8. Humidity Sensors

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For measurements of atmospheric humidity, a variety of different techniques has been used in the past, such as hair hygrometers, polymer sensors, optical instruments, and also those based on thermodynamic properties of moist air. Current sensor technology is mostly based on the psychrometric method, dewpoint measurements, and optical measurements, as well as capacitive sensors. Of special interest are the psychrometric theory and the theory of optical measurements. Technical specifications, exposure recommendations, necessary maintenance associated with different methods, as well as methods of quality control and calibration are presented.

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Water occupies a special place among the constituents of air because it exists in the solid, liquid, or gaseous phase. Furthermore, it exhibits the strongest contribution to the natural greenhouse effect. Due to precipitation, evaporation, and long-range transport, the water-vapor content of air varies considerably throughout the atmosphere. Depending on the temperature, concentrations of water vapor near the surface are on the order of $0.1-30 \times 10^{-3} \, \text{kg m}^{-3}$. The water vapor is mostly concentrated in the lowest kilometer of the atmosphere (atmospheric boundary layer), whereas less than $0.3 \times 10^{-6} \, \text{kg m}^{-3}$ of it is present in the stratosphere. Comprehensive descriptions of water vapor in the atmosphere are contained in textbooks of meteorology and climatology [8.1, 2].

8.1 Measurement Principles and Parameters

The humidity of air is measured as several parameters, such as the degree of saturation or the water-vapor pressure. Some of these parameters are measured but others must be calculated. The following section gives an overview of the different parameters and measurement principles.

8.1.1 Measured Parameters

Most humidity sensors measure relative humidity, which is the ratio of water-vapor pressure in the atmosphere in relation to the water-vapor pressure at saturation for a given temperature. Relative humidity is a temperature-sensitive parameter, which must be taken into account when calculating other humidity parameters. Therefore, a temperature measurement (Chap. 7) is essential. Some instruments measure absolute humidity or mixing ratio directly. Other measured parameters are dewpoint or frostpoint temperature and psychrometric difference – the temperature difference between a dry-bulb and wet-bulb thermometer – used for psychrometric methods. Table 8.1 gives an overview of parameters and their units measured by humidity sensors.

For many applications other humidity parameters are used. These are mainly water-vapor partial pressure, specific humidity, absolute humidity, or saturation vapor pressure that are given in Table 8.2 and possible calculations between humidity units are given in Table 8.3.

Of high importance is the maximum possible amount of water vapor in the air for a given temperature,

known as the water-vapor pressure of saturation. This relationship is given on the basis of the thermodynamic laws by the Clausius–Clapeyron equation [8.1, 2]

$$\frac{dE_w}{dT} = \frac{\lambda}{T\Delta v} \, , \tag{8.1}$$

where E_w is the saturation vapor pressure, T is the absolute temperature, λ is the specific heat of evaporation (λ_v) or sublimation (λ_i), and Δv is the difference between the specific volumes of water and water vapor. Assuming $\lambda = $ const., neglecting the volume of liquid water compared to that of water vapor, and adopting ideality of the gas mixture, it follows with the gas constant of water $R_w = 461.525 \, \mathrm{J \, kg^{-1} \, K^{-1}}$

$$\frac{dE_w}{E_w} = \frac{\lambda}{R_w} \frac{dT}{T^2} \, . \tag{8.2}$$

After integration the saturation vapor pressure can be written as

$$E_w = E_{w0} \exp\left(\frac{\lambda}{R_w T_0} \frac{T - T_0}{T}\right) \tag{8.3}$$

with $E_{w0} = 6.112 \, \mathrm{hPa}$ and $T_0 = 273.15 \, \mathrm{K}$. From (8.3) it follows that with the specific latent heat of evaporation

$$\lambda = \lambda_v = 2.50 \times 10^6 \, \mathrm{J \, kg^{-1}} \, ,$$

the water-vapor pressure over water, and with the latent heat of sublimation

$$\lambda = \lambda_i = 2.83 \times 10^6 \, \mathrm{J \, kg^{-1}}$$

Table 8.1 Measured parameters of humidity sensors

Parameter	Description	Unit	Symbol
Relative humidity	Ratio of water-vapor pressure to saturation water-vapor pressure	%	RH
Absolute humidity	Mass of water vapor per volume of moist air	$\mathrm{kg \, m^{-3}}$	a
Psychrometric difference	Difference between the dry-bulb and wet-bulb (or ice-bulb) temperature	K	$t - t_w$
Dewpoint	Temperature at which the saturation vapor pressure over water is reached	°C	t_d
Frostpoint [a]	Temperature at which the saturation vapor pressure over ice is reached	°C	t_f
Mixing ratio [b]	Mass of water vapor per mass of dry air	$\mathrm{kg \, kg^{-1}}$	r

[a] Below $0 \, °\mathrm{C}$ the dewpoint temperature is lower than the frostpoint temperature at a constant partial water-vapor pressure. Above $0 \, °\mathrm{C}$ the frostpoint temperature is not defined.
[b] The mixing ratio can be replaced with sufficient accuracy by the specific humidity (see Table 8.2) or vice versa.

Table 8.2 Other relevant parameters for humidity measurements

Parameter	Description	Unit	Symbol
Vapor pressure	Partial pressure of water vapor in air	hPa	e
Specific humidity	Mass of water vapor per mass of moist air	$\mathrm{kg \, kg^{-1}}$	q
Saturation vapor pressure over water	Vapor pressures in air in equilibrium with pure bulk water at a flat interface	hPa	E_w
Saturation vapor pressure over ice	Vapor pressures in air in equilibrium with pure bulk ice at a flat interface	hPa	E_i
Virtual temperature	Temperature of dry air if it had the same density as moist air at the same pressure	K	T_v

(both values for $0\,°C$, see Chap. 5) follows the water-vapor pressure over ice. This widely used analytical form is the Magnus equation, which is recommended [8.4] in the form given in Table 8.3. In some English speaking countries the Tetens equation is often used (Table 8.3).

In the ideal-gas approximation the density of moist air is a function of temperature, pressure, and specific humidity [8.1, 2]

$$\rho_a = \frac{p}{R_d T(1 + 0.608q)}\,, \tag{8.4}$$

with the gas constant of dry air

$$R_d = 287.0586\,\mathrm{J\,kg^{-1}\,K^{-1}}\,,$$

the pressure p. Thereby,

$$T_v = T(1 + 0.608q) \tag{8.5}$$

is the virtual temperature (Table 8.3), which can be used in the gas equation together with the gas constant of dry

air instead of that for moist air. An approximation of the virtual temperature with the water-vapor pressure is given in Chap. 7. This parameter is also used as a parameter for humidity measurements.

The specific heat of evaporation and sublimation is a function of temperature (Chap. 5); for the heat of evaporation the following temperature dependence can be used

$$\lambda_v = 2\,500\,827 - 2360\,(T - 273.15\mathrm{K})\left[\mathrm{J\,kg^{-1}}\right]. \tag{8.6}$$

The expressions for the dewpoint and frostpoint temperatures in Table 8.3 follow directly from the Magnus equation in the same table, neglecting the temperature dependency in $f(p, T)$ [8.4, 13] (see footnote in Table 8.3).

8.1.2 Principles of Measurements

Historically many physical and chemical principles have been used to measure atmospheric humidity. Dif-

Table 8.3 Relationship between water-vapor pressure and different humidity units (after [8.4–8]), based on the new ITS-90 temperature scale [8.5, 9]. For dimensions and symbols see Tables 8.1 and 8.2; p: air pressure in hPa, e: water-vapor pressure in hPa, T: absolute temperature in K, t: temperature in $°C$. Note: For the often used calculation according to *Wexler* [8.10–12] a transformation on the ITS-90 scale is recently available [8.9]

Humidity unit	Equation
Relative humidity	$RH = 100\,\frac{e}{E'_{w,i}}$
Water-vapor pressure for saturation with Tetens's equation over water [8.3], only of historical relevance	$E_w = 6.11\,\exp\left(\frac{17.2694(T - 273.16K)}{T - 35.86K}\right)$
Water-vapor pressure for saturation with Magnus's equation (-45 to $+60\,°C$ over water, pure phase) [8.4, 5]	$E_w(t) = 6.112\exp\left(\frac{17.62t}{243.12+t}\right)$
For moist air	$E'_w(t, p) = f_w(p)E_w(t)$ [a,b]
Water-vapor pressure for saturation with Magnus's equation (-65 to $+0.01\,°C$ over ice, pure phase) [8.4, 5]	$E_i(t) = 6.112\exp\left(\frac{22.46t}{272.62+t}\right)$
For moist air	$E'_i(t, p) = f_i(p)E_i(t)$ [a,b]
Dewpoint temperature for water (-45 to $+60\,°C$)	$t_d = \frac{243.12\ln\{e/[6.112f_w(p)]\}}{17.62 - \ln\{e/[6.112f_w(p)]\}}$ [a,c]
Frostpoint temperature for ice (-65 to $+0.01\,°C$)	$t_f = \frac{272.62\ln\{e/[6.112f_i(p)]\}}{22.46 - \ln\{e/[6.112f_i(p)]\}}$ [a,c]
Psychrometric formula for water	$e = E'_w(p, t_w) - 6.53 \times 10^{-4}p\left(1 + 9.44 \times 10^{-4}t_w\right)(t - t_w)$
Psychrometric formula for ice	$e = E'_i(p, t_i) - 5.75 \times 10^{-4}p(t - t_i)$
Absolute humidity	$a = \frac{0.21667e}{T}$ [d]
Specific humidity	$q = 0.62198\,\frac{e}{p - 0.378e}$ [e]
Mixing ratio	$r = 0.62198\,\frac{e}{p - e}$ [e]
Virtual temperature	$T_v = T\,(1 + 0.608q)$

[a] $f(p) = 1.0016 + 3.15 \times 10^{-6}p - 0.074p^{-1}$, $f(p)$ is the enhancement factor (Sect. 8.3.1) and a function of both pressure and temperature, i.e., $f = f(p, t)$ [8.13]. In practice, the temperature dependency ($\pm 0.1\%$) is much weaker than the pressure dependency (0.0 to $+0.6\%$). Therefore, the temperature dependency has been omitted in the formula above. This formula, however, should be used only for pressure around 1000 hPa (i.e., surface measurements) and not for upper-air measurements, for which Table 4.10 in [8.13] should be used.
[b] For lower temperatures, see [8.8, 10].
[c] For dewpoint and frostpoint temperatures outside this range, inversions should be used.
[d] e in hPa and T in K.
[e] e and p in hPa.

Table 8.4 Properties of humidity measurements and applications for mean values and turbulence measurements [8.6, updated]

Type of sensor	Properties Thermodynamic	Absorption of radiation	Material	Application Mean	Turbulent
Hair hygrometer			✓	✓	
Lithium chloride sensor			✓	✓	
Capacity hygrometer			✓	✓	
Psychrometer	✓			✓	
Dewpoint and frostpoint hygrometer	✓			✓	
Ultraviolet hygrometer		✓		(✓)	✓
Infrared hygrometer		✓		(✓)	✓

ferent sensor types and methods, listed in Table 8.4, are used for slow (mean values, seconds to many minutes) and fast response (turbulence measurements, 5−100 Hz) humidity measurements. This chapter concentrates on these methods, and only in Sect. 8.2 are historically relevant methods described.

8.1.3 Siting Considerations

Humidity measurements can be interpreted only in connection with temperature, and are generally measured together [8.4, 7]. The distance between the humidity and temperature sensor should be as short as possible (at most 1 m); however, the sensors should not influence each other, yet measure the same small air volume. Depending on the sensor, radiation protection and ventilation may be necessary. The standard height above ground for humidity measurements is 2.0 m. Except in the case of UV hygrometers or IR hygrometers, sufficient radiation protection may be achieved by installing the sensor inside a meteorological shelter [8.4] (Chaps. 7 and 43). For specific purposes humidity instruments may also be installed in different arrangements as long as the sensor is properly exposed (Chap. 6). Moisture sensors should not be exposed to atmospheric contaminants, rain, or wind. Furthermore, the material of the housing should neither adsorb nor desorb water vapor.

8.2 History

Many methods are available for measuring atmospheric humidity. A comprehensive review of methods available up to the 1960s was given by *Sonntag* [8.14] and *Wexler* [8.15]. Only the most important methods and instruments, which are based on the principles still in use, are reviewed here.

8.2.1 Hygroscopes

Moisture in the air and its effect of increasing the weight of some materials, mainly wood, has been known since antiquity, e.g., in the Western Han dynasty in ancient China between 200 BCE and 10 CE [8.16] from East Asia. The first hygroscope, dated to about 1450, was developed by the German *Nicholas of Cusa* (*Nikolaus von Kues*, lat. *Cusanus*) (1401−1464) [8.17, 18], who used a weight scale and an unspecific hygroscopic material. A more accurate description is from the architect *Leon Battista Alberti* (1404−1472), who used a sponge and a scale to measure the "heaviness and dryness of the wind and air" [8.18]. *Leonardo da Vinci* (1452−1519) made several drawings showing such a system, for instance a scale with a sponge [8.19] in a sketch made for his famous painting *The Last Supper*.

In the seventeenth and eighteenth century, several humidity-dependent materials from animals, plants (Table 8.5), and minerals were tested, but all instruments using these were still classified as hygroscopes because they were only indicators of the humidity. The hygrometer from *Johann Heinrich Lambert* (1728−1777), who used catgut string, dates from this time (Fig. 8.1). The torsion of the material was used to rotate a hand about 360° from low to high humidities [8.20]. At the end of the eighteenth century, the use of terms like saturation or relative amount of water (*Ludwig Achim von Arnim*, 1781−1831) marked the beginning of quantitative hygrometry. A further often-used instrument was built by *Jean-André de Luc* (1727−1817) in 1772 using ivory as a measuring element.

Table 8.5 Hygroscopic material used for hygroscopes (after [8.18])

Source	Material	Hygroscopic properties
Animal and human	Catgut string	Torsion
	Amnion	Expansion
	Ivory	Expansion
	Whalebone	Expansion
	Horn	Expansion
	Leather	Expansion
	Human hair	Expansion
	Sponge	Weight
	Skin	Expansion
Herbal	Cotton	Expansion, weight
	Oat beard	Torsion, flexion
	Hemp, twisted	Torsion, expansion
	Paper	Expansion, weight

Fig. 8.1 Lambert's hygrometer from about 1772 (after [8.18]), using the torsion of catgut string. Translation of the German engraving: two graduations are 3 degrees of humidity within a cubic foot of air (photo © Freunde alter Wetterinstrumente, Riedlingen, Germany)

8.2.2 Hair Hygrometer

The philosopher *Horace Bénédict de Saussure* (1740–1799) experimented with human hair and found that untreated thin and soft hair from men and women – the latter was more usable because of its length – could be used after some preparation [8.18]. This was mainly degreasing by cooking, and treatment with cold water and soda solution. The tension on the hair and hand was exerted by a small weight. A hair hygrometer similar to the prototype of 1781 is shown in Fig. 8.2. From the beginning the scales of the hygrometers were linear, but the extension of the human hair was found to be nonlinear. *Wilhelm Klinkerfues* (1827–1884) devel-

Fig. 8.2 Hair hygrometer according to the prototype of 1781 by Horace Bénédict de Saussure [8.18] (photo © Freunde alter Wetterinstrumente, Riedlingen, Germany)

oped a system to linearize the scale in 1882. Some years earlier he had developed the bifilar hygrometer with a second nonhygroscopic hair to reset the hand. This instrument was produced at Göttingen in 1875 by *Wilhelm Lambrecht* (1834–1904). In 1880 Lambrecht developed the Polymeter, which combined a hair hygrometer and a thermometer, both of which had two scales. The thermometer had an additional scale indicating the water-vapor pressure at saturation, and the hygrometer a scale for the calculation of the dewpoint, which is the difference between the temperature and its value at this scale. He also developed a thermo-hygroscope in 1881. The mechanical connection of a hygrometer with a bimetal-thermometer made it possible to determine the increase or decrease of the absolute humidity. The round form of the hygrometer similar to Lambert's hygrometer (Fig. 8.1) has been prevalent since approximately 1850, and not much has changed in this respect up to now.

The theory of the hair hygrometer is based on *Sresnevsky* 1895 [8.21], who assumed that a hair is a capillary tube. If the hair is immersed in water the hair is filled with water up to the capillary rise. The curvature of the meniscus in the pores of the hair determines the maximum water-vapor pressure in the pores. This was set proportional to the absolute value of the logarithm of the relative humidity. The largest extension of the hair occurs at 100% relative humidity and the largest

contraction was assumed for 7.8%, with no further contraction below this value. For the contraction δL (range 0.0−1.0) follows [8.14, 22]

$$1.104 \delta L = -\log\left(\frac{RH}{100}\right). \tag{8.7}$$

The theory was updated by *Whipple* in 1921 [8.23]. He found that for very narrow capillaries the hydrostatic pressure is larger than the barometric pressure in the upper part of the capillary, where negative pressures of 0.012 hPa for 99% relative humidity and 2.1 hPa for 20% humidity occur. This still forms the basis of the recent theories presented in Sect. 8.3.2.

8.2.3 Other Absorption and Adsorption Hygrometers

The metal-paper coil hygrometers are based on early works with two strips, where one is humidity dependent. The first was made in 1867 by *Robert Wolf* with the bark of a fir tree [8.24]. Several constructions have been reported since that time. The method is still in use with a metallic spiral covered on one side with a hygroscopic material. The principle is similar to a bimetal thermometer.

The first proposals to use goldbeater's skin, a treated outer membrane of the intestine of an animal, which was normally used to produce gold leaf, was already reported by *Vincenzo Chiminello* (1741−1815) in 1783 [8.14] – the so-called goldbeater's skin hygrometer. Because of its faster response time for lower temperatures in comparison to human hair, it remained in use for a long time.

With the invention of radiosondes at the beginning of the 1930s, intensive research started to develop electric and faster sensors. Experiments were done with many chemical solutions and salts. The most successful salt was lithium chloride (LiCl). *Dunmore* [8.25] used copper wire electrodes wound around a glass tube. He found the best results with a 5% aqueous LiCl solution that had a time constant of about 4.5 s. The disadvantage of the sensor was the high resistance and a cross sensitivity to temperature. Tests were made with several materials [8.14, 15], and some progress was achieved by *Jones* in 1960 [8.26] using glass plates coated with a film of barium fluoride (BaF_2) over a metallic electrode. A minimized version of such a sensor (3.0×4.5 mm^2) could reach time constants of down to 0.1 s [8.27].

A problem with these sensors is the temperature dependence and the low calibration stability, so that these sensors were mainly used for radio sounding or similar applications. At the end of the 1950s, the LiCl sensor was modified to a heated dewpoint sensor [8.28],
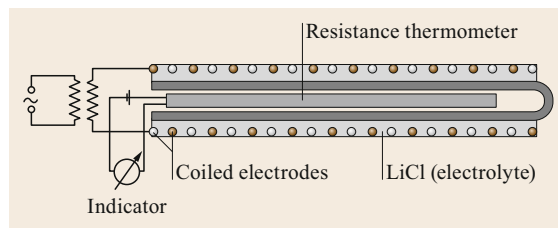

Fig. 8.3 A basic view of a heated lithium chloride sensor (after [8.29])

which is shown in Fig. 8.3. The method is based on the equilibrium between the water-vapor pressure of the heated aqueous LiCl solution and the water-vapor pressure in the air (Sect. 8.3.3). The temperature sensor measures the dewpoint. This type of sensor is still currently in use.

Another class of sensors uses solid materials. Since the 1930s it has been known that graphite changes its resistance with humidity. Mainly through industrial research, carbon humidity elements, also called carbon hygristors, were constructed for radio soundings [8.14, 15]. Polymers were another material found in industrial research that adsorbed water at the surface, changing the resistance. These materials are used as a dielectric of a capacitor [8.30–32]. The benefit is a nearly linear response of capacitance to the change of humidity. The frequency output of a resonant circuit is transformed into a voltage or current. Today, these capacitive polymer sensors are widely used as humidity sensors [8.33, 34], for example the Humicap® technology developed by the company Vaisala Oyj (Sect. 8.3.4).

8.2.4 Psychrometer

Before 1792, *James Hutton* (1726–1797) in Edinburgh found a cooling effect on thermometers with a wet bulb, and *John Leslie* (1766−1832), who found that this resulted from the drying quality of the atmosphere, constructed a differential thermometer in 1790 – called the Leslie hygrometer – which was the prototype of a psychrometer [8.35] (Fig. 8.4). In 1802 *M.A.F. Lüdicke* proposed separation of the U-form of the differential thermometer into two discrete thermometers. In a comparison of the Leslie hygrometer with the devices by de Saussure and de Luc, *Böckmann* found in 1803 [8.36] that the measurements depended on temperature, pressure and, to a large extent, on wind. The first equation describing the behavior of a psychrometer was presented in 1822 by *Joseph Louis Gay-Lussac* (1778−1850).

The theory of the psychrometer [8.37] is based on *James Clerk Maxwell*'s (1831−1879) diffusion theory of 1877 [8.38], the convection theory of *J. Ivory*
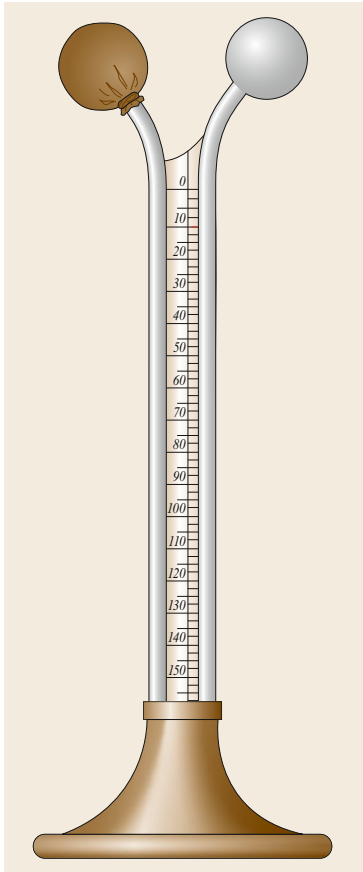
Fig. 8.4 Schematic view of the Leslie differential thermometer with a wet and dry bulb filled with sulfuric acid (with permission from Educational Technology Clearinghouse – University of South Florida)

Fig. 8.5 Historical psychrometer according to August A. Greiner, Munich, 1850 (photo © Prof. Jürgen Baumüller)

1822 [8.35] and *Ernst Ferdinand August* (1795−1870) in 1825 [8.39, 40], and the theory of influence of the wind [8.41], which was for a long time the limiting factor in the application of the method. *Richard Assmann* (1845−1918) developed a psychrometer in the 1880s where both thermometers were ventilated in parallel [8.42, 43], while the earlier type by *August* [8.44] used a nonventilated thermometer (later the wet-bulb thermometer was ventilated), Fig. 8.5. The aspirated psychrometer of *Assmann*, finally described in 1892 [8.45], is still in use and one of the best instruments for measuring humidity (Sect. 8.4.4). Assmann also made the sling or whirling hygrometer more popular [8.46], which has two parallel thermometers – one with a wet bulb, one with a dry bulb, which the user whirls in open air. This instrument is still available.

About 50 years ago, when no fast response hygrometers were available, tests with thin cold wire thermometers, where one was covered with a thin cotton thread, were tested with partial success [8.47].

Because of the complexity of the calculation of psychrometric data, psychrometric charts were developed, the first in 1904 by *Willis H. Carrier*

(1876−1950) [8.48] (Fig. 8.6). Several such charts were developed in the previous century, and psychrometric slide rules were used as well. Nowadays smartphone apps are available, but unfortunately the user cannot be sure that the right equations are used.

8.2.5 Dewpoint and Frostpoint Sensor

The knowledge of obtaining moisture measurements using a cool material that becomes covered with dew if the temperature of the material is lower than the dewpoint has been well known since the Roman Empire. The effect has been applied since the beginning of the nineteenth century to construct several types of dewpoint hygrometers. One of the most impressive is the instrument by *John Frederic Daniell* (1790–1845) from 1820 [8.50, 51] (Fig. 8.7). He used two evacuated and connected glass balloons. The balloon with the thermometer was filled up to 2/3 of its volume with ether.
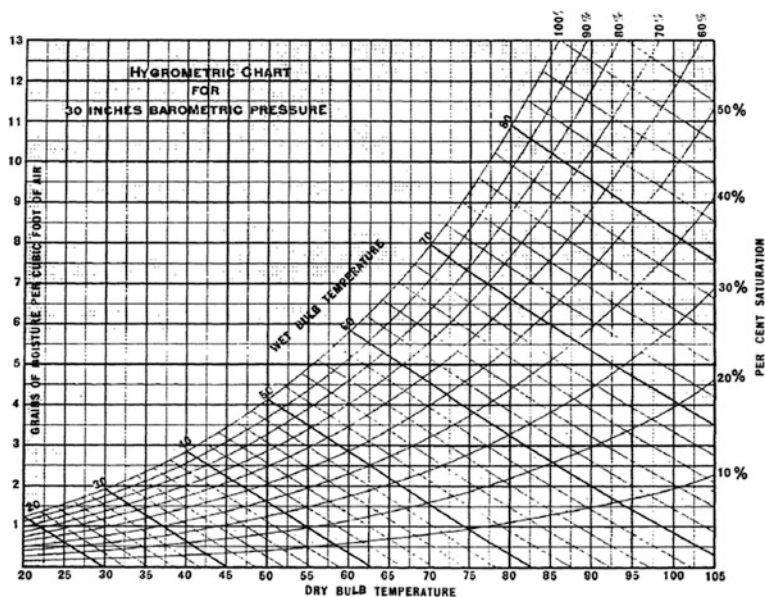
Fig. 8.6 Psychrometric chart according to Carrier 1904 (after [8.48]), temperatures in °F. *Left ordinate*: absolute humidity in grain per cubic foot ($\approx 1/4\,\mathrm{g\,m^{-3}}$). *Right ordinate:* relative humidity, pressure 30 inch (approximately 1015.9 hPa) (after [8.48] with permission from the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta GA, USA)

Fig. 8.7 Dewpoint hygrometer according to Daniell (photo © Prof. Jürgen Baumüller)
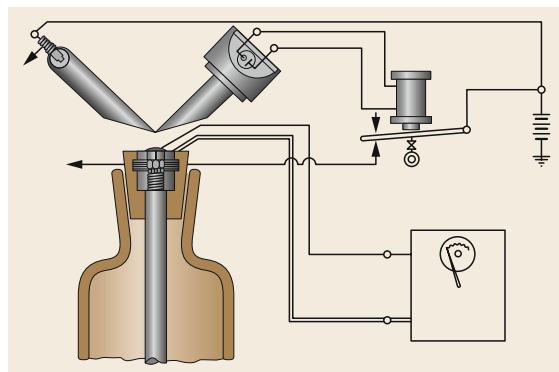
Fig. 8.8 Dewpoint hygrometer according to Thornthwaite (after [8.49] with permission from National Oceanic and Atmospheric Administration, Central Library)

The other balloon was covered with a gauze bandage and was wetted with ether that evaporated. Therefore it cooled down and the ether in the other balloon evaporated too and cooled the balloon. At the dewpoint in the air a dew film covered the balloon and the dewpoint temperature could be measured with the thermometer. This type of hygrometer – also called visual dewpoint hygrometer – was used up to the twentieth century.

The prototype of the currently used photoelectric chilled-mirror dewpoint hygrometers is the device by *Charles Warren Thornthwaite* (1899–1963) from 1939 [8.49] (Fig. 8.8). It is a photoelectric system with a mirror of chromium-plated copper. The mirror is con-

Table 8.6 First developments of fast response hygrometers (for an overview see [8.63])

Hygrometer type	Institution	Year, Reference
UV hygrometer, Lyman-alpha line	Institute of Oceanology, Moscow, Russia	1973 [8.52]
	Institute of Cosmos Research, Berlin, former GDR	1973 [8.53]
	National Center for Atmospheric Research, Boulder CO, USA	1973 [8.54]
	Royal Netherlands Meteorological Institute, De Bilt, The Netherlands	1986 [8.55]
UV hygrometer, Krypton line	Campbell Sci. Inc., Logan UT, USA	1985 [8.56]
IR hygrometer	Institute of Atmospheric Physics, Moscow, Russia	1962 [8.57]
	Flinders University, Adelaide, Australia	1978 [8.58]
	Okayama University, Okayama, Japan	1982 [8.59] [a]
	Main Meteorological Observatory, Potsdam, former GDR	1989 [8.60]
	University of Guelph, Canada	1989 [8.61] [a]
	Royal Netherlands Meteorological Institute, De Bilt, The Netherlands	1991 [8.62] [a]

[a] Including measurement of carbon dioxide

nected by a copper rod with a cooling liquid and is heated. The dew on the mirror can be detected with a lamp and a photocell. Heater and photocell are parts of an electric circuit.

Besides visual and photoelectric dewpoint hygrometers, other electrical sensors, such as radiometric and crystal oscillator dewpoint hygrometers were constructed [8.14, 64].

8.2.6 Fast Response Hygrometers – Optical Sensors

Progress in the use of the eddy-covariance method (Chap. 55) at the beginning of the 1960s required the development of fast response sensors for water-vapor flux measurements (latent heat flux). The first versions of fast response psychrometers or adsorption hygrometers were not successful for general use [8.47]. Only the optical systems following Bouguer–Lambert–Beer's law incorporated a change that allowed practical use of (8.21). The first infrared sensors were less practical due to the low sensitivity and long path lengths necessary [8.57]. At the end of the 1960s, sensors for measuring the UV light in the Lyman-alpha line of 121.56 nm were developed for satellite applications. Used together with a hydrogen lamp, the Lyman-alpha hygrometer was developed at the beginning of the 1970s almost in parallel in the USA, the Soviet Union, and the former GDR [8.52–54], but only the American device was commercially produced for many years, by AIR Inc., Boulder, CO. About ten years later a second type of UV hygrometer was developed using a krypton lamp [8.56]. The benefits of this device were a longer lifetime and easier production. But the absorption band is not directly located in the Lyman-alpha band and has a cross sensitivity to oxygen. Fast response hygrometers are nowadays an important part of all measuring complexes for turbulent energy fluxes. There has been a significant change in measuring systems within the last 15−20 years. While sensors that were commercially available in the 1990s mainly used UV absorption lines, at present there is almost exclusive use of sensors working with the IR absorption lines. This is because the hydrogen lamp for hygrometers working at the Lyman-alpha line is not very stable, and the lamps were mainly handmade. Lyman-alpha hygrometers are only in use today for aircraft applications. At the same time, the sensitivity of IR sensors has been increased and these sensors have been the only commercially available sensors since the end of the 1990s. The pioneering work in the development of fast-response hygrometers is shown in Table 8.6.

8.3 Theory

This section gives a short introduction to the theory of the exact definition of relative humidity. Furthermore, the theories of the different measurement methods are briefly described.

8.3.1 Fundamental Equations of Relative Humidity

Relative humidity is a key observable quantity in atmospheric science, especially in climate monitoring, the SI compatible definition and measurement of which poses a great metrological challenge. In the climate system, heat and matter fluxes of water are essentially controlled by the differences of chemical potentials of water between the ocean, sea ice, and humid air at their mutual interfaces. These chemical potential differences can be exactly expressed in terms of the relative fugacity of atmospheric water vapor [8.65]. The relative humidity according to the World Meteorological Organization (WMO) definition can be recovered from the

relative fugacity as its ideal-gas limit. Considering humid air to be a nonideal binary gaseous mixture of water vapor and dry air, relative humidity, in its most general and physically rigorous form, is defined by the relative fugacity RF [8.65–68]

$$RF\left(\chi_w^{(g)}, T, p\right) = \frac{f_w^{(g)}\left(\chi_w^{(g)}, T, p\right)}{f_w^{(g)}\left(\tilde{\chi}_w^{(g)}(T,p), T, p\right)},$$

$$f_w^{(g)}\left(\chi_w^{(g)}, T, p\right) = \chi_w^{(g)} p\, \varphi_w^{(g)}\left(\chi_w^{(g)}, T, p\right). \quad (8.8)$$

The relative fugacity is a function of three independent variables, namely the mole fraction of water (subscript $_w$) in humid air (superscript $^{(g)}$ for the gas phase), $\chi_w^{(g)}$, the temperature T, and the pressure p. The functions $f_w^{(g)}\left(\chi_w^{(g)}, T, p\right)$ and $\varphi_w^{(g)}\left(\chi_w^{(g)}, T, p\right)$ denote the fugacity and the fugacity coefficient of water in humid air, where the latter is given in analytical form by its virial approximation [8.67]. The quantity $\tilde{\chi}_w^{(g)}(T,p)$ is the water-vapor mole fraction of saturated humid air (term with $\sim$), i.e., of humid air in thermodynamic equilibrium with the condensed phase of water, which can either be pure or air-saturated water (i.e., an ideal mixture of water (solvent) and dry air (solute)) or pure hexagonal ice. The definition of relative humidity in terms of relative fugacity is motivated by the fact that the relative fugacity is the generating observable quantity for the thermodynamic driving force, the so-called Onsager force [8.66, 69], controlling the exchange of water between the vapor and condensed phases of humid air [8.66].

The standard WMO definition of relative humidity RH is obtained as the ideal-gas limit of the relative fugacity [8.70]

$$\lim_{p \to 0} \varphi_w^{(g)}\left(\chi_w^{(g)}, T, p\right) = 1$$

$$\to RH\left(\chi_w^{(g)}, T, p\right) = \lim_{p \to 0} RF\left(\chi_w^{(g)}, T, p\right) = \frac{\chi_w^{(g)}}{\tilde{\chi}_w^{(g)}}. \quad (8.9)$$

The fugacity coefficient,

$$\varphi_w^{(g)}\left(\chi_w^{(g)}, T, p\right) = \frac{f_w^{(g)}\left(\chi_w^{(g)}, T, p\right)}{\chi_w^{(g)} p}, \quad (8.10)$$

is closely related to the so-called enhancement factor (subscript E) of humid air [8.67, 71] with respect to the condensed water phase $^{(c)}$

$$f_{E,w}^{(c)}(T,p) = \frac{\tilde{\chi}_w^{(g)}(T,p)p}{e_w^{(c)}(T)}$$

$$\approx \frac{\varphi_w^{(g)}\left(1, T, e_w^{(c)}\right)}{\varphi_w^{(g)}\left(\tilde{\chi}_w^{(g)}, T, p\right)} \Pi^{(c)}(T,p) \geq 1. \quad (8.11)$$

The enhancement factor describes the effect of air on the saturated partial pressure of water vapor,

$$\tilde{p}_w = \tilde{\chi}_w^{(g)} p. \quad (8.12)$$

The approximation sign in (8.11) results from the neglect of the solubility of air in liquid water. The quantity $\Pi^{(c)}(T,p)$ denotes the dimensionless Poynting correction factor for liquid water [8.71]

$$\Pi^{(c)}(T,p) = \exp\left\{ \frac{1}{R_w T} \int_{e_w^{(c)}(T)}^{p} v_w^{(c)}(T,p')\, \mathrm{d}p' \right\}$$

$$\approx \exp\left\{ \frac{\left[p - e_w^{(c)}(T)\right] v_w^{(c)}}{R_w T} \right\}. \quad (8.13)$$

Here, $e_w^{(c)}(T)$ is the saturation vapor pressure of pure water vapor with respect to the condensed water phase, which can be stable liquid water, supercooled liquid water, or hexagonal ice. The quantity $v_w^{(c)}(T,p)$ is the specific volume of the condensed phase, and R_w is the specific gas constant of water. The enhancement factor is fully determined by the thermodynamic functions $\tilde{\chi}_w^{(g)}(T,p)$, $e_w^{(c)}(T)$, and $v_w^{(c)}(T,p)$, which are provided by TEOS-10 (Thermodynamic Equation Of Seawater – 2010) [8.72] on the basis of the corresponding IAPWS (International Association for the Properties of Water and Steam) formulations for fluid water, supercooled water, and hexagonal ice (Chap. 5).
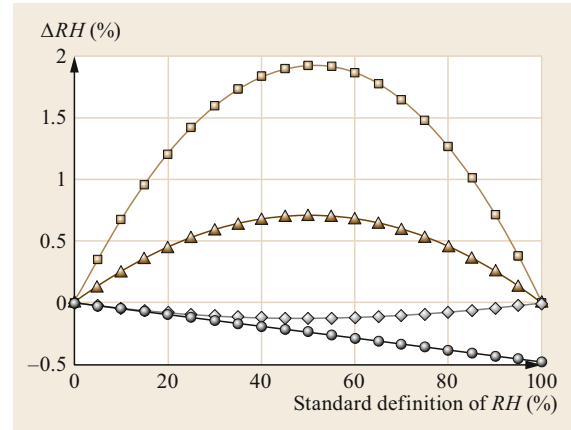
Fig. 8.9 Differences between the standard definition of relative humidity according to WMO (Table 8.3) and four nonstandard definitions at 40 °C and 1000 hPa. The nonstandard definitions are of the form where the relative humidity is quantified by the mixing ratio ($RF = (m/m_{sat}) \times 100\%$, *squares*), the specific humidity (*triangles*), the fugacity (*diamonds*), and the IUPAC (International Union of Pure and Applied Chemistry) definition (*circles*) (after [8.70] with permission from IOP Publishing)

Table 8.7 Contraction of normal and rolled hair on the basis of a simplified theory [8.73] and on the basis of validation measurements [8.14]

Relative humidity (%)	Normal hair		Rolled hair	
	$\overline{m}\%$	$\frac{\Delta L_0}{\Delta L_{0s}}$	$\overline{m}\%$	$\frac{\Delta L_0}{\Delta L_{0s}}$
100	100	1.000	100	1.000
90	75	0.939	72	0.927
80	65	0.877	62	0.854
70	57.5	0.813	55	0.782
60	51	0.746	49	0.709
50	45.5	0.676	43.5	0.636
40	40	0.604	38	0.564
30	35	0.514	33	0.477
20	29	0.392	27.5	0.357
10	20	0.218	20	0.210
5	13.5	0.120	13.5	0.115
1	5.3	0.025	5.3	0.025
0	0	0.000	0	0.000

The mole fraction of water vapor, $\chi_w^{(g)}$, can be easily transformed into any other meteorological humidity metrics such as the water-vapor mass-mixing ratio and the specific humidity [8.65, 70] (Fig. 8.9). The differences between the real-gas and ideal-gas formulations of relative humidity are quantified in [8.70].

8.3.2 Hair Hygrometer

The first steps toward a theory of hair hygrometers were already described in Sect. 8.2.2 [8.21–23], and these still form the basis for the recent theory. The contraction of the hair is given by [8.74]

$$\frac{\Delta L}{L} = \frac{\rho_v R^* T}{Y M_w} \ln \frac{100}{RH} , \qquad (8.14)$$

with the mass density of water vapor ρ_v, the universal gas constant R^*, the modulus of elasticity of the hair Y (in units of Pa), the molecular weight of water M_w, and length of the saturated hair L.

In a simple model [8.73] it was assumed that between the cells of the hair are flexible chains of molecules that can absorb the moisture. The distance between the cells is L and the contraction in the moist state is ΔL_s, and in the dry state ΔL_0 with $\Delta L_{0s} = L_s - L_0$. From this theory follows a linear relationship between the logarithm of the scale of the hygrometer $(\Delta L_{0s}/\Delta L_0) - 1$ and the ratio $(m_s - m)/m$, with m the absorbed mass of water (index s in the case of saturation)

$$\log \xi + \varsigma \log \frac{m_s - m}{m} = \log \left(\frac{\Delta L_{0s}}{\Delta L_0} - 1 \right). \qquad (8.15)$$

The results of the theory [8.73] were validated for normal and rolled hair with the coefficients $\xi = 1.612$ and $\varsigma = 0.3733$ [8.14]. The results are given in Table 8.7.

8.3.3 Lithium Chloride Heated Condensation Hygrometer (Dew Cell)

The basis of this method [8.4, 29, 75] is the physical circumstance (Raoult's law) that the equilibrium vapor pressure at the surface of a saturated salt solution is less than that for a similar surface of pure water at the same temperature, and that lithium chloride has a very low equilibrium vapor pressure (Sect. 8.2.3). If the aqueous salt solution is heated, the vapor equilibrates with the vapor pressure of the ambient air. At this point, the balance will shift from condensation to evaporation, and eventually, there will be a phase transition from the liquid solution to a solid hydrate (crystalline) form (efflorescence). The transition point may be detected through a characteristic decrease in the electrical conductivity of the solution as it crystallizes. The temperature of the solution at which the ambient vapor pressure is reached provides a measure of the ambient vapor pressure. Due to the underlying physical principle, the hygrometer does not work below 15% relative humidity at $0\,°C$ [8.4]. The ambient dewpoint can be determined by empirical relationships.

8.3.4 Capacitive Hygrometer

In capacitive humidity sensors the dielectric material can either be a sandwiched structure with two electrode surfaces on each side or it can be placed between two interleaved comb electrodes. The ceramic aluminum oxide or, more recently, dielectric poly-
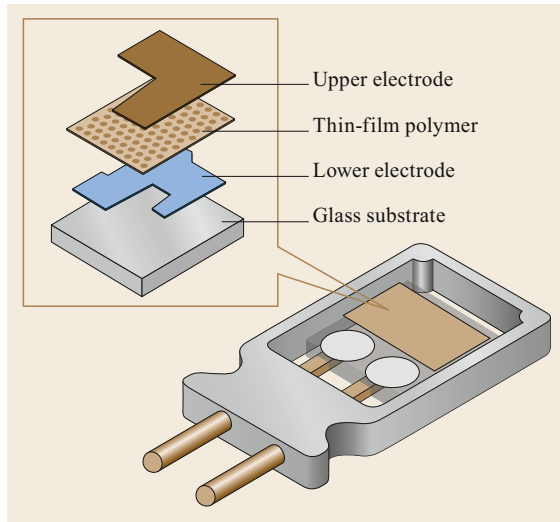
Fig. 8.10 Schematic configuration of the capacitive hygrometer (source: Vaisala Oyj, Finland)

Fig. 8.11 Comparison of the factor $(K/D)^n$ for the three psychrometer theories for different liquids (1: water, 2: methyl alcohol, 3: propyl alcohol, 4: toluene, 5: ethyl propionate) (after [8.37])

mer film is positioned between these electrodes [8.32, 75], where atmospheric water-vapor molecules are deposited. A capacitive-type thin film humidity sensor called Humicap® was developed by Vaisala Oyj in Finland and is now widely used. The schematic of a polymer humidity sensor is shown in Fig. 8.10. It consists of two electrodes that are attached to a glass or ceramic highly insulating substrate. A thin film sensing layer of cellulose acetate is applied on top of one of the two bottom electrodes. Finally, a water-permeable layer of gold is deposited as the upper electrode on top of the polymer layer and electrically connected to other of the two bottom electrodes. The thickness of the gold layer is around $10-20$ nm and porous enough to allow water-vapor transport through it. Due to the significant difference in the relative permittivity (dielectric constant) of $\varepsilon_r = 80.1$ for water and $\varepsilon_r = 1.00059$ for air at 18 °C and 50 Hz, the capacity changes dramatically, and the output signal is proportional to the relative humidity [8.8]. The sensor capacitance changes from 45 to about 70 pF for a relative humidity range of $0-100\%$, and it shows a rapid response time of approximately 1 s to reach 90% of the output value [8.32].

8.3.5 Psychrometric Method

The first theoretical derivation of the psychrometric method was proposed in 1822 by *Ivory* [8.35], later called convection or mixing theory [8.14]. It was assumed that the air in contact with the wet bulb is always saturated and the heat of evaporation originates from the same air. This method does not consider different ventil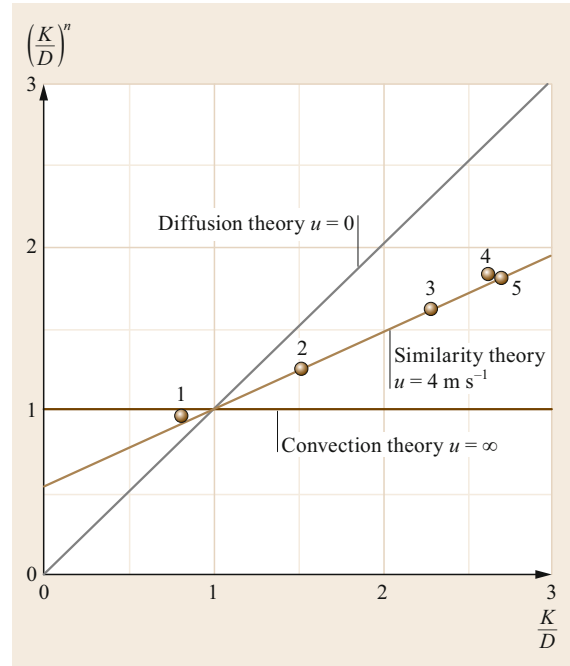ation velocities and applies for a well-ventilated psychrometer. The theory of nonventilated air is called diffusion theory [8.14] and was developed by Maxwell [8.38]. In both theories the heat transfer is not exactly determined, leading to a third theory – the similarity theory (following Reynolds similarity theory).

The basis of all theories is the psychrometric equation

$$e = E(t_w) - \frac{c_p p}{\gamma \lambda_v} \left(\frac{K}{D}\right)^n (t - t_w) , \tag{8.16}$$

with the water-vapor pressure e, the dry-bulb temperature t in °C, the wet-bulb temperature t_w in °C, the water-vapor pressure for saturation E, the specific heat capacity for constant pressure c_p, the pressure p, the ratio of the molecular masses of water vapor and dry air $\gamma = 0.62198$, the specific heat of evaporation λ_v, the diffusion coefficient for heat K, the diffusion coefficient for water vapor D, and the exponent n, which is the ratio of the wind speed at the boundary layer u_h and the ventilation speed u. For the convection theory with $u = \infty$ follows $n = 0$ and for the diffusion theory $n = 1$. For the similarity theory, n is in the interval from 0 to 1 and depends on the construction of the psychrometer. The three theories are illustrated in Fig. 8.11.

It is obvious that water is the preferential liquid for psychrometers, because for all three theories K/D and $(K/D)^n$ are approximately 1, which reduces the parameters in (8.15), and the generally used psychrometer equation (Sect. 8.4.2) follows. Further theories were developed to investigate special effects of psychrometer construction like laminar flow, heat conduction, etc. [8.14].

8.3.6 Dewpoint and Frostpoint Hygrometers

The basic principle of most dewpoint and frostpoint hygrometers lies in the temperature of the liquid or solid condensate layer that is in equilibrium with the vapor phase in the air above. From the measured dewpoint or frostpoint [8.4]

$$t_d = \frac{243.12 \ln\{e/\left[6.112 f_w(p)\right]\}}{17.62 - \ln\{e/\left[6.112 f_w(p)\right]\}} \tag{8.17}$$

$$t_f = \frac{272.62 \ln\{e/\left[6.112 f_i(p)\right]\}}{22.46 - \ln\{e/\left[6.112 f_i(p)\right]\}} , \tag{8.18}$$

the water-vapor pressure for saturation can be calculated over water or ice using the enhancement factor (8.11) $f_{w,i}(p) = 1.0016 + 3.15 \times 10^{-6} p - 0.074 p^{-1}$, which describes the deviation of the equilibrium vapor pressure in presence of another gas at higher pressure. The relative humidity can be calculated as

$$RH_w = 100 \frac{e}{E_w(t)} = 100 \frac{E_w(t_d)}{E_w(t)}, \tag{8.19}$$

$$RH_i = 100 \frac{e}{E_i(t)} = 100 \frac{E_i(t_f)}{E_i(t)}. \tag{8.20}$$

The definition of the dewpoint is related to a plane surface covered with a film of water. But water droplets have a curved surface over which the saturation vapor pressure is higher due to the Kelvin effect. Contaminants in the condensate layer may lower the dewpoint or frostpoint (Raoult effect), but can be minimized with careful maintenance of the hygrometer. Both effects can together raise or lower the dewpoint, but they are minimized if the critical droplet size is large, which reduces the curvature effect and lowers the concentration of the soluble contaminant [8.4].

8.3.7 Optical Method

All optical hygrometers make use of Bouguer–Lambert–Beer's law

$$I = I_0 \exp(-\rho_v k x) , \tag{8.21}$$

where I is the light intensity at the detector, I_0 the light intensity of the lamp, ρ_v the absolute humidity, k the mass absorption coefficient, and x the path length between lamp and receiver. Emission and detection efficiencies as well as any absorption do not affect I_0. For absolute humidity measurements, the lamp intensity must be known. For turbulence measurements only the relative fluctuations need to be determined. However, knowledge of k and x is required for proper scaling of fluctuations in ρ_v. The physical principle of optical instruments is shown in Fig. 8.12. Water-vapor concentrations can be measured at specific absorption lines in the ultraviolet and infrared band wavelengths.

The absorption coefficient for water vapor used in the UV range with a spectral resolution of 0.05 nm [8.76, 77] and for oxygen in the same spectral range with a spectral resolution of about 0.1 nm [8.77, 78] are shown in Fig. 8.13.

Of practical relevance are the wavelengths shown in Table 8.8. The advantage of the Lyman-alpha band is the negligible absorption by oxygen. Unfortunately, the emission of atomic hydrogen lamps is not very stable. Therefore krypton lamps are often used, which are more stable, but emit at two wavelengths, which are absorbed both by water vapor and oxygen. The absorption by ozone is negligible. Because of the oxygen cross sensitivity, the sensor can only be used under constant pressure conditions and is not well suited for absolute measurements.

In the IR range, different wavelengths are used, some with cross sensitivities between water vapor and carbon dioxide.
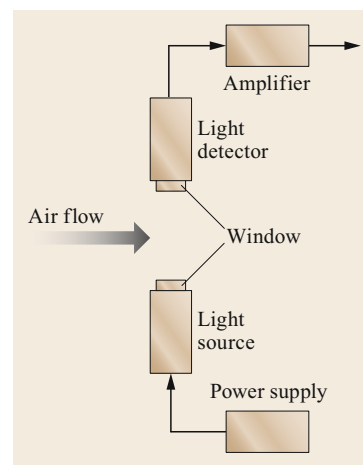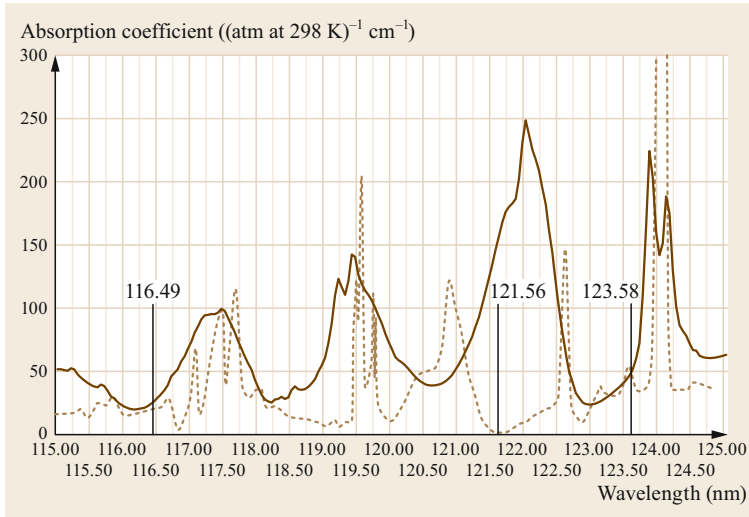
Fig. 8.12 Schematic representation of an absorption hygrometer (after [8.6])

Table 8.8 Selected spectral lines of the water-vapor absorption

Range	Wavelength (µm)	Radiation source	Measuring path	Absorber
UV	0.12156	Atomic hydrogen (Lyman-alpha)	(3–10) mm	H_2O
	0.12358 0.11647	Krypton	(5–15) mm	H_2O, (O_2, O_3)
IR-A,B	Different wavelengths	Stable light bulbs	(0.125–1) m	H_2O, CO_2

Fig. 8.13 Volume absorption coefficient of water vapor between 115 nm and 125 nm (*solid line*) (after [8.76]) and for oxygen (*dotted line*) (after [8.78]), the data were transformed from base e (ln) to base 10 (log) (after [8.79, 80], © authors)

8.4 Devices and Systems

In addition to Sect. 8.2, this section describes humidity sensors that are still in use and can be applied for measurements with different accuracy and response characteristics.

8.4.1 Hair Hygrometer

Hair hygrometers [8.4, 7, 31] are still in widespread use as single instruments for room climate. These instruments appeal due to their simplicity, and for applications with relaxed requirements, they are often preferred over electronic sensors (Fig. 8.14).

The basic design of these instruments and the preparation of the hairs has not changed much since the original work of de Saussure. They typically use a bundle of specially prepared hair, which has been degreased and specially aged for durability. It is important that the hair has not been chemically treated. Often longer hairs of women are preferred. After being degreased, the hair must undergo a special aging procedure with low and high temperatures applied. Details are often a trade se-

cret of the producer. For low temperatures, hair treated by rolling is preferred. Besides hair, synthetic or textile fibers may also be used. Similar instruments are also available as metal-paper coil or bispiral hygrometers. One side of a metallic spiral is covered with a hygroscopic material. Such instruments, however, should not be used for very high or low humidities and are not as accurate as hair hygrometers, but they have a good long-term stability [8.81].

The change of the length of the hair with the humidity is a nonlinear function. At high humidity, the change in length is smaller than at low humidity, which can be compensated for by using linkages and levers to provide a nonlinear amplification. However, chemical treatments with barium or sodium sulfite may increase the linearity. Temperature effects can be compensated for by the insertion of a bimetallic strip into the sensor support. However, hair hygrometers have a hysteresis for increasing and decreasing humidity.

Hair hygrometers are rarely used for atmospheric measurements. But they do have certain advantages for

Fig. 8.14 Hair hygrometer (photo © Feingerätebau K. Fischer GmbH, Drebach, Germany)
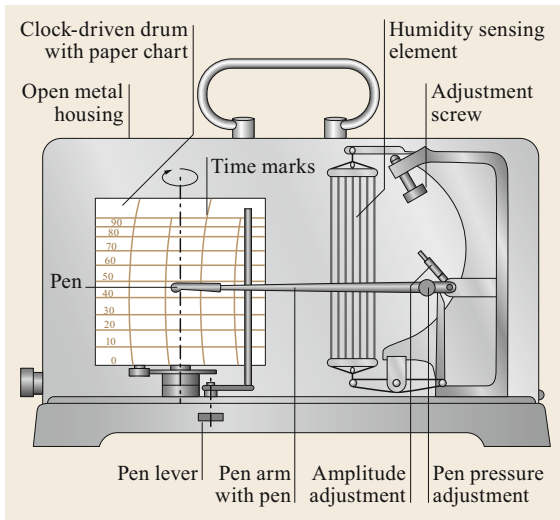

Fig. 8.15 Hair hygrograph (after [8.7] with permission of VDI e. V., Düsseldorf, Germany)

Fig. 8.16 Example of a hair hygrometer with analog voltage output (after [8.7, 82] with permission of VDI e. V., Düsseldorf, Germany)

measurements at low temperatures, when psychrometers, for example, can no longer be used. Still in use for climatological measurements in meteorological screens (Chap. 7) is the drum recorder with a spring mechanism (hygrograph, Fig. 8.15). The change in length of the sensing hair can be converted into an analog electrical signal, e.g., by an inductive displacement transducer [8.82]. Figure 8.16 shows an electric hair hygrometer using a bimetal temperature compensation.

Hair hygrometers should be employed in moderate climates that are neither very dry nor very wet. Good

instruments have an accuracy of $\pm 3\%$. The response time strongly depends on temperature, ranging from half a minute for high temperatures to several minutes for low temperatures. High humidities of nearly 100% relative humidity regenerate the hair. If this is not the case, such as in a dry climate or for indoor measurements, the regeneration should be made by covering the instrument with a sheet – wetted with warm water – for about 30 min. If a hygrometer is not regenerated, the indicated humidity increases for most of the instruments over a period of several years before it stays constant [8.81].

In polluted air, the hair should be cleaned by washing with water. In ammonia-polluted air hair hygrometers should not be used. Besides the regeneration, a zero-offset occurs due to changes of the tension of the hair. This can be corrected during regeneration by turning the adjustment screw. Regular comparison with an

Assmann aspiration hygrometer or another higher quality hygrometer are essential (Sect. 8.4.4).

Hysteresis in the hair sensing element is a short-term effect and not a cause for significant errors [8.4]; however, hysteresis in the mechanism may be significant, in particular if it is polluted. Therefore, the hygrometer should by tipped lightly to reduce any tension in the mechanical system before the measurement. It should be noted that the hair hygrometer measures the humidity above liquid water even at temperatures below 0 °C.

8.4.2 Lithium Chloride Heated Condensation Hygrometer (Dew Cell)

Because of the progress of the capacitive hygrometers and the effort required for maintenance, this sensor type is no longer produced.

8.4.3 Capacitive Hygrometer

Over a period of the last forty years capacitive sensors using thin polymer films as dielectric material have become the most widely used humidity sensors because of their small size, low maintenance, and nearly linear response [8.33]. These sensors were at first developed by Vaisala Oyj for radiosondes under the trademark Humicap®, but are now used for all types of humidity measurements from meteorological to industrial applications [8.34]. Due to the dependence of relative humidity on temperature, these sensors are often combined with temperature sensors in the same housing.

The basic design of the capacitive polymer humidity sensors consists of an upper electrode, a polymer film, and a lower electrode on a glass substrate as shown in Fig. 8.10. For surface-based measurements, the sensor element and its electronics are typically mounted in a tube, sometimes combined with a Pt100 platinum thermometer. To minimize particulate contamination, the sensor is shielded by a filter cap. The filter cap is part of the sensor and technical parameters like response time need to consider the effect of the protective cap. The sensor shown in Fig. 8.17 is typical for most producers of meteorological instruments. Capacitive sensors are considered stable in arid conditions, but may experience nonnegligible drift at higher humidities [8.83].

To address problems, which may occur at high relative humidities, several manufacturers have introduced heated polymer humidity sensors. By heating the sensor, the immediate sensor environment is at lower relative humidity than the surrounding air. An integrated measurement of the humidity sensor temperature allows calculating the ambient relative humidity using

$$RH_{\text{ambient}} = RH_{\text{sensor}} \frac{E_{\text{w}}(t_{\text{sensor}})}{E_{\text{w}}(t_{\text{ambient}})} , \qquad (8.22)$$

where RH_{ambient} is the relative humidity of the surrounding air, RH_{sensor} is the relative humidity by the heated sensor at its elevated temperature t_{sensor}, and t_{ambient} is the ambient air temperature, which must be measured nearby, but outside the air parcel impacted by the heated humidity sensor. This technique requires an additional measurement of the sensor temperature, which must be calibrated to the same level or better than the corresponding air temperature measurement.

Capacitive sensors for low absolute humidities used in radiosondes are described in Chap. 46.

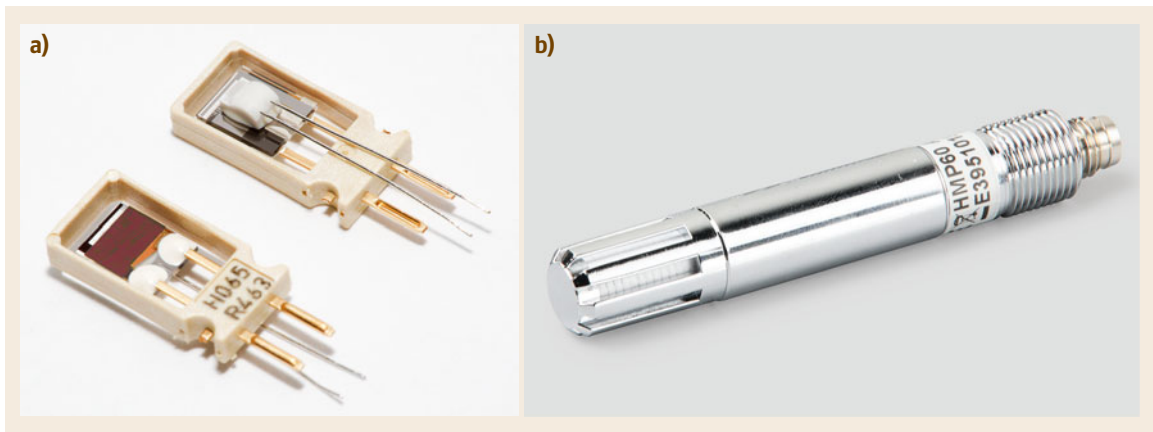**Fig. 8.17a,b** Capacitive humidity sensor: **(a)** sensor element (*lower*: view of the temperature sensor, *upper*: view of the humidity sensor); **(b)** housing of the sensor with filter screen and electronic tube (photos © Vaisala Oyj., Vantaa, Finland)

Table 8.9 Error in derived relative humidity resulting from errors in the psychrometer difference at 50% relative humidity [8.4] updated

Air temperature in °C	Error in relative humidity for an error of the psychrometer difference of	
	0.5 K (%)	0.1 K (%)
−30		12.1
−20	27.2	5.6
−10	13.9	2.8
0	8.4	1.7
10	5.3	1.1
20	3.7	0.7
30	2.7	0.5
40	2.2	0.4
50	1.8	0.3

8.4.4 Psychrometer

The psychrometer measures the psychrometric difference between a dry-bulb and wet-bulb thermometer while both thermometers are radiation shielded and ventilated with at least $3.5\,\mathrm{m\,s^{-1}}$, because at lower ventilation rates, there is a sensitivity to the ventilation speed. Furthermore, the atmospheric pressure at the level of the station must be measured with sufficient accuracy. The wet bulb has a wick fitting closely around the sensing element (well-washed cotton, without synthetic fibers).

The formula currently used to calculate water-vapor partial pressure in hPa [8.8, 84] over water at standard atmospheric pressure of 1013.25 hPa is

$$e = E'_w(p, t_w) - 6.53 \times 10^{-4}$$
$$\times p\left(1 + 9.44 \times 10^{-4} t_w\right)(t - t_w). \quad (8.23)$$

For temperatures above 30 °C the following equation should be applied

$$e = E'_w(p, t_w) - 6.53 \times 10^{-4}\left(p - E_w(p, t_w)\right)$$
$$\times \left(1 + 9.44 \times 10^{-4} t_w\right)(t - t_w). \quad (8.24)$$

The water-vapor partial pressure over ice (ice-covered wet-bulb thermometer, t_i) is

$$e = E'_i(p, t_i) - 5.75 \times 10^{-4} p(t - t_i). \quad (8.25)$$

The factors (numerical value and pressure and temperature-dependent parts) in the summand with the psychrometer difference is called the psychrometer coefficient with the dimension $\mathrm{hPa\,K^{-1}}$ – sometimes also called the psychrometer constant – and a function of temperature and pressure. These formulae are tabulated in more recent psychrometer charts [8.85] and can

be used for calculation, using the measured dry-bulb and wet-bulb temperatures as a basis. The uncertainty of the psychrometer coefficient per 0.1 K error of the wet-bulb temperature is $0.15 \times 10^{-4}\,p\,\mathrm{K^{-1}}$ [8.86] (Table 8.9). A pressure difference of 10 hPa in comparison to the standard air pressure causes an error of the psychrometer difference of about 1%. The resulting error of the relative humidity is temperature-dependent (Table 8.10). Therefore, near sea level the calculation can be made using the standard pressure if no extreme low pressure system passes the station. For stations above sea level the partial pressure of water vapor should be calculated with the local pressure. Because psychrometer charts and diagrams are often no longer in use, apps to calculate relative humidity from psychrometer readings should only be used if they are well documented and use pressure as an input parameter.

Below 0 °C, the psychrometer difference is small and can cause large errors in relative humidity as shown in Table 8.9. The error in wet-bulb temperature under these conditions can be large, because the cotton wick must be fully covered by ice. This can be realized for single measurements but is a problem for continuously running electric psychrometers. In principle, water can be replaced by an ammonia solution, but only for psychrometers without metallic parts. Because of these problems, in winter psychrometers are replaced by hair hygrometers or, more recently, by capacitive hygrometers.

For all types of psychrometers, several requirements must be fulfilled [8.4]:

- At sea level the ventilation speed should not be lower than $2.5\,\mathrm{m\,s^{-1}}$ (better $3.5\,\mathrm{m\,s^{-1}}$) and not larger than $10\,\mathrm{m\,s^{-1}}$. At lower pressure the speed limits should be adjusted inversely proportional to the density of the atmosphere. Typically, a ventilation speed of $3.5\,\mathrm{m\,s^{-1}}$ is used, which does not need a correction for height above sea level.
- The ventilation speed should not be impacted by the wind field if the instrument is not in a meteorological screen, otherwise the ventilation speed has a dependency on the wind direction and speed. A vertical orientation of the flow around the thermometer is preferred.
- The wet bulb and dry bulb must be protected from radiation using a ventilated double shield, which should be polished, unpainted, and thermally isolated from other parts of the psychrometer.
- Both thermometers should be separately ventilated with an inflow of ambient air close to the thermometers.
- Great care should be taken to prevent transfer of heat from an aspirating motor or from the outer shields to the thermometers. Also recirculation of

Table 8.10 Psychrometer coefficient in hPa K^{-1} as a function of the pressure and the wet-bulb temperature (only for water) for water or ice on the cotton wick; difference to the standard values of 0.667 hPa K^{-1} (water) or 0.575 hPa K^{-1} (ice): bold (< 1%) and bold-italic (< 5%), for equations see Table 8.3

Pressure (hPa)	Water on cotton wick						Ice on cotton wick
	Wet-bulb temperature in °C						
	−10	0	10	20	30	40	
1030	**0.666**	*0.673*	*0.679*	*0.685*	*0.692*	*0.698*	*0.592*
1020	**0.660**	**0.666**	*0.672*	*0.679*	*0.685*	*0.691*	*0.587*
1010	*0.653*	**0.660**	**0.666**	*0.672*	*0.678*	*0.684*	*0.581*
1000	*0.647*	*0.653*	*0.659*	**0.665**	*0.671*	*0.678*	**0.575**
990	*0.640*	*0.646*	*0.653*	*0.659*	**0.665**	*0.671*	*0.569*
980	*0.634*	*0.640*	*0.646*	*0.652*	*0.658*	**0.664**	*0.564*
970	0.627	*0.633*	*0.639*	*0.645*	*0.651*	*0.657*	*0.558*
960	0.621	0.627	*0.633*	*0.639*	*0.645*	*0.651*	*0.552*
950	0.614	0.620	0.626	0.632	*0.638*	*0.644*	*0.546*
940	0.608	0.614	0.620	0.625	0.631	0.637	0.541
930	0.602	0.607	0.613	0.619	0.624	0.630	0.535
920	0.595	0.601	0.606	0.612	0.618	0.623	0.529
910	0.589	0.594	0.600	0.605	0.611	0.617	0.523
900	0.582	0.588	0.593	0.599	0.604	0.610	0.518
890	0.576	0.581	0.587	0.592	0.598	0.603	0.512
880	0.569	0.575	0.580	0.585	0.591	0.596	0.506
870	0.563	0.568	0.573	0.579	0.584	0.590	0.500
860	0.556	0.562	0.567	0.572	0.577	0.583	0.495
850	0.550	0.555	0.560	0.566	0.571	0.576	0.489

air must be prevented. This may be a problem inside screens or in low winds and stable stratification.

- The water reservoir and wick should be arranged such that the distilled water reaches the wet-bulb thermometer, but not affect the temperature of the dry bulb. Furthermore, the level in the water reservoir should be nearly constant.
- The cotton wick of the wet bulb should fit tightly around the sensing element and extend at least 2 cm up the stem of the thermometer. Before installation, it should be washed thoroughly in an aqueous solution of sodium bicarbonate at a dilution of 5 g per liter, and rinsed several times in distilled water. Alternatively, a solution of pure detergent in water may be used.
- The response time of both thermometers should be similar. For the same bulb dimension, the wet-bulb thermometer will be faster.

Several systematic errors may occur, which depend partly on the construction of the psychrometer [8.4]:

- The index error of the thermometers should be corrected. The effects of the index error and all other temperature errors are presented in Table 8.9.
- The space between the sensors and the radiation shield should not be bridged by water droplets or

ice, as this would enable heat conduction from the shield to the sensor.
- At temperatures below 0 °C, it must be determined whether the bulb is covered with ice (completely) or with supercooled water.
- Errors due to contamination of the wet-bulb wick or to water impurities.
- Errors due to heat conduction from the thermometer stem to the wet-bulb system if the stem is insufficiently covered.

Common types of psychrometers are the August psychrometer for use in meteorological screens, the Assmann aspiration psychrometer, and electrical psychrometers based on the Assmann principle. Mercury thermometers, which are used in older instruments, have been replaced by alcohol liquid-in-glass thermometers. The Assmann aspiration psychrometer is considered a reference psychrometer for comparison experiments. There is a large number of electrical instruments available, most of which were developed at research institutions, with only a few being commercially available. Those based on the Assmann principle are the most common. In accordance to a proposal of the World Meteorological Organization, a WMO reference psychrometer was developed and is used as a WMO primary standard.
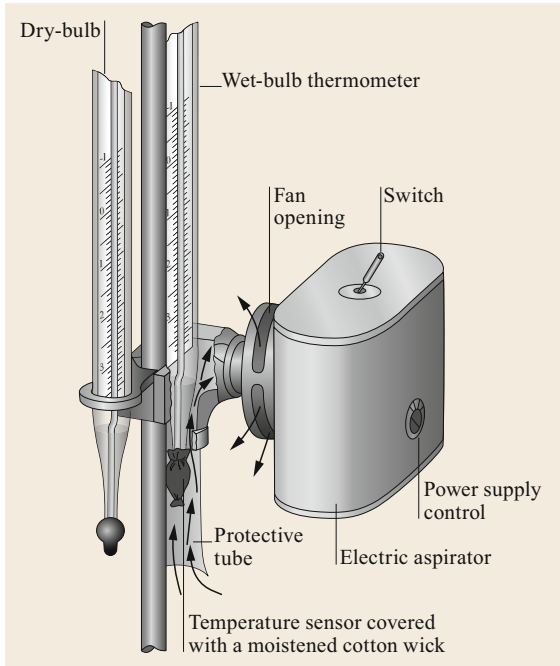
Fig. 8.18 Psychrometer according to August, with forced ventilation of the wet-bulb thermometer (after [8.7] with permission from VDI e. V., Düsseldorf, Germany)

Psychrometer According to August

The psychrometer according to August [8.39, 40] for measurements in meteorological screens (Figs. 8.5, 8.18) using liquid-in-glass thermometers is still in widespread use at climate stations (Chap. 43). These instruments have two vertically oriented thermometers, but only the wet-bulb thermometer is ventilated. The wetting of the bulb must be done by hand before each measurement. The aspirator is driven by a spring or, more recently, an electrical motor. Ventilation should be started approximately 5 min before the measurement.

Psychrometer According to Assmann

The Assmann aspirated psychrometer [8.4, 7, 14, 45] uses liquid-in-glass thermometers, originally filled with mercury and more recently with alcohol. This instrument is not suitable for continuous measurements, but rather the Assmann aspirated psychrometer is still among the most accurate humidity measuring instruments. Besides the original version, many similar constructions are currently in use. In 1987 the World Meteorological Organization compared a large number of these psychrometers against the WMO reference psychrometer. This study found that psychrometers with the original dimensions were the most accurate instruments [8.84].

The dry and wet thermometers are protected against radiation by a double radiation shield and are ventilated.

The distance between both bulbs and the radiation shield is large enough that water droplets or ice cannot bridge this gap, which would otherwise lead to heat conduction. Both thermometers are ventilated separately. The ventilation speed should be about $3.5 \, \mathrm{m \, s^{-1}}$ so that it is not reduced significantly by the larger wet bulb. Normally a spring driven aspirator is used. The speed may be controlled by the number of rotations made by the casing box of the spring within a certain time interval. The spring may also be replaced by an electric motor. Details of the construction are illustrated in Fig. 8.19.

The measurements should be made following the standard operating procedures listed below. During the measurements, the instrument should be vertically oriented so that the influence of the wind speed is minimized. The instrument should not be oriented towards the sun and should be placed sufficiently far from the body of the observer. Installation on a separate boom is helpful. The typical height of measurement is $1.25–2.0 \, \mathrm{m}$. Before taking measurements the instrument should be in equilibrium with the air, which can be tested by taking several readings of the dry temperature. Outdoor psychrometric measurements should be repeated at least three times and averaged because of the fast changing air temperature. The order of the steps is [8.4]:

- Moisten the wet bulb.
- Wind the spring drive (or start the electric motor).
- Wait $2–3 \, \mathrm{min}$ or until the wet bulb reading has stabilized.
- Read the dry-bulb thermometer.
- Read the wet-bulb thermometer.
- Check the reading of the dry-bulb thermometer again.

Electrical Psychrometer

Many types of electrical psychrometers, where the liquid in glass thermometers are replaced by Pt100 resistance thermometers (Chap. 7), are available, often built by research institutes. Of the commercially produced psychrometers, the types that best fulfill any given requirement are constructed similarly to the Assmann aspiration psychrometer. One such instrument is the psychrometer according to *Ernst Frankenberger* (1899–1985) [8.87], with resistance thermometers (Pt100) and a double screen radiation shield in the same dimension as the original instrument. Figure 8.20 shows this instrument, which is suitable for continuous measurements above $0 \,^{\circ}\mathrm{C}$.

A disadvantage of this instrument is the nonvertical orientation of the tubes of the thermometers, which can generate a slight dependence of the ventilation speed on the wind speed and direction. Furthermore, the length of the cotton wick between the sensor and the water
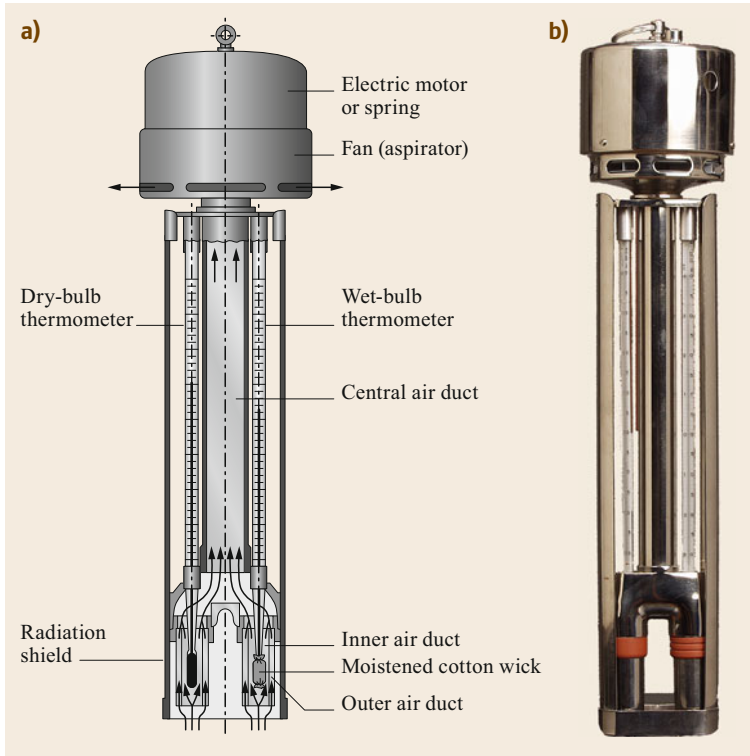
Fig. 8.19 (a) Schematic view of an Assmann aspirated psychrometer (after [8.7] with permission from VDI e. V., Düsseldorf, Germany). **(b)** A production model (photo © Theodor Friedrichs & Co., Schenefeld, Germany)
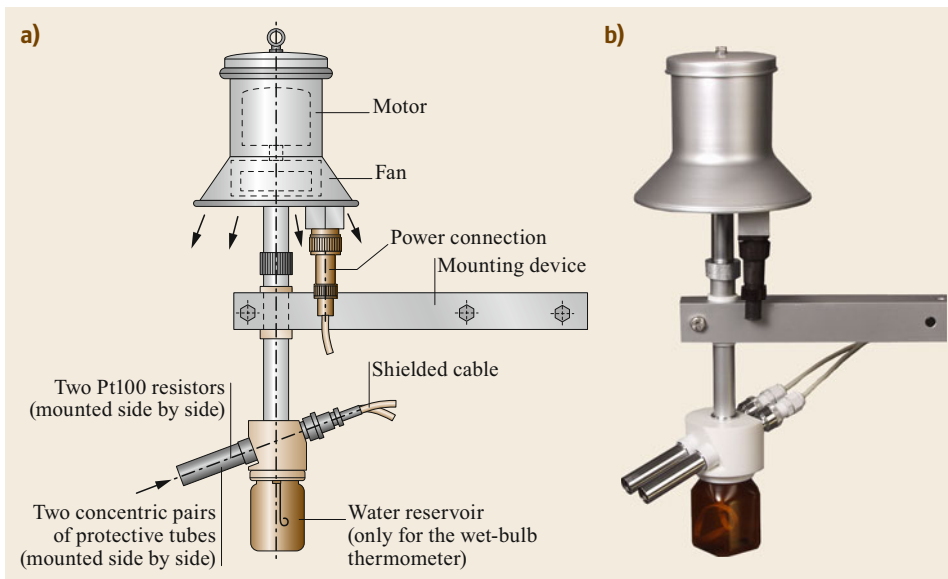

Fig. 8.20 (a) Schematic view of the psychrometer according to Frankenberger (after [8.7] with permission from VDI e. V., Düsseldorf, Germany), and **(b)** a recently produced type (photo © Theodor Friedrichs & Co., Schenefeld, Germany)

level can change, and the water flow can be interrupted at high evaporation or if the water level in the reservoir is allowed to drop too low. The water level should be checked every few days, especially during summer. To reduce possible re-circulation under conditions of weak winds or stable stratification, sensor and aspirator should be separated, which can be easily realized. The tubes of the thermometers should be oriented towards north (northern hemisphere).

Below $0\,°C$, water in the wet-bulb wick may freeze, leading to measurement ambiguity. To avoid this problem and since the water-vapor pressure does not depend
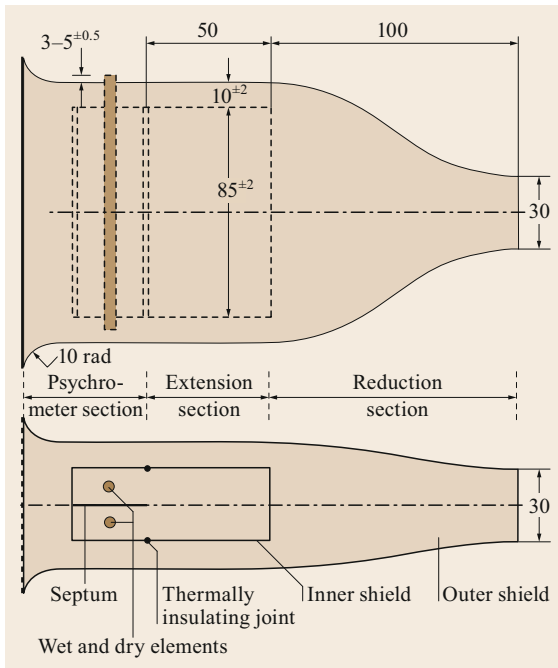
Fig. 8.21 Construction details of the proposal for a WMO reference psychrometer (after [8.88] with permission from World Meteorological Organization, Geneva, Switzerland). *Upper*: top view. *Lower*: side view

on temperature, a heated psychrometer was used. The heated psychrometer has a dry-bulb thermometer for ambient temperature and a heated and ventilated chamber ($\approx 10\,°C$) with wet-bulb and dry-bulb thermometers according to the psychrometric principle [8.4]. The relative humidity at ambient temperature can then be calculated based on these measurements.

The WMO Reference Psychrometer
In 1957, the second session of the WMO Commission for Instruments and Methods of Observation (CIMO) at Paris recommended building a reference psychrometer, which was directed by the Working Group on Hygrometry (lead by *Russell G. Wylie*, Australia). A final report was given at the sixth session in Helsinki in 1973. First, four types were constructed in the USA, Australia, the UK, and Japan. The main recommendations were to achieve a psychrometer coefficient close to the theoretical value of 6.53×10^{-1} hPa K^{-1} at 20 °C, 1000 hPa and 50% relative humidity. The construction sketch is shown in Fig. 8.21. In this design, evaporation at the wet-bulb thermometer should be very efficient, and an external heating or heat conduction from the mounting should be excluded. Both thermometers should be double shielded, well-ventilated, and horizontally oriented. The water level should be constant, which can be im-

plemented using an airtight reservoir above the sensors (not shown in Fig. 8.21), a downpipe, and a reservoir below the wet-bulb sensor having a constant water level.

According to these recommendations, finally two WMO reference psychrometers were constructed in Germany (former GDR) [8.89] and Australia [8.88]. The comparison of both reference psychrometers with the standard Assmann psychrometer showed good agreement within the given accuracy [8.84].

The WMO reference psychrometer is a primary standard for meteorology, because its performance is very predictable with few external influences only. This instrument can be used inside a screen together with other instruments. Special attention needs to be given to the aspiration and the cleanliness of the wet-bulb thermometer. Comparison experiments should be conducted by experienced personnel following WMO recommendations [8.88].

8.4.5 Dewpoint and Frostpoint Hygrometers

Dewpoint and frostpoint hygrometers are among the most stable and accurate instruments [8.8], since they measure dewpoint or frostpoint temperature directly. For that reason, they are often used as reference instruments [8.4]. Most dewpoint and frostpoint hygrometers are based on the chilled mirror principle [8.90]. In these instruments, a small mirror is cooled until water condenses on its surface, either as liquid water or ice. An electronic detector senses the reflectivity of this condensate and regulates the mirror temperature such that the measured reflectivity remains constant. Under this condition, the condensate is in equilibrium with the gas phase of water in the air above the mirror, and the temperature of the condensate is a direct measurement of the equilibrium temperature. This temperature represents the dewpoint temperature, if the condensate on the mirror is liquid, or the frostpoint temperature, if the condensate is ice.

Cooling of the mirror may be done using electronic Peltier coolers, through cryogenic cooling or a combination of both. Some research instruments have also used Stirling coolers. Some systems have an automatic mirror-cleaning heating cycle, in which volatile contaminants are evaporated, or use a mechanical wiper to clean the mirror.

A dewpoint or frostpoint hygrometer requires a minimum flow rate of approximately $0.25-1$ L min^{-1} to achieve an acceptable response time and stable operations [8.4]. For temperatures below 0 °C the phase of the condensate on the mirror must be known to distinguish between supercooled water, i.e., the mirror
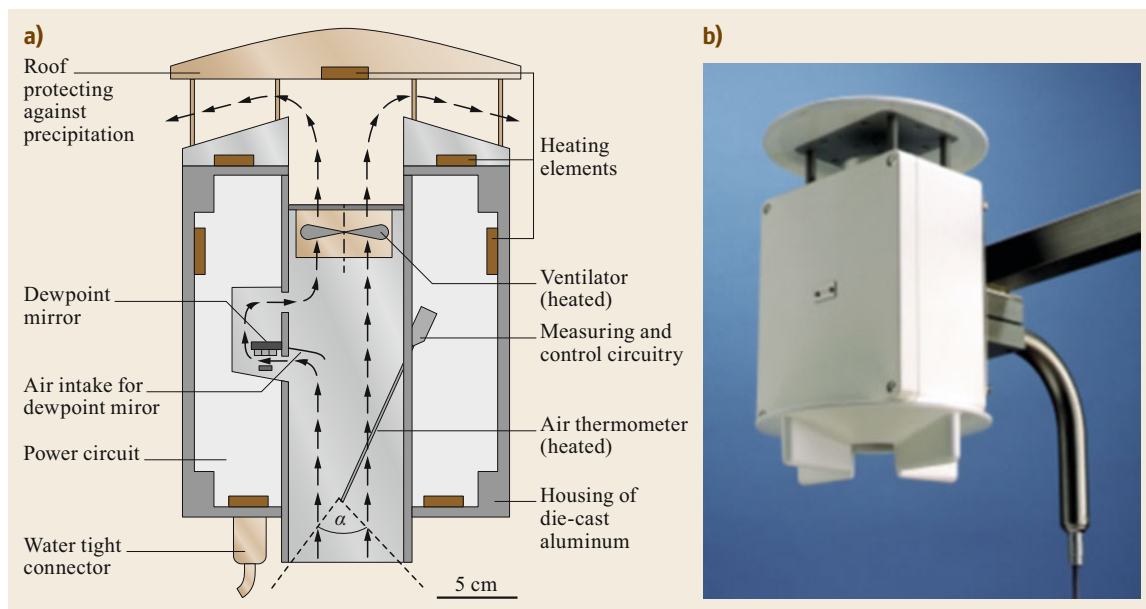
Fig. 8.22a,b Dewpoint hygrometer Thygan VTP6: **(a)** Schematic view (after [8.91] with permission from Meteolabor AG, Wetzikon, Switzerland); **(b)** sensor (photo © Meteolabor AG, Wetzikon, Switzerland)

temperature corresponds to dewpoint temperature, and ice, i.e., the mirror temperature corresponds to frost-point temperature.

One dewpoint hygrometer, used occasionally as reference instrument for atmospheric water-vapor concentrations, is made by Meteolabor AG [8.91, 92] (Fig. 8.22). Less complicated but still highly accurate instruments are available from other manufacturers. But dewpoint hygrometers are seldom used as in-situ sensors because of possible contamination. They are the standard instrument in dewpoint generators for humidity calibration. Dewpoint hygrometers are also used in balloon borne and aircraft observations for measurements of upper air humidity (Chap. 46).

8.4.6 Optical Hygrometers

Optical instruments are the only instruments suitable for measuring humidity fluctuations at frequencies up to about 100 Hz. These instruments are mainly used for turbulence and flux measurements (Chap. 55), less frequently for measurements of humidity (absolute humidity, mixing ratio) due to possible drifts and long-term stability issues. IR hygrometers dominate the market despite their lower sensitivity and have almost completely replaced the more sensitive but less stable UV hygrometers. Infrared hygrometers are available as either an open-path instrument for measurements near the wind sensor, or as a closed-path instrument, where

an inlet near the anemometer is connected to the analyzer through a tube. Some trace-gas analyzers may also measure water vapor, usually based on the principles discussed here (Chap. 16).

UV Hygrometers

The Lyman-alpha hygrometer was the first instrument used for humidity flux measurements. Due to the high light absorption of water vapor in the Lyman-alpha band (Fig. 8.13), the instrument – composed of a hydrogen lamp and a detector – is very sensitive, even for path lengths as short as 10–20 mm and low absolute humidities. Because of the low stability of the lamp, this system is mainly used on aircrafts (Chaps. 48 and 49).

The more stable krypton hygrometer KH20 produced by Campbell Sci. Inc. (Fig. 8.23) uses a low-pressure krypton glow tube as a light source and is still in use. The krypton lamb emits a minor band at 116.49 nm (band 1) and a major band at 123.58 nm (band 2). Radiation at 123.58 nm is strongly attenuated by water vapor, whereas absorption by other gases is relatively weak (Fig. 8.13). Radiation at the shorter wavelength (116.49 nm) is attenuated by water vapor as well as oxygen molecules, but the intensity of the transmitted beam is considerably attenuated by magnesium fluoride windows used at the lamb and detector tubes [8.56]. The measured signal I (I_{01} and I_{02} are the intensities of the source at both wavelengths) depends
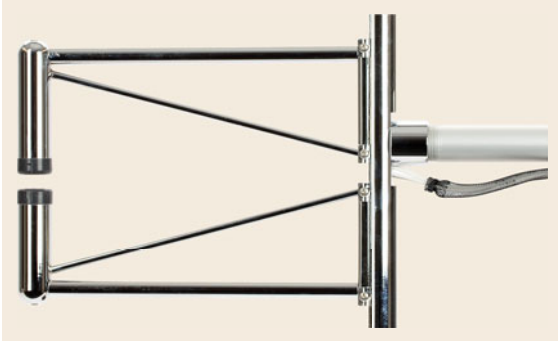
Fig. 8.23 Krypton hygrometers (image © Campbell Scientific, Inc., Logan UT, USA, 2017). The design of Lyman-alpha hygrometers was similar, but with a slightly larger lamp

on the path length x, the mass absorption coefficients k, and the densities ρ of both absorbers: water vapor (index w) and oxygen (index O) [8.56, 93]

$$I = I_{01} \exp\left[-x(k_{v1}\rho_v + k_{O1}\rho_O)\right] + I_{02} \exp\left[-x(k_{v2}\rho_v + k_{O2}\rho_O)\right], \qquad (8.26)$$

where the indices 1 and 2 refer to the two wavelengths at 116.49 nm and 123.58 nm, respectively.

The absorption coefficient at the short wavelength is half of that at the longer wavelength [8.94]. Since only the signal of these two wavelengths is measured, it is possible to extract the water-vapor absorption signal from the combined measurement with an combined value k_v. The fraction of the oxygen absorption of band 1 is f and of band 2 is $(1-f)$. The simplified (8.26) is

$$I = I_0 \exp(-xk_v\rho_v) \times \left[f \exp(-xk_{O1}\rho_O) + (1-f)\exp(-xk_{O2}\rho_O)\right]. \qquad (8.27)$$

For most applications, the additional oxygen absorption can be ignored and the basic equation for the calculation of krypton hygrometer KH20 is

$$\ln(V) = \ln(V0) - \rho_v x K_v , \qquad (8.28)$$

with the intercept $\ln V0$ in $\ln(\text{mV})$, $\approx 8-10\ln(\text{mV})$, the calibration coefficient (effective absorption coefficient for water vapor) K_v in $\ln(\text{mV})\,\text{m}^3\,\text{g}^{-1}\,\text{cm}^{-1}$, the coefficient xK_v in $\ln(\text{mV})\,\text{m}^3\,\text{g}^{-1}$ for a given path length x in cm and the absolute humidity ρ_v in $\text{g}\,\text{m}^{-3}$. This simplification is possible because only fluctuations of absolute humidity are of interest (see Chap. 55) and the oxygen concentration is assumed not to change (for nearly constant air pressure, therefore no application on

aircrafts possible). Nevertheless, small corrections are recommended [8.95, 96].

Equation (8.26) can also be used for calibration: assuming a constant absolute humidity, the path length can be changed to determine the calibration coefficient. This method was already developed for Lyman-alpha hygrometers because of the low source stability but can also be applied for krypton hygrometers [8.97]. But here the calibration is against oxygen and assumes a similar contamination of the windows or the source for both gases – oxygen and water vapor [8.98].

IR Hygrometers

The absorption of infrared radiation by water vapor is not as strong as that of ultraviolet radiation. Therefore, the absorption is often measured at two nearby wavelengths, where one is strongly absorbed by water vapor, the other not. Alternatively, in closed-path systems, two measurements may be taken, where one measurement is that of the air sample, the other that of dry reference gas. From the difference of both signals the concentration can be calculated. The devices often measure not only water vapor but also carbon dioxide. Because the sensitivity is much lower than for UV devices, the path length of approximately 15 cm is about tenfold that of the UV devices. To increase the path length, mirror systems are designed that reflect the light beam multiple times. A chopper system measures the different spec-

Temperature controlled optics and detector provide stable measurements – even in wide temperature fluctuations

Scratch-resistant sapphire lenses for simple cleaning in the field

Ambient air temperature measurements at the optical path

High-performance brushless chopper motor provides dependable long-term operation

Precision optical components reduce sensitivity to contamination in dusty environments

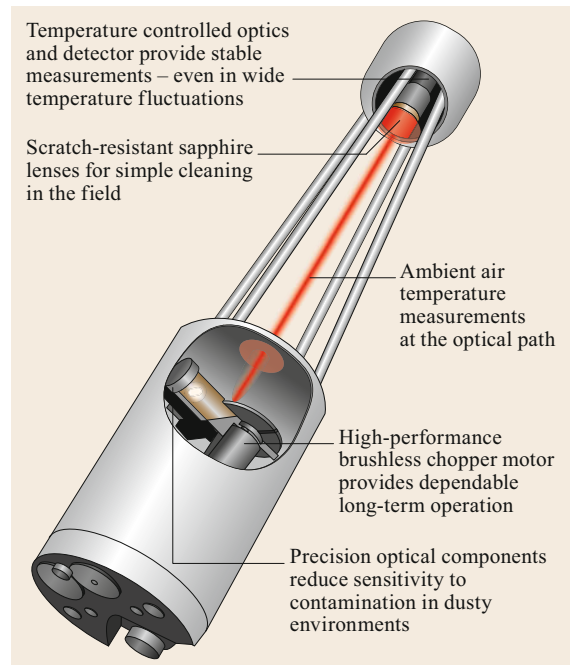**Fig. 8.24** Open-path H_2O-CO_2-gas analyzer (LI-7500-DS) (image: ©, LI-COR, Inc., Lincoln NE, USA)
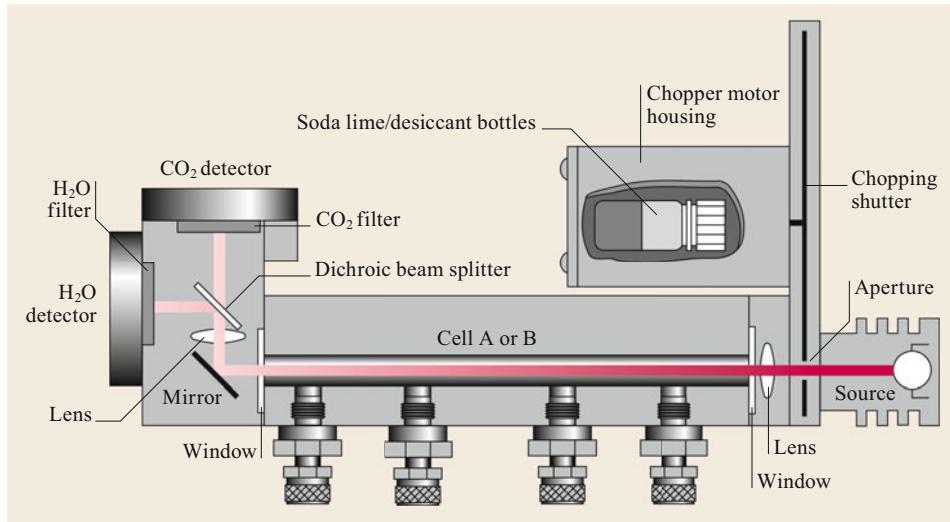
Fig. 8.25
Closed-path gas analyzer (LI-7000), for details see text (image: ©, LI-COR, Inc., Lincoln NE, USA). One cell measures the air sample, while the other measures the dry reference gas

tral lines separately. Due to the fast response time the systems can measure at a sampling rate up to 20 Hz. The frequency of measurement is currently limited by the sensitivity of the electronics and not by any physical principle.

IR-hygrometers are available as open-path (Fig. 8.24) and closed-path systems (Fig. 8.25). While open-path systems measure the air volume of interest directly, i.e., near the sonic anemometer for eddy-covariance measurements (Chap. 55), the closed-path instrument extract air from a volume of interest using a tube and measure the water-vapor concentration in a closed cell nearby. Both systems detect the concentration as mass density (mass unit per volume) with some differences [8.99]. In the open-path system the concentration is affected by ambient temperature, requiring a specific density correction for water vapor – the WPL-correction according to *Webb*, *Pearman*, and *Leuning* [8.100] –, which is only a few percent for water vapor but may be large for trace gases. The advantage of open-path systems is a good frequency response, which is only limited by the path length. In closed-path systems, the optical cell has a uniform temperature and pressure, so that the mass density can be easily converted into the mass-mixing ratio

$$r_{wm} = \frac{R^* T}{M_d(p-e)} \rho_v ,$$ (8.29)

(where R^* is the universal gas constant and M_d the dry air molar mass, ρ_v the density of water vapor), or into the mol fraction

$$\chi_w = \frac{R^* T}{M_v(p-e)} \rho_v ,$$ (8.30)

with M_v the molar mass of water vapor. For more details see Chap. 55 and Table 55.3. The frequency response of closed-path systems is significantly slower than open-path systems due to the extractive sampling and transport of the air sample to the optical cell through the sampling tube. For turbulent flows the Reynolds number in the tube should always be larger than the critical Reynolds number of about 2500.

Manufacturers have recently attempted to combine the benefits of both systems, building closed-path systems that have very short sampling lines (about 1 m), or open-path systems with high-frequency temperature and pressure measurements. The direct measurement of the mixing ratio does not require the WPL-correction (Chap. 55).

8.4.7 Comparison of the Methods

The number of sensor principles and sensor types has significantly decreased in the last 20 years. One reason is that the capacitive polymer sensor, which has a nearly linear output signal, has been significantly improved and is now considered sufficiently stable. In contrast, lithium chloride dew cells are nearly out of use. Similarly for fast hygrometers, UV hygrometers have been replaced by IR hygrometers, which are more stable and have recently expanded their sensitivity range to low absolute humidities. The classical hair hygrometer has been used for a long time and continues to be used, mainly for indoor measurements or for instruments with mechanical registration. Psychrometers and dewpoint hygrometers continue to be used as reference instruments and for special applications, mainly in research. A brief description of advantages and disadvantages of each method is given in Table 8.11.

Table 8.11 Advantages and disadvantages of the different methods

Devices	Advantages	Disadvantages
Hair hygrometer	Simple mechanical instrument	Long time drift, regeneration necessary
Lithium chloride hygrometer	First electrical sensor to replace hair hygrometers	Handling of lithium chloride solution difficult, rarely used anymore
Capacitive hygrometer	Simple and stable electrical sensor	Screen may be necessary
Assmann psychrometer	High accuracy, reference instrument	No electrical output, difficult measurements $< 0\,°C$
Electrical psychrometer	Electrical instrument, accurate	Not suitable for temperatures $< 0\,°C$
Dewpoint and frostpoint sensor	Often very accurate, reference instrument	High level of maintenance required for accurate measurements
UV hygrometer	Fast response hygrometer, very sensitive at low absolute humidities	Unstable light source, rarely used anymore
IR hygrometer	Fast response hygrometer, sensitive over a large range of humidities, open-path and closed-path instruments	Density and other corrections necessary, especially for flux applications

8.5 Specifications

Typical uncertainties of different humidity sensors are given in Table 8.12. Most of the available dewpoint and capacitive sensors may be considered WMO working standards or even as reference standards (Sect. 8.6.1 and Table 8.14). In many applications the limiting factor is the housing of the sensor, not the sensor itself, in particular in low-cost installations. Details of the possible influences of sensor enclosures on the measurements are described in Chap. 7.

Typical response times are given in Table 8.13. For turbulence measurements, optical sensors are generally used; for moving platforms, such as balloons and aircrafts capacitive polymer sensors and dewpoint and frostpoint hygrometers may also be found (Chaps. 46, 48, and 49).

Table 8.12 Typical characteristics for humidity sensing methods [8.7]. Some high quality sensors may have better characteristics than listed here

Method	Typical total uncertainty	Temperature range	Humidity range
Hair hygrometer	$\pm 5\%\,RH$	-10 to $50\,°C$	$> 40\%\,RH$
Capacitive hygrometer	$\pm 3\%\,RH$	0 to $45\,°C$	$5-100\%\,RH$
	$\pm 5\%\,RH$	-10 to $0\,°C$	$5-95\%\,RH$
Psychrometer	$\pm 2\%\,RH$	0 to $50\,°C$ wet-bulb temperature	$> 5\%\,RH$
Dewpoint and frostpoint hygrometer	$\pm 0.2\,K$	-100 to $50\,°C$ dewpoint or frostpoint temperature	
Optical hygrometer	$\pm 5-10\%$ of absolute humidity	-10 to $50\,°C$	

Table 8.13 Typical time constant (63%) in seconds at 85% relative humidity for humidity sensing methods [8.4, updated]

Method	20 °C	0 °C	−20 °C
Hair hygrometer			
Ordinary human hair	32	75	440
Rolled hair	10	10	12
Goldbeater's skin	10	16	140
Electrical capacitive hygrometer	$1-10$	$1-10$	$1-10$
Psychrometer	$30-50$	$30-50$	$30-50$
Dewpoint and frostpoint hygrometer	$1-50$	$1-50$	$1-50$
Optical hygrometer	< 0.01	< 0.01	< 0.01

8.6 Quality Control

The section dealing with quality control for humidity sensors includes the definition of standards, calibration procedures, and the detection of typical errors.

8.6.1 Reference Standards

The WMO has developed a system of standards and instruments for calibration [8.4]. The requirements for these standards are given in Table 8.14. The primary standards (Sect. 8.6.2) should be available at the national standards and calibration laboratories. Secondary standards are required for national or regional calibration laboratories of meteorological services, etc. These standards must be compared against a primary standard every year. Reference standards for indoor calibration have almost a similar accuracy as secondary standards. Chilled-mirror dewpoint hygrometers or the WMO reference psychrometer [8.88] may be used as secondary or reference standards. Outdoor comparisons of humidity measurements may be done against working standards. These standards are chilled-mirror dewpoint hygrometers or the Assmann aspiration psychrometer

and must be compared against a reference standard at least annually. For an easy verification of the calibration of an instrument, salt solutions (Sect. 8.6.3) may be used. Ultraviolet hygrometers may also be calibrated in-situ by changing the path length (Sect. 8.4.6).

8.6.2 Primary Standards

Primary standards are maintained at the national metrology laboratories, where three different methods are in use [8.4]. The gravimetric method is based on an exact determination of the mass-mixing ratio. This is obtained by removing the water vapor from an air sample with a drying agent like phosphorous pentoxide (P_2O_5) or magnesium perchlorate ($Mg(ClO_4)_2$). The mass of the agent is determined by weighing before and after absorption of the vapor. Therefore a complex apparatus is required to accurately control the measurement conditions to determine the density of the sample.

The dynamic two-temperature standard humidity generator saturates air at one temperature. The saturated

Table 8.14 Typical measurement range for humidity standard instruments [8.4]

Standard instruments	Dewpoint temperature		Relative humidity	
	Range (°C)	Uncertainty (K)	Range (%)	Uncertainty (%)
Primary standard				
Requirement	−60 to −15	0.3	5−100	0.2
	−15 to +40	0.1	5−100	0.2
Gravimetric humidity generators	−60 to −35	0.25		
	−35 to +35	0.03		
	+35 to +60	0.25		
Standard two-temperature humidity generator	−75 to −15	0.25		
	−15 to +30	0.1		
	+30 to +80	0.2		
Standard two-pressure humidity generator	−75 to +30	0.2		
Secondary standard				
Requirement	−80 to −15	0.75	5−100	0.5
	−15 to +40	0.25	5−100	0.5
Chilled-mirror hygrometer	−60 to +40	0.15		
WMO reference psychrometer			5−100	0.6
Reference standard				
Requirement	−80 to −15	1.0	5−100	1.5
	−15 to +40	0.3	5−100	1.5
Chilled-mirror hygrometer	−60 to +40	0.3		
WMO reference psychrometer			5−100	0.6
Working standard				
Requirement	−15 to +40	0.5	5−100	2
Chilled-mirror hygrometer	−10 to +30	0.5		
Assmann psychrometer	−10 to +25		40−90	1
Electrical capacitive hygrometer	−20 to +40		5−90	2
	+15 to +30		5−90	1

Table 8.15 Saturated salt solution at 25 °C and their characteristic relative humidity [8.4, 101, updated]

Salt	Chemical symbol	Relative humidity (%)	Solubility (g/100 mL)
Potassium sulfate	K_2SO_4	97.3	23
Barium chloride	$BaCl_2$	90.3	37
Potassium chloride	KCl	84.3	34
Sodium chloride	NaCl	75.3	36
Potassium iodide	KI	68.9	144
Sodium bromide	NaBr	57.6	91
Magnesium nitrate	$Mg(NO_3)_2$	52.9	71
Potassium carbonate	K_2CO_3	43.2	112
Magnesium chloride	$MgCl_2$	32.8	54
Calcium chloride	$CaCl_2$	29.0	135
Potassium acetate	KCH_3COO	22.5	228
Lithium chloride	LiCl	11.3 [8.101]	83
Lithium bromide	LiBr	6.4	160

air is then heated up to a second temperature for which the relative humidity can be calculated on the basis of the water-vapor pressure for saturation at the first temperature.

The dynamic two-pressure standard humidity generator has two chambers, one filled with air saturated over liquid water at the pressure p_0. The air is expanded isothermally into a second chamber at a lower pressure p. Both chambers must have the same temperature. The relative humidity in the second chamber is defined by the ratio of the pressures in each of the two chambers through Dalton's law [8.4, 14]

$$RH = 100\frac{e}{E_w} = 100\frac{p}{p_0} \quad \text{in \%}. \tag{8.31}$$

Relative humidity with respect to saturation over ice is defined analogously to the procedure given above if the air at high pressure has been saturated over ice.

Most humidity generators use dewpoint hygrometer as a reference instrument. Recently, well-calibrated capacitive hygrometers have also been used as a reference sensor.

8.6.3 Salt Solutions

Air above the surface of a saturated salt solution equilibrates at a characteristic value of relative humidity (Table 8.15), which may depend slightly on temperature. This effect can be used for the calibration of small humidity sensors. Great care needs to be taken that the salt solution is properly saturated and that the entire system is thermally well equilibrated when a sensor calibration or calibration check is performed. Using an array of different salt solutions allows calibration over a large range of relative humidities. This method is very practical for checks of individual small sensors,

but does not supersede the comparison with reference hygrometers [8.4].

8.6.4 Quality Control Procedures

The quality control of humidity measurements must be part of the quality control procedures of all sensors at a meteorological station (Chaps. 3 and 43). A typical range of relative humidity is between 10 and 100%, with maximal changes within 1 min (10 min, 1 h) of 10% (30%, 50%). Nearly constant values within 6 h are questionable and constant values within 12 h are to be considered erroneous [8.102]. The upper limit of humidity is 100%, corresponding to saturation water-vapor pressure over water at a given temperature. Small values of supersaturation over water may be possible for a short amount of time (minutes), while supersaturation over ice may last significantly longer (up to hours). Table 8.16 gives some sensor-specific criteria that may be applied in quality control procedures. If the cause for invalid data cannot be determined and rectified, then a specialist should check the sensor and measurement setup.

Humidity sensors should be installed in meteorological screens or in a ventilated double shield for protection against radiation and rain. For open installations such as for optical instruments, a radiation error correction may be necessary and the instrument may fail all together under rainy conditions. If the sensor does not provide internal error coding, parallel rain detection may be necessary. Significant air pollution may lead to contamination of dry-bulb and wet-bulb wicks, mirrors or sensor windows. Wind may affect the ventilation rate leading to a dependence of the measurements on the wind direction in many instruments. Ventilation rates greater than $2.5\,\mathrm{m\,s^{-1}}$ should be guaranteed for all wind directions and wind speeds.

Table 8.16 Typical tests criteria for humidity measurements

Method	Error	Reason
All instruments	RH < minimum for climate zone	Humidity too low for the method, new calibration necessary
Hair hygrometer	RH > 100% for more than 1 h	New calibration necessary
	RH = const. for more than 3−6 h	Mechanics must be cleaned
Capacitive hygrometer	RH > 100% for more than 1 h	New calibration necessary
	Low sensitivity	Filter cap may be contaminated
Psychrometer	RH ≥100% for more than 1−3 h	Dry-bulb thermometer is wet or wet-bulb thermometer is dry
	Unusually small differences between dry-bulb and wet-bulb temperature	No or low aspiration or contamination of the wick of the wet-bulb thermometer
Dewpoint and frostpoint hygrometer	Measured dewpoint temperature larger than ambient temperature for more than 1−3 h, or reduced sensitivity	Mirror contaminated or detector dirty; most instruments give an error code
Optical hygrometer	Measured absolute humidity larger than saturation absolute humidity for the ambient temperature for more than 1−3 h, or reduced sensitivity	Windows contaminated or reduced signal of the light source

8.6.5 Calibration of Optical Hygrometers

Optical hygrometers can be calibrated with gases with a given humidity. For this, a calibration tunnel is installed in the optical path and the calibration gas flows through at a controlled and not too large flow rate. The zero-point must first be calibrated normally with dry nitrogen gas. Next, for the span calibration, a certain water-vapor concentration can be generated with dewpoint generators. The dewpoint can be easily recalculated as absolute humidities. Optical systems for water vapor that are applied for other trace gases like carbon dioxide can be calibrated in a similar way with a zero-gas and one or more calibration gases with a given concentration (see also Chap. 55). In any case, the calibration instructions of the manufacturer should be carefully applied.

8.6.6 Documentation and Metadata

Sensors have significantly changed over the last 20−30 years. Sensors such as lithium chloride dew cell have been almost completely replaced by the capacitive polymer sensors in automatic weather stations. For the maintenance of atmospheric climate records as well as for operational observations it is vital that all sensor changes, updates, replacements, and other measures impacting the observations are meticulously documented [8.83]. This includes documentation of parallel observations with old and new sensors during periods of transition and overlap and other comparison experiments. However, calibration updates and comparisons with working or reference standards must be documented. These efforts are of utmost importance and constrain the impact that sensor changes may have on long-term climate records or input observations for short-term weather forecasting.

8.7 Maintenance

Some general rules for maintenance should be followed for all instruments [8.4]: Sensors and housings should be kept clean, as well as the meteorological screen if necessary. This is very important for radiation shields, but particularly for those of psychrometers. Some sensors, for example chilled-mirror, optical hygrometers, and hair hygrometers, may be regularly cleaned with distilled water. Where available, instructions by the manufacturer should be consulted.

Monthly comparisons with a working reference hygrometer, such as an Assmann aspiration psychrometer, are essential. For sensors relying on air temperature measurements, such as psychrometers and dewpoint hygrometers, that temperature sensor should be checked as well, which may easily be done with the Assmann psychrometer. Calibration against a reference standard in the laboratory should be done at regular intervals, such as annual or biannual and should include checks of the electronic data acquisition system.

Table 8.17 gives an overview of required maintenance for the most commonly used sensor types. Further information is given in Sect. 8.4.

Table 8.17 Maintenance of humidity measurement systems [8.7, updated]

Maximum interval	Hair hygrometer	Capacitive hygrometer	Psychrometer	Dewpoint and frost-point hygrometer	Optical hygrometer
1 week	Regeneration of hair and readjustment, if necessary		Refill water	Clean mirror, if not done automatically	Clean window with methanol or ethanol
1 month	Function and plausibility check, comparison with working reference such as Assmann psychrometer				
3 month	Check the mechanical function	Check and replace the filter cap, if necessary	Replacement of the cotton wick; may be required more frequently in areas with high levels of air pollution; inspection of the aspirator		Calibration in a climate test chamber, for IR hygrometers after 6−12 months, if necessary
2 year	Calibration of the instrument				
If a check indicates a possible malfunction, an instrument is to be replaced					

8.8 Application

Humidity is a standard meteorological parameter measured at nearly all meteorological stations (Chaps. 43 and 45) and is an important parameter for determining evapotranspiration (Chap. 57) and latent heat flux (Chap. 55). Many physical and chemical processes in the atmosphere involve water vapor. Absolute humidity and water-vapor pressure are sufficient to characterize an air mass; however, but the relative humidity must always be recorded together with air temperature.

8.8.1 Climatology of Humidity

Modern data acquisition technologies allow sampling rates of 1−10 s. Typical averaging intervals for humidity are 10 min, but intervals of 30 min or 60 min are also used. For standard meteorological measurements in Central Europe the daily mean is calculated from 24 values a_i, which may be relative humidity, absolute humidity or water-vapor pressure, recorded at one-hour intervals between 23:50 UTC of the previous day and 23:50 UTC of the current day [8.7]

$$\overline{a_{\text{day}}} = \frac{1}{24} \sum_{i=0}^{23} a_i . \tag{8.32}$$

For other time zones the averaging times must be adjusted accordingly. The climatological daily mean is calculated according to (8.32). If more than four continuous hourly values are not available, the daily mean is calculated from the arithmetic mean measured at 00:00 UTC, 06:00 UTC, 12:00 UTC and 18:00 UTC. At climate reference stations, the mean of the humidity values obtained at 6:30 UTC, 13:30 UTC and 20:30 UTC is calculated from only these three readings.

8.8.2 Daily and Annual Cycles

Long-term averages of humidity carry only a limited significance. The frequency distributions of hourly averages are of higher significance. Instead of monthly means of relative humidity, the mean value at a fixed time, e.g., at 3 p.m., may be a better indicator for characterizing humidity at a station.

The daily cycle may be more instructive because high temperatures are related to low relative humidity and vice versa; for example, during a fine summer day the absolute humidity or the water-vapor pressure may not show significant changes or a daily cycle, whereas temperature and relative humidity do show a significant daily cycle (Fig. 8.26).
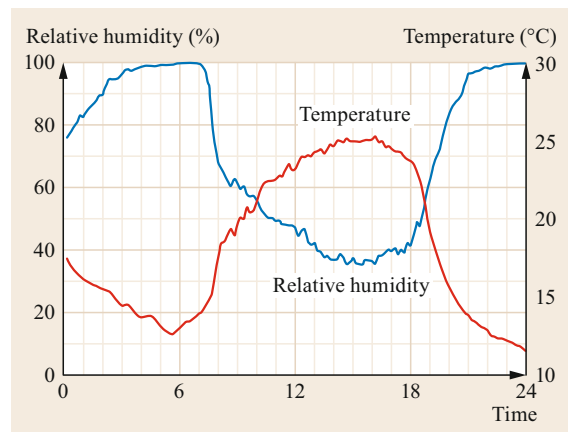

Fig. 8.26 Daily cycle of relative humidity and temperature during an arbitrary summer day (Bayreuth, Germany, Aug. 28, 2017)

8.9 Future Developments

The last review of hygrometry, including new developments in thermodynamics and devices, was made more than 20 years ago [8.8] and is a main reference in this field of research and measurements [8.4]. Since that time, the number of commercially used measurement principles has significantly decreased. Significant progress has been made to reduce drift in capacitive sensors particularly in humid environments. Dewpoint hygrometers (except Thygan) are rarely used as in-situ instruments but they remain important laboratory reference instruments and essential instruments in humidity generators. The development of the capacitive polymer technology continues with an expanding use of heated polymer sensors. A significant extension of the use of well-calibrated capacitive polymer hygrometers seems likely in the near future.

8.10 Further Readings

A comprehensive review of the diverse sensors, applications and maintenance of hygrometry is given by:

- VDI: Umweltmeteorologie, Meteorologische Messungen, Luftfeuchte (Environmental Meteorology, Meteorological Measurements, Air Humidity, in German and English), VDI 3786 Blatt(Part) 4, (Beuth-Verlag, Berlin 2013)
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- G. Korotcenkov: Handbook of Humidity Measurement, Volume 1: Spectroscopic Methods of Humidity (CRC Press, Boca Raton, London, New York 2018)
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