be expressed as a simple rule of thumb: for every  $1^\circ\text{C}$  difference in the dew point and dry bulb temperatures ( $T_{DB}$ ), the RH decreases by 5%, starting with RH = 100% when the dew point equals the  $T_{DB}$ . The derivation of this approach, a discussion of its accuracy, comparisons to other approximations, and more information on the history and applications of the dew point are given in the Bulletin of the American Meteorological Society (Lawrence 2005). The relationship between the dew point temperatures and the RH in the digital form is given in Table 1.11.

Absolute humidity in relation to the water vapor pressure can be presented as following:

$$a = \frac{e_w M_w}{R_w T} \quad (1.16)$$

where  $R_w$  is gas constant of water vapor. Due to the strong temperature dependence of the absolute humidity, a normalization is usually carried out in technical

**TABLE 1.11**  
**Values of Relative Humidity at Selected**  
**Temperatures and Dew Points**

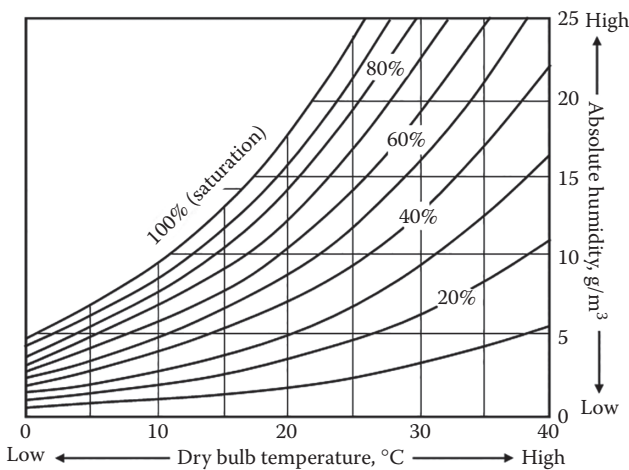
Dew Point Temperature, °C	Air Temperature, °C									
	0	5	10	15	20	25	30	35	40	50
0	100	70	50	36	26	19	14	11	8	5
5	—	100	71	51	37	28	21	16	12	7
10	—	—	100	72	53	39	29	23	17	10
15	—	—	—	100	73	54	40	30	23	14
20	—	—	—	—	100	74	55	42	32	19
25	—	—	—	—	—	100	75	56	43	26
30	—	—	—	—	—	—	100	75	58	34
35	—	—	—	—	—	—	—	100	76	46
40	—	—	—	—	—	—	—	—	100	60
50	—	—	—	—	—	—	—	—	—	100

Source: Bell, S., A beginner’s guide to humidity measurement, National Physical Laboratory, Teddington, Middlesex, UK, TW11 OLW, <http://www.npl.co.uk>; <http://www.rotronic.com/>, 2012.

applications. The normalization factor is related to the atmospheric pressure and a gas temperature of  $T = 0^{\circ}\text{C}$ .

Graphically, the relation between temperature, absolute humidity, and RH can be represented as a psychrometric chart shown in Figure 1.7.

This method is a graphical representation of properties of various mixtures of air and water vapor was invented early in the twentieth century by a German engineer named Richard Mollier. At first, the chart can



**FIGURE 1.7** Simplest psychrometric chart at 1 atm total pressure. (Data extracted from <http://www.sensirion.com>.)

be rather daunting, because it displays so much information in a small space. However, once the basic information elements are understood, the chart becomes an essential reference tool when designing temperature and humidity control systems (Bindon 1965).  $T_{DB}$  on the chart is the temperature that we measure with a standard thermometer that has no water on its surface. This chart was calculated for standard atmospheric pressure and temperatures of  $0^{\circ}\text{C}$ – $40^{\circ}\text{C}$ , which are adequate for most greenhouse or livestock housing applications. When people refer to the temperature of the air, they are commonly referring to its  $T_{DB}$ . Psychrometric charts are printed mostly for a sea level atmospheric pressure.

A psychrometric chart contains a lot of information packed into an odd-shaped graph. A detailed description of using a psychrometric charts for obtaining necessary information on the properties of the moist air one can find in the book by Harriman (2002). Harriman (2002) in his book describes each of the properties of moist air in turn, and then shows how these can be found quickly by using a psychrometric chart. One can also use the Internet sites of the companies, developing psychrometers. The chart is useful both for the information it contains, and the relationships it shows between air at different conditions. It not only shows the *trees* in the psychrometric jungle but also shows the whole *forest* as well, allowing an engineer to gain a sense of how easy or difficult it might be to change the air from one condition to another. For example, it provides an invaluable aid in illustrating and diagnosing environmental problems such as why heated air can hold more moisture, and conversely, how allowing moist air to cool will result in condensation.

For example, follow any horizontal line (representing a specific amount of moisture in the air) from left to right on the chart (i.e., from lower to higher temperature levels): note that RH decreases as temperature increases, so long as the quantity of moisture in the air does not change. For example, the water load in air at  $25^{\circ}\text{C}$  at 80% RH equates to about 25,000 ppm. At  $55^{\circ}\text{C}$ , this same 25,000 ppm is less than 21% RH. Again, follow any horizontal line, but this time from right to left (i.e., from higher to lower temperatures): note that RH levels increase, although the amount of moisture in the air remains constant. Finally, 100% RH is reached at the left edge of the chart, when the temperature drops to the dew point. The air is now saturated and will have to give up water (e.g., as condensation) at any lower temperature. Note also that moving from left to right on the chart along the upward curving RH lines correspond to increasing amounts of moisture in the air. This shows that maintaining a constant level of RH, as the temperature rises, requires adding moisture to the air. Conversely, if the temperature falls, the downward sloping

RH lines indicate that water has to be removed from the air to maintain RH at a constant level. More detailed description of a psychrometric chart one can find on many sites related to psychrometrics and psychrometers.

### 1.3.1 OTHER ABSOLUTE MOISTURE SCALES

In addition to the previously mentioned values such as absolute humidity, D/F PT, and volume ratio, which are absolute scales and do not change with temperature, there are other absolute scales as well:

- % Moisture by volume,  $%M_V$
- Grams per cubic meter,  $\text{g/m}^3$
- Humidity ratio (LB water/LB dry air or g water/g dry Air),  $W$
- Specific humidity (LB water/LB mixture or g water/g mixture),  $q$

Comparison of indicated values is shown in Table 1.12.

The  $%M_V$  can be defined in a least two ways:

$$%M_V = \frac{\text{Number of H}_2\text{O molecules per unit volume}}{\text{Total number of molecules per unit volume}} \quad (1.17)$$

$$%M_V = \frac{P_W}{P_T} \quad (1.18)$$

where:

$P_W$  is the partial pressure due to water vapor

$P_T$  is the total pressure (usually atmospheric pressure)

In some countries a popular moisture measurement scale is *grams of water vapor per cubic meter*. This scale is based on the density of water vapor at STP. There are several different STP values that are given by various standard organizations. Grams of water vapor per cubic meter calculated for different air humidity are listed in the last column in Table 1.12. In our case, we use the STP of the International Union of Pure and Applied Chemistry (IUPAC). The STP of the IUPAC is 0°C and 100 kPa. The density of air at STP was given as 1275.4 g/m<sup>3</sup>. If 100% water vapor could exist at STP, it would have a density of ~800.00 g/m<sup>3</sup>. However, one should take into account that pure water vapor (100% H<sub>2</sub>O by volume) cannot exist at STP because 0.6% water vapor by volume has a dew point of 0°C at this pressure. The last column on Table 1.12 is calculated using a value of 7.9317 g/m<sup>3</sup> for each 1% of water vapor by volume (MAC 1999).

**TABLE 1.12**  
Moisture/Humidity Scales

% Moisture by Volume	Humidity Ratio, $W$	Specific Humidity, $q$	Dew Point Temperature, $t_d$		Grams per Cubic Meter
	LBH <sub>2</sub> O LB Dry air	LBH <sub>2</sub> O LB Mixture	°F	°C	g/m <sup>3</sup>
$%M_V$					
0.0	0	0	-460	-273.3	0.00
0.5	0.00313	0.00312	28	-2.2	3.81
1.0	0.00628	0.00624	45	7.2	7.62
2.0	0.0127	0.0125	64	17.8	15.24
5.0	0.0327	0.0317	92	33.3	38.10
10.0	0.0691	0.0646	115	46.1	76.19
20.0	0.155	0.135	141	60.6	152.38
30.0	0.267	0.210	157	69.4	228.58
40.0	0.415	0.293	169	76.1	304.77
50.0	0.622	0.383	179	81.7	380.96
60.0	0.933	0.483	187	86.1	457.15
70.0	1.45	0.592	194	90.0	533.35
80.0	2.49	0.713	201	93.9	609.54
90.0	5.60	0.848	207	97.2	685.73
95.0	11.80	0.922	209	98.3	723.83
100.0	∞	1	212	100.0	761.92

Source: MAC, *The Humidity/Moisture Handbook*, Machine Applications Corporation, Sandusky, OH, <http://www.macinstruments.com/pdf/handbook.pdf>, 1999.



The humidity ratio  $W$  is sometimes referred to as moisture content or the mixing ratio. It is the mass of water vapor per unit mass of dry air. The humidity ratio ( $W$ ) can be calculated if the % moisture by volume ( $\%M_V$ ) is known.

$$\text{Humidity ratio} = W = 0.622 \cdot \frac{\%M_V}{(100 - \%M_V)} \quad (1.19)$$

This equation is valid only for the normal mixture of gases in the atmosphere. When a different mixture of gases is present as is found inside a boiler flue, the factor 0.622 must change. This factor is the ratio of the molecular weight of water vapor (18.015) to the average molecular weight of the other gases (28.965 in the case of air):

$$\frac{18.015}{28.965} = 0.622 \quad (1.20)$$

Note that the  $\%M_V$  scale is totally independent of the molecular weights of the other gases in the mixture, as in a boiler or direct fired oven.

*Specific humidity* is the ratio of the mass of water vapor to the total mass of the mixture of water vapor and dry air. The specific humidity ( $q$ ) can be calculated if the  $\%M_V$  is known.

$$\begin{aligned} \text{Specific humidity} &= q \\ &= 0.622 \cdot \frac{\%M_V}{(100 - \%M_V) + 0.622 \cdot \%M_V} \end{aligned} \quad (1.21)$$

The factor 0.622 is for normal air only. It must be corrected if the average molecular weight of the gases is different than air.

One should note that the above-mentioned moisture scales are preferred by people that work in specific disciplines (MAC 1999). When dealing with human comfort at normal ambient temperatures  $RH$  is the preferred scale. Weather forecasters (meteorologists) and heating, ventilating, and air-conditioning engineers (HVAC) use  $RH$  regularly.

$\%M_V$  is the most intuitive of the absolute scales. People who work in the areas of combustion and pollution control engineering routinely measure flue gas constituents in  $\%M_V$ . On account of the linear nature of this scale it is easy to display and easy to regulate using normal set point proportional–integral–derivative (P.I.D.) controllers. For these reasons,  $\%M_V$  is also used in the areas of food processing, product drying, and product humidifying.

*Humidity Ratio* ( $W$ ) is preferred by people who work in the product drying process because it can be directly used in energy calculations. This scale is also commonly used as the vertical axis on most psychrometric charts. As this scale is very nonlinear and goes through many orders of magnitude, it is a difficult scale to display or use in a control mode. Since it is simple to convert between scales,  $\%M_V$  is used for display and control of the moisture level, and then converted to humidity ratio for calculations.

*Dew Point Temperature* ( $T_d$ ) is widely used by people who are concerned with the possibility of water condensing in pipes carrying compressed air or other gases. Dew point is also used by those working with sampling systems for the same reason. Condensation in lines can be avoided by maintaining the working fluid at a temperature well above its dew point or by drying a fluid to a dew point well below the lowest temperature to which it will be exposed.

## REFERENCES

- Bell S. (2012) A beginner's guide to humidity measurement. National Physical Laboratory, Teddington, Middlesex, UK, TW11 OLW (<http://www.npl.co.uk>; <https://www.rotronic.com/>).
- Bindon H.H. (1965) A critical review of tables and charts used in psychrometry. In: A. Wexler (Ed.), *Humidity and Moisture*, Vol. 1. Reinhold, New York, pp. 3–15.
- Campbell M.K., Farrell S.O. (2007) *Biochemistry* (6th ed.), Tomson Leaning, Belmont, CA, pp. 37–38.
- Chen Z., Lu C. (2005) Humidity sensors: A review of materials and mechanisms. *Sensor Lett.* 3(4), 274–295.
- Cracolice M.S., Edward P.I. (2006) *Basics of Introductory Chemistry*. Thompson, Brooks/Cole Publishing Company, Belmont, CA.
- Fleming W.J. (1981a) A physical understanding of solid state humidity sensors. *Soc. Automot. Eng. Trans.* Section 2, 90, 1656–1667.
- Fleming W.J. (1981b) A physical understanding of solid state humidity sensors. SAE Technical Paper 810432.
- Harriman III L.G. (Ed.) (2002) *The Dehumidification Handbook*, Munters Corporation, Amesbury, MA.
- Harrison L.P. (1965) Fundamental concepts and definitions relating to humidity. In: Wexler A. (Ed.), *Humidity and Moisture*, Vol. III, Reinhold Publishing Corporation, New York, pp. 3–70.
- Hattingh J. (2001) The importance of relative humidity measurements in the improvement of product quality. In: *Proceedings of 2001 NCSL International Workshop & Symposium* ([http://www.ncsli.org/i/c/TransactionLib/C01\\_R7.pdf](http://www.ncsli.org/i/c/TransactionLib/C01_R7.pdf)).
- Heber K.V. (1987) Humidity measurement at high temperatures. *Sens. Actuators.* 12, 145–157.



- Lawrence M.G. (2005) The relationship between relative humidity and the dew point temperature in moist air: A simple conversion and applications, *Bull. Am. Meteorol. Soc.* 86, 225–233.
- Lide D.R. (Ed.) (2005) *CRC Handbook of Chemistry and Physics*. CRC Press, Boca Raton, FL.
- MAC (1999) *The Humidity/Moisture Handbook*, Machine Applications Corporation, Sandusky, OH (<http://www.macinstruments.com/pdf/handbook.pdf>).
- Nitta T. (1981) Ceramic humidity sensor. *Ind. Eng. Chem. Prod. Res. Dev.* 20, 669–674.
- Petrucci R.H., Herring F.G., Madura J.D., Bissonnette C. (2017) *General Chemistry: Principles & Modern Applications: AIE (Hardcover)*. Pearson/Prentice Hall, Upper Saddle River, NJ.
- Rittersma Z.M. (2002) Recent achievements in miniaturised humidity sensors—A review of transduction techniques. *Sens. Actuators A.* 96, 196–210.
- Sikarwar S., Yadav B.C. (2015) Opto-electronic humidity sensor: A review, *Sens. Actuators A.* 233, 54–70.
- Smith F.G. (Ed.) (1993) *Atmospheric Propagation of Radiation*. Volume 2 of *The Infrared & Electro-Optical Systems Handbook*, J.S. Accetta, D.L. Shumaker (Eds.), Infrared Information Analysis Center, Ann Arbor, MI; SPIE Optical Engineering Press, Bellingham, Washington, DC.
- Spomer L.A., Tibbitts T.W. (1997) Humidity. In: Langhans R.W. and Tibbitts T.W. (Eds.), *Plant Growth Chamber Handbook*, Iowa State University, Ames, IA, pp. 43–64.
- Srivastava R. (2012) Humidity sensor: An overview. *Intern. J. Green Nanotechnol.* 4, 302–309.
- Visscher G.J.W. (1999) Humidity and moisture measurement. In: Webster J.G. (Ed.), *The Measurement, Instrumentation, and Sensors: Handbook*, CRC Press, Boca Raton, FL, Chapter 72.
- Wernecke R., Wernecke J. (2014) *Industrial Moisture and Humidity Measurement: A Practical Guide*, Wiley-VCH, Weinheim, Germany.
- Wexler A. (Ed.) (1965) *Humidity and Moisture*, Volumes 1–3, Reinhold Publishing Corporation, New York.
- Wiederhold P.R. (1997) *Water Vapor Measurement: Methods and Instrumentation*, CRC Press, New York.
- WMO (2008) World Meteorological Organization. Guide to Meteorological Instruments and Methods of Observation, Appendix 4B, WMO–No. 8 (CIMO Guide), Geneva, Switzerland.



**Taylor & Francis**

Taylor & Francis Group

<http://taylorandfrancis.com>