Chapter 3

Humidity

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CONTENTS

PLANT RESPONSE

Atmospheric water vapor (*humidity*) affects plants in growth chambers directly by conditioning transpiration and other gas exchange and indirectly by modifying the plant's energy balance and physical and biological environments.

The most significant and direct influence of humidity on plants is on *transpiration*, the evaporation of water from plant surfaces into the atmosphere (Ford and Thorne, 1974, 1986; Hoffman, 1972, 1973, 1979; Monteith, 1973; Mortenson, 1986; O'Leary and Knecht, 1971; Penman, 1948, 1956; Rawson et al., 1977; Rosenberg et al., 1983; Sellers, 1965). Transpiration generally increases as humidity decreases; however, the integrated influence of humidity, temperature (plant and ambient), irradiance, air movement, plant permeability to water vapor (stomata, cuticle), plant and soil water status (availability of water for evaporation), and evaporating surface extent (and orientation) determines transpiration rate increase (Aldrich et al., 1983; Barrs, 1973; Carlson et al., 1972; Decker, 1965; Forde et al., 1977; Gates, 1980). The balance and dynamics of water loss by transpiration and gain by root absorption determine plant water status. The probability of water deficit and subsequent adverse effects on growth increases with transpiration rate (Hoffman, 1979; Krizek, 1970). The translocation of water and growth materials from roots to shoots is also motivated by transpiration (Bloodworth et al., 1965). Abnormal plant growth and early senescence caused by mineral nutrient imbalance (Collier and Tibbitts, 1984; Demidenko and Golle, 1939; Freeland, 1936; O'Leary and Knecht, 1972; Tibbitts and Bottenberg, 1976; Tromp and

Oele, 1972; Wiersum, 1966) or plant growth regulator imbalance (Hoffman and Rawlins, 1971; Hughes, 1966; Pareek et al., 1969) may result from either deficit or excess transpiration under very high or low humidity, respectively. Postharvest quality is also affected by storage humidity (Grierson and Wardowski, 1975).

Humidity also affects transpiration and other gas exchange through direct control of stomatal opening (Lange et al., 1971; Schulze et al., 1974). Guard cells sense humidity and respond by adjusting turgor, thereby changing stomatal aperture. Although enormously beneficial for plant water use efficiency, stomatal closure may prove an overall detriment to plant yield by reducing carbon dioxide uptake and net photosynthesis.

Transpiration-induced evaporative cooling is a major component of shoot energy balance. The extent of cooling depends on many environmental and plant parameters. It is not unusual, however, for transpiration to remove more than 75 % of the radiant energy intercepted by a well-watered herbaceous plant canopy exposed to high irradiance (Decker, 1965; Hanan, 1984). This translates to a temperature reduction of as much as 30°C for a single, large, rapidly transpiring leaf under high irradiance or as little as 2 or 3°C under low irradiance or low transpiration rates (Gates, 1980). Humidity also reduces the incident radiant energy load through strong absorbance of infrared radiation in natural environments (Hale and Querry, 1973; Wolf, 1965; Wolf and Zissis, 1989). Although this effect of water vapor probably is insignificant in growth chambers because of the short radiation path, liquid water surrounding or below lamps is often used to reduce infrared irradiance on plant surfaces.

Humidity also very significantly affects the chamber physical environment (energy balance and environmental control)(ASHRAE, 1989; Esmay and Dixon, 1986; Rasmussen, 1972; Solvason and Hutcheon, 1965). It increases the specific heat of air, and its condensation or evaporation is accompanied by large latent heat energy exchange between water and the chamber atmosphere or heat exchangers. This has a direct impact on chamber temperature control and energy requirement. Humidity less significantly affects the chamber chemical (atmospheric pollution) and biological (pathogens, other microorganisms, etc.) environments (Stone, 1957).

The consequential influence of humidity on plant growth, its tendency for continuous change in any plant growth environment, and its tendency toward extreme levels in enclosed environments mandate its measurement and control in growth chambers to ensure consistent plant response and subsequent interpretation of experimental results (Tibbitts, 1978). This chapter reviews humidity as an environmental factor and discusses its measurement and control in growth chambers.

NATURE

GENERAL

Moisture technically refers to the water content (mechanically mixed, rather than chemically combined) of any solid, liquid, or gas, whereas *humidity* specifically means the water vapor content of a gas. Atmospheric humidity ranges from nearly 0 to more than 4% of the mass of air and averages about 3%, making it the third most common atmospheric constituent (Rasmussen, 1972). It comes from evaporation from open water surfaces (oceans, lakes, puddles, rivers), evaporation from wet exposed or contained solid surfaces (soil, animals, plants, ice [sublimation]), or by formation during chemical reactions (i.e., burning or other oxidation of organic substances). Humidity is lost from air by condensation into suspended water droplets or ice crystals in the atmosphere (clouds or fog) or onto solid surfaces. Humidity also decreases through chemical reaction with atmospheric or terrestrial constituents (Fehsenfeld and Albritton, 1980).

DEFINITIONS AND UNITS

A plethora of terms is used to describe humidity. Fortunately, most are easily converted from one to another through application of appropriate psychrometric charts and tables (Fig. 1)(Table 2)(Anon., 1968; Bindon, 1965; Carrier, 1911; Esmay and Dixon, 1986; Harrison, 1965a; List, 1966; Mangold et al., 1983; Tanner, 1972; Wilhelm, 1976). Application of psychrometric relationships to the operation of growth chambers often requires familiarity with more than one system of terminology. Chamber design, operation, and servicing compel knowledge of one set of terms, and characterizing humidity effects on plant processes requires another (and sometimes a third) to translate these to a form suitable for journal publication.

The physical behavior of dry air and water vapor mixtures approximates that of a perfect gas within the temperature and pressure range of most growth chambers (Threlkeld, 1970):

$$pV = nRT_K, \qquad [1]$$

where p = the pressure (Pa), V = the volume (m^3), n = the gas concentration (mol), R = the gas constant ($8.31 \cdot 10^7$ $erg \cdot mol^{-1} T_K^{-1}$), and T_K = the absolute temperature (K). According to Dalton's Law, atmospheric pressure is the integrated sum of its individual component gas pressures.

Absolute humidity, also referred to as *water vapor density* or *water vapor concentration*, establishes *water vapor pressure. Water vapor pressure* (e , $dyne \cdot cm^{-2}$ or Pa) is independent of pressure exerted by other atmospheric gases and is directly related to *absolute humidity* (ρ_v, $g \cdot cm^{-3}$) by:

$$e = [\rho_v \cdot M_v^{-1}] \cdot [RT_K] = 4.61 \rho_v \cdot T_K \cdot 10^3, \qquad [2]$$

where T_K is the ambient temperature and M_v is the molecular mass of water (18.016 $g \cdot mol^{-1}$). Sometimes vapor density is expressed as $moles \cdot m^{-1}$, where moles is determined from $\rho_v \cdot M_v^{-1}$.

Vapor density is calculated from vapor pressure by:

$$\rho_v = eM_v \cdot [RT_K]^{-1} = e[217 \cdot 10^{-6}] \cdot T_K^{-1}. \qquad [3]$$

The force driving evaporation (transpiration) is the water vapor pressure difference usually expressed in terms of *vapor saturation difference* (VSD, Pa) or vapor pressure deficit between the evaporating surface and the surrounding atmosphere:

$$VSD = e_s - e, \qquad [4]$$

where e_s is the *saturation vapor pressure.* Any difference between the air temperature and the evaporating surface temperature must be accounted for in determining VSD. Air is *saturated* (can absorb no more water) when it co-exists in neutral equilibrium with a plane surface of pure condensed phase (liquid or solid) water at the ambient temperature (T_C, °C) and pressure:

$$\log e_s = 0.026404 T_C + 0.82488, \qquad [5]$$

where T_C is greater than 0°C (Rose, 1966; Rosenberg, 1974). The water vapor capacity of air increases rapidly as temperature increases, approximately doubling for every 10°C rise throughout the plant growth temperature range (Table 1). Evaporation rate (E) is directly proportional to the vapor saturation difference between the wet surface (leaf) and surrounding atmosphere:

$$E = VSD \cdot r_v^{-1} \cdot g \cdot m^{-3} \cdot s^{-1}, \qquad [6]$$

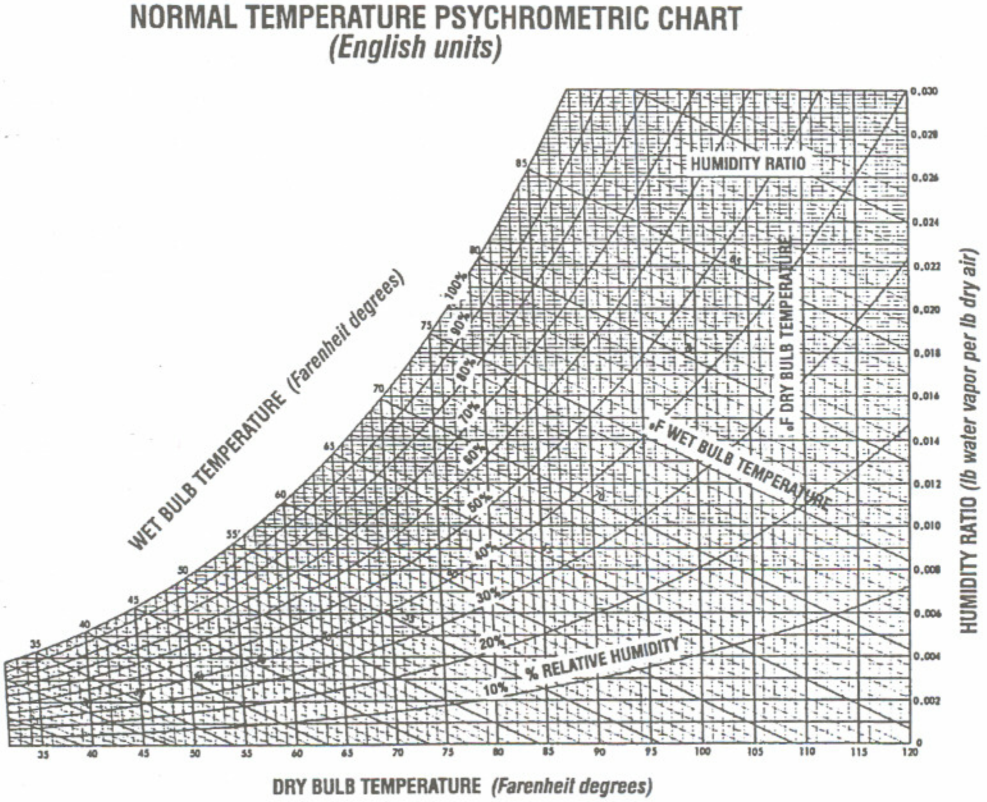
where r_v is the vapor diffusion resistance between the leaf evaporating surface and the surrounding atmosphere. VSD is therefore recommended for describing humidity effects on plants. Since the leaf internal atmosphere is seldom less than 98% saturated, the rate of water evaporation from a transpiring leaf is determined primarily by atmospheric humidity.

Relative humidity (h_r) is the ratio of ambient vapor pressure or density to that at saturation at the same air temperature:

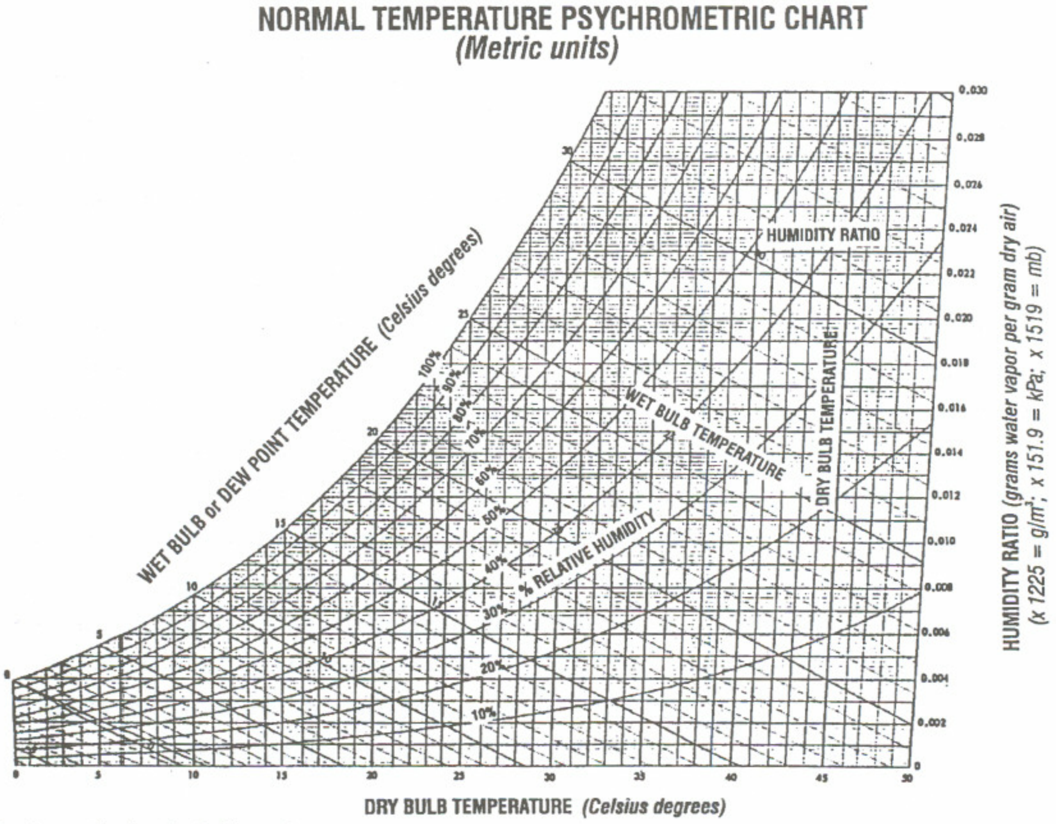
$$h_r = e \cdot e_s^{-1} \cdot 100\% = \rho_v \cdot \rho'^{-1}_v \cdot 100\%. \qquad [7]$$

It is humidity expressed as a percentage of

Figure 1. Two examples of psychrometric charts for determining humidity from wet bulb depression or dew-point measurements.



a. Psychrometric chart in English units.



b. Psychrometric chart in Celsius units.

what the air potentially holds at that same temperature. Relative humidity changes with temperature, even if water vapor density does not (Table 1). As air temperature increases, its water vapor capacity increases and relative humidity decreases, even though no actual change in water content or vapor density (evaporation potential) occurs. Inconsistent conclusions regarding humidity effects on plants (or other processes) can ensue if relative humidity rather than vapor density is the basis for interpretation. An understanding of relative humidity, however, is still important because it is easily the most commonly used term and will likely continue to be widely used.

Specific humidity (h_s), another expression of water vapor density, is the mass concentration of water vapor (m_v) in a given mass of moist air (m_{ma}):

$$h_s = m_v \cdot m_{ma}^{-1} = m_v(m_v + m_{da})^{-1} \qquad [8]$$

or

$$h_s = [(M_v \cdot M_{da}^{-1})e] \cdot [P_{ma} - \{1-(M_v \cdot M_{da}^{-1})\}e]^{-1}, \qquad [9]$$

or

$$= [0.622e] \cdot [P_{da} - 0.378e]^{-1}, \qquad [10]$$

where m_{da} is the mass of dry air; $M_{da,}$ the molecular mass of dry air (28.966 g· mol^{-1}, at one atmosphere pressure); $P_{ma,}$ the moist air pressure; and $P_{da,}$ the dry air pressure. *Dry air* is defined as that from which all water vapor and unnatural contaminants (e.g., smoke, pollen, dust, and gaseous pollutants) have been removed (Parsons, 1989). *Moist air* is a mixture of dry air and humidity.

Mixing ratio or *humidity ratio* (r) is the ratio of the water vapor mass to the dry air mass with which it is associated:

$$r = m_v \cdot m_{da}^{-1} \qquad [11]$$

or

$$r = [(M_v \cdot M_{da}^{-1})e] \cdot [P_{ma} - e]^{-1} \qquad [12]$$

or

$$r = [0.622e] \cdot [P_{ma} - e]^{-1} \qquad [13]$$

Specific humidity and mixing ratio are related by:

$$h_s = r \cdot [1+r]^{-1} \text{ and } r = h_s[1-h_s]^{-1}. \qquad [14]$$

Although commonly used by heating and air conditioning engineers, specific humidity and mixing ratio seem of limited application to growth chambers except perhaps during their initial design. Specific humidity and mixing ratio are often used to identify the energy exchange required to heat or cool a given air mass or to depict the dryness of industrial process gases (ASHRAE, 1989; 1990). Routine use of specific humidity in plant growth and other common situations is inconvenient because it requires measurement of atmospheric pressure as well as humidity and temperature to calculate the masses or pressures in determining vapor den-

Table 1. Temperature effect of saturated air on relative humidity (h_r), absolute humidity (r_v), mixing ratio (r), and vapor pressure (e_s) (Hyland and Wexler, 1983a; 1983b).

T_C	h_r	r_v	r	e_s
(°C)	%	g $H_2O \cdot m^{-3}$ *air*	g $H_2O \cdot Kg^{-1}$ *dry air*	Pa
.0	100	4.9	3.8	610
1.0	100	5.2	4.1	656
2.0	100	5.6	4.5	705
3.0	100	6.0	4.8	757
4.0	100	6.4	5.1	812
5.0	100	6.9	5.5	871
6.0	100	7.4	5.9	934
7.0	100	7.9	6.3	1000
8.0	100	8.4	6.7	1071
9.0	100	9.0	7.2	1146
10.0	100	9.6	7.7	1226
11.0	100	10.2	8.2	1310
12.0	100	10.9	8.8	1400
13.0	100	11.6	9.4	1495
14.0	100	12.3	10.0	1596
15.0	100	13.1	10.7	1702
16.0	100	13.9	11.4	1815
17.0	100	14.7	12.2	1934
18.0	100	15.6	13.0	2060
19.0	100	16.6	13.9	2193
20.0	100	17.6	14.8	2334
21.0	100	18.7	15.7	2483
22.0	100	19.9	16.7	2639
23.0	100	21.1	17.8	2805
24.0	100	22.4	18.9	2979
25.0	100	23.9	20.1	3163
26.0	100	25.4	21.4	3357
27.0	100	27.0	22.7	3561
28.0	100	28.8	24.1	3775
29.0	100	30.7	25.7	4001
30.0	100	32.8	27.3	4238

Table 2. Psychrometric table indicating vapor saturation difference (VSD) as a function of wet bulb depression and wet bulb temperature (List, 1949).

	Wet Bulb Temperature, °C										
Δt*	-50	-40	-30	-20	-10	0	10	20	30	40	50
	VSD(mb or k Pa·10)										
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.6220	0.6296	0.6372	0.6448	0.6524	0.6600	0.6676	0.675	0.683	0.690	0.698
2	1.2441	1.2593	1.2745	1.2896	1.3048	1.3200	1.3352	1.350	1.366	1.381	1.396
3	1.8662	1.8889	1.9117	1.9345	1.9572	1.9800	2.0028	2.026	2.048	2.071	2.094
4	2.4882	2.5186	2.5489	2.5793	2.6096	2.6400	2.6704	2.701	2.731	2.761	2.792
5	3.1102	3.1482	3.1862	3.2241	3.2620	3.3000	3.3380	3.376	3.414	3.452	3.490
6	3.7323	3.7778	3.8234	3.8696	3.9145	3.9600	4.0055	4.051	4.097	4.142	4.188
7	4.3544	4.4075	4.4606	4.5137	4.5669	4.6200	4.6731	4.726	4.779	4.833	4.886
8	4.9764	5.0371	5.0978	5.1586	5.2193	5.2800	5.3407	5.401	5.462	5.523	5.584
9	5.5984	5.6668	5.7351	5.8034	5.8717	5.9400	6.0083	6.077	6.145	6.213	6.282
10						6.6000	6.6759	6.752	6.828	6.904	6.980
11							7.3435	7.427	7.510	7.594	7.677
12							8.0111	8.102	8.193	8.284	8.375
13							8.6787	8.777	8.876	8.975	9.073
14							9.3463	9.453	9.559	9.665	9.771
15							10.0138	10.128	10.242	10.355	10.469
16							10.6814	10.803	10.924	11.046	11.167
17							11.3490	11.478	11.607	11.736	11.865
18							12.0166	12.153	12.290	12.426	12.563
19							12.6842	12.828	12.973	13.117	13.261
20								13.504	13.655	13.807	13.959
21								14.179	14.338	14.498	14.657
22								14.854	15.021	15.188	15.355
23								15.529	15.704	15.878	16.053
24								16.204	16.386	16.569	16.751
25								16.880	17.069	17.259	17.449
26								17.555	17.752	17.949	18.147
27								18.230	18.435	18.640	18.845
28								18.905	19.118	19.330	19.543
29								19.580	19.800	20.020	20.241
30								20.255	20.483	20.711	20.938
31								20.931	21.166	21.401	21.636
32								21.606	21.849	22.092	22.334
33								22.281	22.531	22.782	23.032
34								22.956	23.214	23.472	23.730
35								23.631	23.897	24.163	24.428

*Dry bulb temperature minus wet bulb temperature

sity. These parameters are not routinely measured directly in humidity determinations.

Parts per million (ppm) is also used to express humidity for certain applications. For example, mixing ratio or specific humidity is often expressed as ppm (especially in industrial gas use). The basis for definition of ppm, like *percent*, must be clearly specified because it can represent very different measures. Parts per million humidity is calculated on a volume basis from:

$$ppm_v = [V_v \cdot V_{ma}] \cdot 10^6 = e_a \cdot [P_{ma} - e_a]^{-1} \cdot 10^6 \qquad [15]$$

or on a mass basis from:

$$ppm_m = ppm_v \cdot [m_v \cdot m_{ma}^{-1}], \qquad [16]$$

where V_v and V_{ma} are the volumes of vapor and moist air, respectively.

Two additional water vapor density indicators are dew point and wet bulb temperatures. If air containing water vapor is cooled without changing its water content or barometric pressure, the *dew point temperature* (T_d) is the temperature at which air just reaches saturation (e_s equals e) and humidity begins to condense. Dew point defines water vapor concentration or water vapor pressure if the concurrent *dry bulb tem-*

perature (ambient air temperature, T_a) is known (Kale and Laby, 1956; List, 1949). When the dew point temperature is reached, cooling slows considerably because the condensing water releases a large amount of latent heat. Thus dew point temperature is useful to meteorologists for predicting daily low temperatures and to engineers for design of growth chambers.

Wet bulb temperature (T_w), the temperature of a wetted thermometer in an *unsaturated* atmosphere, is always lower than dry bulb temperature because of evaporative cooling. The difference between wet and dry bulb temperatures is a function of humidity (Table 2, Fig. 1) (Harrison, 1965b). Wet and dry bulb psychrometers, which employ this principle for measuring humidity, are probably the most simple, common, and accurate routine measure of humidity.

Water potential (ψ, ergs$\cdot$ cm^3, dyne$\cdot$ cm^{-2} or Pa), the newest terminology for describing humidity, is a measure of water's thermodynamic availability (or degree of interaction) for biological and physical processes relative to that of pure, free water (Aslying, 1963; Edlefsen and Anderson, 1953; Kramer et al., 1966; Taylor, 1968). Water potential is determined from measurements of water vapor pressure:

$$\psi = [RT\ln(e\cdot e_s^{-1})]\cdot V_w^{-1}, \qquad [17]$$

where V_w (cm$^3\cdot$ mole^{-1}) is the molar volume of water in the system under observation.

Of the prevalent terminologies describing humidity, water vapor density or other parameters from which water vapor density is readily derived (i.e., relative humidity, vapor pressure, dew point temperature, wet bulb temperature, vapor saturation difference) are appropriate for characterizing controlled environments; however, simultaneous air temperature measurement must accompany all of these. Although water potential is rarely, if ever, used, this term has the great advantage in plant water relations studies not only of being directly related to evaporation and other processes, but also of enabling direct and consistent comparison of atmospheric water status to plant and soil water status (and the tendency for water movement between them)(Table 3). Atmospheric water potentials at low humidities are enormously lower than plant or soil water potentials.

IN PLANT GROWTH CHAMBERS

FLUCTUATIONS

Humidity in chambers usually is influenced by a combination of factors including outside air water vapor content, exchange between chamber and outside air, evaporation rate from chamber sources including plants, refrigerant temperature, and others (Watson, 1965). Water vapor concentration in growth chambers characteristically fluctuates over a diurnal period from less than 2 to about 4% (near saturation) by mass when no direct humidity control is provided. Even a single heating and cooling cycle of 1 to 3 minutes can perturb chamber humidity 1 to 2% (20 to 40% relative humidity). Growth chambers generally exhibit greater fluctuations and extremes in humidity than the outside environment because they enclose a relatively

Table 3. Temperature effects on relative humidity (h_r) and water potential (ψ). Note that when relative humidity is held constant, water potential (which directly affects evaporation and other plant-humidity interactions) changes significantly with temperature.

h_r, %	15°C	20°C	25°C	30°C
	ψ*, MPa			
99.99		-0.135		
99.90		-1.35		
99.00	-13.3	-13.6	-13.8	-14.0
98.5	-20.1	-20.1	-20.8	-21.1
98.0		-27.3		
97.5	-33.6	-34.2	-34.8	-35.3
95.0		-69.2		
90.0		-142.2		
80.0		-301.2		
60.0	-677.9	-689.6	-701.4	-713.1
30.0		-1625.4		
10.0		-3108.5		

*ψ = Water Potential = $[RT\ln(e\cdot e_s^{-1})]\cdot V_w^{-1}$, with $R\cdot V_w^{-1} = 4.62\cdot 10^4$; T = K; $e\cdot e_s^{-1} = h_r$

small volume isolated from the buffering capacity of the surrounding atmosphere, contain a relatively high density of plant material which greatly increases humidity through transpiration, and employ cooling coils that decrease humidity by direct condensation of moisture from the air. Unregulated humidity in many chambers decreases during the light period because of the increased cooling required and increases during the dark period. Seasonal climatic changes also often affect chamber humidity as a result of forced exchange or leakage between chamber and outside air.

SOURCES

Humidity is introduced into growth chambers by evaporation from moist solids (including transpiration), evaporation from free water surfaces, evaporation from atomized water, direct vapor injection, and exchange with a more humid outside atmosphere. The continuous, relatively turbulent air flow characteristic of growth chambers enhances transpiration and other evaporation by diminishing surface boundary layers and rapidly removing the humidity from the wet surfaces. These effects combine to steepen the vapor concentration gradient between the source and surrounding atmosphere. The contribution from transpiration depends predominately on canopy density (total leaf area) and leaf permeability to water, which, in turn, depends on species, irradiance, leaf temperature, leaf water status, humidity, etc. Free water surfaces in growth chambers eventuate primarily from condensate on cooling coils and "slop" from irrigation. Open automatic irrigation or hydroponic systems also contribute to chamber humidity. Enclosed automatic irrigation systems combined with controlled drainage virtually eliminate irrigation water as a humidity source.

SINKS

Humidity is removed from growth chambers primarily through condensation within the chamber and exchange with outside air. Condensation occurs on any surface at or below dew point temperature. Chamber cooling coils are usually the site of such condensation. In fact, humidity control systems in chambers often use the cooling coils to reduce humidity to a base level from which humidity subsequently is increased to desired levels by injecting vapor. Condensation may also occur on chamber walls and other surfaces whenever their temperature is below the dew point, such as during the programmed rapid change from night to day temperatures and otherwise when air temperature increases more rapidly than that of the chamber structural components. At very high humidities, condensation may even be caused by temperature fluctuations within individual temperature control cycles in some chambers. When condensation occurs in electrical systems, a shock hazard exists and control failures can result. Although condensation on plant surfaces (dew) is prevalent at night in natural environments, especially when radiation cooling is high, it normally does not occur in growth chambers except those specifically designed to produce condensation (i.e., Percival and other manufacturers). Detection and measurement of dew uses some of the same techniques as for humidity (Noffsinger, 1965). Exchange with outside air, which is significant in most chambers, usually decreases chamber humidity levels.

MEASUREMENT

Humidity is perhaps the most difficult environmental factor to monitor. Although accurate and relatively simple instantaneous measurement is feasible, no practical, reliable, continuous humidity measurement is available.

WHAT TO MEASURE

The ideal humidity observation is one directly relevant to plant response or yield. Vapor saturation difference (VSD) is probably the most useful index because it correlates straightaway to evaporation (transpiration) and stomatal activity. However, vapor saturation difference is not commonly measured directly in plant research but is usually derived from the more common measurements of relative humidity, vapor pressure, dew point temperature, or wet bulb temperature, accompanied by simultaneous dry bulb temperature measurements. Although plants do not respond in a linear fashion to changes in relative humidity, relative humidity is our customary term. Therefore, its continued use is recommended *along with the calculation of vapor saturation difference*. Humidity measuring equipment is usually calibrated only in terms of relative humidity. Where the effects of plant water status are under study, the interaction of soil, plant, and atmospheric water status can be compared directly if all are expressed as water potential. The minimum measured and recorded information should include the diurnal average humidity and dry bulb temperature readings.

SENSORS AND DEVICES

There are many methods for measuring humidity (Forrester, 1979; Instr. Soc. Am., 1985; Krigman, 1985; Müller, 1965; Wexler, 1970; Wexler and Amdur, 1965; Wexler and Ruskin, 1965; Wexler and Wildhack, 1965; Wiederhold, 1978). Humidity measurement techniques include gravimetric, elongation, volumetric, psychrometric, hygoscopic (sorption), electrolyte resistance, electrolytic, radiation refraction (microwave and radio), radiation aborsption or attenuation (infrared, ultraviolet, microwave, alpha), radiation scattering (neutron), nuclear magnetic resonance, color metric, piezoelectric, electrical capacitance, thermal (heat capacity), thermal conductivity, paper hygrometry (sorption), diffusion, combustion, electrolysis, heat of absorption, piezoelectric sorption, sonic hygrometry, surface acoustic wave, crystal oscillograph dew point, thermal dew point, and others. Direct measurements of humidity require isolation of the gas and a means of measuring the water content (chemical absorption, condensation, gravimetric) and are therefore impractical as a routine technique for monitoring humidity. Such measurements are usually employed during calibration. Customary measurements for growth chambers include *psychrometric* (wet-dry bulb), *electrochemical*, *hygroscopic* (hair, etc.), *dew point*, and *electrocapacitive*. Almost regardless of the technique used, most sensors are not accurate throughout the entire humidity span.

Psychrometers. The *wet-dry bulb psychrometer* is probably the most common humidity measurement. It consists of two matched response thermometers, the *dry bulb* and *wet bulb* (Bindon, 1965; Tanner, 1972; Wylie, 1962). The sensing element of the dry bulb is directly exposed to the measured gas, and the measuring element of the wet bulb is covered with a sheath saturated with distilled or deionized water. Evaporation from the wet bulb cools it to a degree determined by humidity (Harrison, 1965b). This technique can achieve a measurement accuracy of 0.1% relative humidity and is routinely capable of an accuracy of 1 to 2% (although this degree of accuracy is not achieved unless the psychrometer is well-designed, maintained, and aspirated). It is therefore an excellent secondary calibration standard and has been adopted by the World Meteorological Organization (1959) as the international reference standard for humidity measurement at the earth's surface. Its accuracy depends on the accuracy of temperature measurement, thoroughness of wetting of the wet bulb sensor, exposure to the gas (thickness of the surrounding b*oundary layer* of stagnant air), purity of the distilled water, degree of thermal conduction along the thermometer, shielding from radiant heat exchange, and the accuracy of the psychrometric formula used. These factors should all be considered when selecting a psychrometer. Consistent and accurate measurements dictate air movement across the psychrometer sensing elements at a velocity of at least 5 $m \cdot s^{-1}$ to obtain required wet bulb cooling. Both sensors should be enclosed by a hood to ensure thorough and identical exposure to the air stream and minimize radiant energy exchange. Prolonged use of a wet-dry bulb psychrometer requires continuous replacement of the distilled water and rinsing of the wick to prevent errors resulting from solute accumulation or biological growth in the reservoir or sheath. If these processes are combined, care must be taken to ensure that the flowing water supply itself does not significantly influence sensor temperature.

Change in sensor electrical property. Electronic sensors include electrochemical and capacitance. *Electrochemical* hygrometers measure humidity as electrical conductivity of aqueous solutions, surface resistivity of impervious solids, volume resistivity of porous solids, electrical resistance of dimensional variable materials, electrical resistance of temperature-controlled, saturated salt solutions, electrolyte impedance, electrolysis current flow, and phase transition changes (Hedlin, 1965; Hicks, 1947; Wexler, 1957). Of these, conductivity and resistance measurements are the most common. The main advantage of electrolytic hygrometers is their potential for monitoring and control and their comparably high accuracy of 1.5% relative humidity. However, these sensors require frequent recalibration (Ross, 1975) and constant temperatures to ensure this degree of accuracy. A main disadvantage of electrochemical sensors is high susceptibility to chemical and particulate contamination (for example, exposure to cigarette smoke invalidates the response of most of these sensors). Their accuracy decreases markedly at low and high humidities.

Capacitance hygrometers, which measure the change in capacitance of a solid state or polymer absorptive element, seem to be the most reliable technique for routine humidity control and monitoring. Of these, the solid state sensors are particularly useful for growth chamber applications because of their simplicity, low maintenance requirement, and reliability. They are also compatible with goals of automated operation and typically yield outputs appropriate for advanced signal processing in monitoring and control systems. They can be miniaturized, have relatively fast response, can withstand gaseous and liquid hydrocarbon atmospheres, and can be made intrinsically safe. Elements are typically produced as anodized aluminum strips with thin porous outer coatings, usually of gold. Films of aluminum oxide form between these materials, having electrical properties that respond to water vapor but are insensitive to most other common gases or liquids. Humidity is inferred from measurements of the capacitance of the oxide layer. These sensors can also be produced with integral temperature controls for applications such as low-temperature humidity measurement. Some advanced sensors have built-in microprocessor-based compensation for poor sensitivity at low humidity, and all capacitance sensors are susceptible to errors from temperature, aging, and contamination.

Polymer film sensors afford flexibility in optimizing sensitivity and response for specific applications. In addition, the elements can be easily standardized by trimming the resistance in the measuring circuit, making interchangability within ± 2% for sensors with accuracies of ± 3% over the range 0-90% relative humidity and temperatures of 0-55°C.

Although their use is becoming more widespread lately, capacitance sensors are still relatively expensive, and these sensors have comparatively complex and expensive support electronics (Nelson and Amdur, 1965).

Change in sensor physical property. *Hygroscopic* hygrometers are the oldest and one of the most commonly used methods for measuring humidity (Zwart, 1966). Ever since Leonardo da Vinci (c. 1500) observed the change in weight of a ball of wool with change in humidity, investigators have attempted to use porous or cellular materials as sensitive elements in hygrometers. These devices measure humidity as a calibrated change in mass, dimension, or twist (Goillot, 1952). This dimensional change is used to activate a simple mechanical linkage that drives a switch or indicating device. Among the natural substances used in hygrometry are cotton, wool, raw silk, linen, nylon, seed capsules, feathers, hair, natural sponge, egg shell membranes, gold beater's skin, squid skin, paper, straw, wood chips, and horn (Müller, 1965). The most common sorption hygrometer utilizes change in length of hair (Davey, 1965; Müller, 1965) or various manufactured materials such as nylon (Abbott, 1954; Gustafson, 1965). No other material has proven as satisfactory as blond human hair, which expands about 2.5% over the range of 0 to 100% relative humidity. The hair hygrometer has undergone only minor changes since its development in 1783 by de Saussure. The simplicity and convenience of hair hygrometers resulted in their widespread use for monitoring and controlling humidity in growth chambers, greenhouses, and dwellings. Because total change in hair length over the measurement range is only about 2.5%, a mechanical system is usually required to amplify and linearize the change. Accuracy attainable by hygroscopic techniques is typically within 5% relative humidity (Cotton, 1970; Hanan, 1984). Response is slow (8 to 10 minutes or more), is nonlinear (absorption per unit change in humidity increases with approach to saturation [responsiveness decreases]), exhibits hysteresis (may be as high as 5 to 15%; often confounded by hysteresis in the measuring linkage and in the pen when a graphical recorder is used), is inconsistent in expansion from hair source to source, and is temperature sensitive (thermal expansion and contraction in both the element and the linkage). Accuracy, therefore, varies considerably among instruments depending on design, maintenance, and calibration of the linkage (correction for nonlinear response, changes in hair length, measured humidity range or span, etc.), and sensor (Cotton, 1970; Ross, 1964). Immaculate cleanliness of sensing surfaces, especially removal of all traces of fatty substances, is essential for successful sorption humidity measurements. Sensing elements should be washed weekly with distilled water when in use and stored at 50 to 60% relative humidity when not in use. Exposure of hair sensors to relative humidities below about 15% or above about 85% often causes permanent shifts in calibration. Hair sensors are also prone to changes due to aging or attacks by microorganisms and mites. Manufactured hygroscopic materials are vulnerable to the same problems as hair with the possible exception of the mites. Frequent calibration of hygrometers, therefore, is essential to ensure accurate humidity measurements. One calibration method that can be accomplished during routine washing involves soaking the element in distilled water and setting the indicator at 95 to 97% relative humidity when the sensor is remounted and before it begins to dry (U.S. Navy, 1950).

Dew point hygrometry. Dew point hygrometers measure humidity by direct determination of the dew point temperature. This is accomplished by optical, mechanical, thermal, or electrical techniques. Optical detection senses a change or interruption in the refection due to water condensation on a mirror chilled in a controlled fashion. Mirror temperature at the onset of condensation, detected electro-optically or visually, is the dew point. Another technique monitors the temperature decline of a solid surface being cooled at a constant rate. Dew point is detected as a change in the rate of cooling due to release of latent heat energy by condensing water vapor at the dew point. These sensors are usually expensive and temperamental and require some sort of remote sampling system to remove the sensor from adverse environments or inconvenient locations. Careful design of these sampling systems, however, is necessary to prevent introduction of measurement errors from gas absorption or desorption, gas leakage, condensation, gas temperature change, and pressure change (Cortina, 1985).

Radiation absorbance. The strong water vapor absorption by certain wavelengths of electromagnetic and types of atomic radiation have been used for humidity measurement. Infrared gas analyzers commonly used for measuring carbon dioxide concentrations in net photosynthesis studies in growth chambers are also frequently used to make accurate humidity measurements in the same studies. These sensors are usually very expensive to purchase and maintain and require a sampling system similar to that required for dew point sensors. Recent application of infrared diode lasers to humidity measurement (to a projected precision of 0.006 ppm) (Cooper et al., 1991) makes infrared-based measurement more affordable.

Change in sensor chemical property. Certain chemicals that exhibit a color change with change in water content sometimes are used to detect humidity levels (Blinn, 1965). These indicators, usually cobaltous chloride or cobalt thiocyanate (Unwin, 1980) impregnated in blotting paper, are inexpensive, easily stored, not easily damaged, and may be used in many variations. Humidity indications from 8 to 80% can be determined by comparison with a color guide printed next to indicating color spots for easy reading. Indicators have a temperature-caused error of 2.5% per 5°C deviation from a base of 24°C. They are damaged by excessive humidity or condensation, which dilutes the spots and results in nonuniform chemical distribution and inconsistent color response. Because traditional color humidity measurements require visual assessment, they are of limited use in monitoring or controlling growth chambers. They are sometimes useful, however, for resolving humidity gradients over very small distances, especially in the static environments prevalent in many plant microclimates. Color humidity indicators are also being used in fiber optic measurement systems currently being developed—so this technique, therefore, may have broader application to growth chambers in the future.

Calibration of Sensors

General. All sensors require frequent periodic calibration against a vapor standard or accurate psychrometer (Cole and Reger, 1970). The sensor and its readout should be calibrated as a unit. If this isn't possible, a two-stage calibration is recommended where a laboratory-calibrated, humidity measuring instrument is used to calibrate the in situ unit (under the application conditions). This procedure has the added advantage of accounting for "site" effects such as air flow, thermal, etc. Sensors should be replaced whenever calibration can no longer be satisfactorily restored.

The ultimate humidity calibration standard employed by the National Bureau of Standards (NBS) is the gravimetric hygrometer (Cole and Reger, 1970; Penman, 1958; Ross, 1975; Wexler and Hyland, 1964). It extracts all the water vapor from a measured volume of test gas by passing it through a strong desiccant. Absolute humidity is determined directly as the increase in desiccant mass. Measurements can be made to 0.1% relative humidity over much of the biological range. Accuracy drops to about 1% at very low humidities. Although superior to other methods, the gravimetric hygrometer is unwieldy and may require up to 30 hours for accurate determinations at low humidities. An alternative volumetric hygrometer, which provides comparable data, determines absolute humidity from the change in volume or pressure of a test sample sealed in a chamber with a strong desiccant. Another alternative is the two-pressure humidity generator and reference hygrometer developed by the NBS for common, although probably not routine, calibrations (Cole and Reger, 1970).

Test gases for calibration purposes can be precisely produced in small volumes by equilibration of the air with aqueous solutions of various salts (Lang, 1967; O'Brien, 1948; Ross, 1964; Winston and Bates, 1960) or sulfuric acid (Hanan, 1984). Saturated salt solutions are the easiest to prepare and most stable. A very high degree of temperature control is required to avoid error resulting from water condensation on chamber surfaces. A dew point generator first saturates the airstream by bubbling it through distilled water. It then passes it through cooling coils at the dew point temperature corresponding to the desired humidity. Although more complicated than saturated salt solution techniques, this procedure is more practical for psychrometers since it provides a continuous, consistent stream of humid gas with sufficient flow rate and volume to perform the calibration. Condensation in the outflow tubing must be prevented by maintaining its temperature slightly above the dew point temperature. The precise temperature control mandatory for success of the dew point technique can be attained easily with simple thermoregulators (Spomer, 1982).

In lieu of these more direct and elaborate calibration techniques, simultaneous measurement (split gas stream) of the test gas with the sensor under calibration and a good, aspirated wet-dry bulb psychrometer can be quite adequate. A properly designed and maintained psychrometer is an acceptable secondary standard for humidity calibration because its fundamental response is consistent (unlike most other humidity sensors). The Assman psychrometer (Unwin, 1980; Yoshitake and Shimizu, 1965) is frequently used for this purpose although it may be too bulky to use in some locations.

Accuracy and precision. The degree of resolution of the humidity sensor required for plant growth control is not generally known. It should be as high as practically possible within equipment and time constraints.

PROCEDURES

Where practicable, continuous monitoring of humidity at multiple sites within the chamber is recommended. The minimum recommendation is a single measurement during each segment of the daily temperature and light regime. Any single observation should account for short-term fluctuations that accompany control cycle temperature oscillations. Measurements should be accomplished with the most direct or primary sensor consistent with cultural or experimental constraints and to an accuracy and precision equal to or exceeding that resolvable by plant response (although precision of plant response is generally unknown). In addition, observations should be made in a nonintrusive manner, introducing neither mass nor energy into the system under analysis or otherwise disturbing the plants. Measurement technique depends on many practical limitations, including requisite accuracy and precision, need for remote measurement (chamber closed), speed (response time), expense, difficulty, and availability.

The sampling location for humidity within the chamber is considered much less critical than that for radiation or temperature. Measurement should be made in a location representing average conditions to which the plants are exposed or at least in a location representative of plant exposure. This is assumed to be at the top surface of the plant canopy in the center of the growing volume. A sensor location near a wall is satisfactory where chamber airflow is vertical because lateral humidity gradients commonly are insignificant. Because humidity normally increases as the airstream passes through a plant canopy, a wall location may not be good for chambers with horizontal air flow. The lower the humidity, the greater the relative increase. Whenever the sensor is located near a wall, its readings should be calibrated to account for any difference from the top center of the plant canopy.

ERRORS IN MEASUREMENT

Errors are common in growth chamber humidity measurement, including incomplete sensor contact with the area of interest, improper choice of sensor, inaccurate calibration of the sensor or measurement system, improper coordination of measurements with control cycles, and inadequate maintenance of the sensor and measurement system.

Regardless of the parameter measured, its accurate characterization requires the realization that the sensor measures only the condition at the sensor (Unwin, 1980). The sensor, therefore, must be in direct contact with the environment under observation or control. Although this concept seems obvious, improperly deployed sensors are a common source of humidity measurement error. Humidity measurement may itself introduce error by exchanging energy (sensible, radiant) or mass (water vapor) with the environment. Almost all sensors modify the nearby humidity somewhat by absorption or release of moisture. Although in most cases this is an insignificant and transient effect, psychrometers continuously evaporate relatively large amounts of water into their surroundings, both increasing humidity and reducing air temperature in the process. If the modified air is discharged close to the measurement point or if the measured system has a relatively small volume, subsequent humidity and temperature readings may be influenced. Dew point sensors also decrease surrounding air temperature, whereas resistance sensors (both humidity and temperature) increase it. Psychrometer or other sensor aspiration may change air movement rates and patterns or air temperature and thereby affect measurement accuracy as well as plant growth. The consequence of these effects depends on the total volume of air influenced. In any case, care should be taken to ensure dispersal of the vented air. It is always better to draw air across the sensors and place the wet and dry bulb sensors in parallel rather than sequential positions in the airstream. If a series arrangement is unavoidable, the dry bulb should precede the wet bulb.

Psychrometric and dew point evaluation of humidity are based directly on temperature measurement, and all humidity measurements require registration of dry bulb temperature. Thermal measurement errors at any point can considerably influence humidity readings. Inaccurate sensor calibration, mismatched wet-dry bulb sensors, heat exchange through mounting hardware, heat exchange through radiation, self-heating (resistance type), or incomplete contact between the thermometer and its environment can all be the source of such errors.

All sensors that absorb water as part of their measurement (resistance, hygroscopic, capacitance) exhibit *hysteresis*, whereby a sensor at a particular humidity produces a different output on the meter if its previous measurement was at higher rather than lower humidity (Handegord et al., 1965; Unwin, 1980). Hysteresis also significantly reduces sensor response, especially for detecting relatively small fluctuations.

Condensation and particulate or chemical contamination invalidate sensor output or significantly reduce its accuracy or responsiveness. Contaminants either chemically combine with the sensor, changing its equilibrium vapor pressure from that at calibration, or affect vapor pressure (Handegord et al., 1965).

Another, somewhat subtle, but significant measurement error results from failure to integrate measurement over two or more heating-cooling cycles. Both humidity and temperature fluctuate during these cycles. Physical or electronic integration techniques may be required to ensure consistent humidity control. Instantaneous measurements not synchronized with the heating-cooling or humidification-dehumidification cycles rarely represent average conditions and therefore yield inconsistent control and monitoring of growth chamber humidity.

CONTROL

GENERAL

Control of humidity requires the capability to sense and increase or decrease humidity in the system. Control is complicated by the energy exchange accompanying water phase changes as humidity is increased or decreased so the requirement for simultaneous control of temperature and humidity poses special problems (Davis and Achenbach, 1965; Solvason and Hutcheon, 1965). Likewise, control is complicated by condensation or freezing on, or evaporation or sublimation from, refrigeration coils. Condensation reduces humidity and counteracts its increase, whereas evaporation of water from moist coils has the opposite effect. Efficient and effective humidity control therefore compels its coupling to or coordination with temperature control. Chamber environmental and plant factors other than those associated with temperature control (radiation, air movement, transpiration, irrigation, etc.) also interact with the water environment to determine humidity. The dynamic nature of plant transpiration especially confounds and buffers humidity control.

Because changes in humidity tend to be resisted by the functioning growth chamber and its contents, large quantities of water are often required to increase humidity, and large condensing systems are required to decrease humidity. It's not a very efficient process; however, careful design of the cooling coils to ensure maximum surface area to reduce the need for lower coolant temperatures and selection of coolant within the normal operating dew point range, if possible, can greatly improve the efficiency of humidity control. The equipment must have adequate capacity, response time, and accuracy to maintain humidity at desired levels with acceptable alterations of other environmental parameters. Proportional control is used when a high precision of control is required.

The same sensor should not be used to control and monitor humidity without verification of its accuracy and correlation to humidity within the plant canopy. A set of independent and preferably more precise sensors should be used to verify the accuracy of the control sensors. A different kind of humidity sensor from that operating control equipment (and preferably one utilizing another principle not vulnerable to identical response errors) should be used to routinely verify the humidity control sensor response, accuracy, and calibration.

INCREASING HUMIDITY

When the amount of transpiring tissue is low or when set point temperatures are low, large quantities of water (frequently many liters per day) must be introduced into the chamber to maintain higher-than-ambient humidity levels. This is done by direct injection or evaporation from temperature or osmotically controlled water baths.

Direct injection humidification is commonly achieved through steam injection into the chamber or into the circulating airstream. Unlike vaporization techniques, steam adds heat to the air, but its effect on temperature is much less significant than the cooling that results from vaporization techniques; steam's heat capacity is 540 times less than its latent heat of condensation. The quick response of steam systems is sufficient for proportional humidity control systems, whereby humidity is injected in direct proportion to humidity deviation from set point. Injected steam must be free of the additives routinely added for pH, fungal, and bacterial control in steam heating systems. These chemicals often have phytotoxic activity even at low concentration (Tibbitts, 1978). The use of simple resistive heating elements for direct steam generation is a feasible alternative to the use of heating system steam.

Evaporation from atomized water sprayed into the circulating airstream within the air-handling plenum is probably the most common method of chamber humidification. This is done outside the growing area to prevent deposition of water droplets directly onto plant surfaces. Atomized injection is most effective when the spray is directed perpendicular to, or against, the airstream to maximize vaporization efficiency and to minimize transport of water droplets into the growing area. Pressures of 138 to 414 kPa (20 to 60 psi) are required for proper misting. Pressure injection nozzles are subject to clogging and wear and must be cleaned, readjusted, and replaced routinely to ensure a sufficiently fine mist. Other misting methods involve pneumatic or centrifugal formation of the fog. Only distilled water should be used in atomizing systems to avert salt deposits on chamber and plant surfaces and reduce servicing and maintenance.

Evaporation from water baths or wet pads into the circulating airstream is another technique sometimes used for humidifying small growth chambers. Air, saturated by blowing across or bubbling through a water bath or blowing across or through wet pads, is introduced directly into the chamber. If sufficient air-water bath surface exposure is furnished to ensure vapor equilibrium, air humidity (absolute water content) is a function of bath water temperature. The process requires a high degree of contact with the exposed water surface (bath or pad surface area, air flow rate and turbulence, bubble density, path length, size) and introduces considerable sensible heat into the chamber, especially at higher humidities (Liebmann, 1965; Shiba and Ueda, 1965). Higher humidities have higher dew points, which means that higher bath temperatures are required to add humidity. The bath heats the air, necessitating additional cooling, which, in turn, tends to decrease humidity. Bath temperature control is often supplanted by adding a cooling coil at the desired dew point temperature downstream from the bath. Excess moisture is thereby condensed onto the coils before entering the growing chamber. Salt accumulation is minimized through the use of only distilled or deionized water and replacement (flowthrough or scheduled exchange) or routine dilution of the bath water. Water level is usually maintained by a float system with a temperature cutoff required on the water bath heater circuit to prevent heater burnout in the event of water supply disruption.

Precise humidity control can be attained in small chambers by equilibration of chamber air with water baths containing salt solutions formulated for a prescribed vapor pressure (Wexler and Hasegawa, 1954; Young, 1967). Each humidity level requires a unique solution concentration, and humidity change requires a solution change. It mandates a very efficient vapor exchange system, intensive monitoring, routine adjustment or replacement of bath solution to maintain the desired vapor pressure, and constant solution temperature to ensure good humidity control. The useful duration and range of control with a single salt solution can, however, be increased through control of bath temperature (Ganzer and Rebenfeld, 1987). This method is impractical except in very small chambers or larger chambers with very little other humidity exchange.

Decreasing Humidity

Close humidity control also requires dehumidification to offset evapotranspiration, high humidity of ambient air, and excess humidification. Most environmental control chambers have no dehumidification mechanism other than condensation onto cooling coils or exchange with drier outside air.

Water condenses on surfaces at or below the dew point temperature. Therefore, a defined humidity can be obtained by controlling the temperature (dew point) of a cooling coil in the circulating airstream (Jerger and Coonan, 1965; Sukhatme and Chato, 1965). This is sufficient in many applications when the chamber carries a small evapotranspiration load. Two parallel cooling coils are often used, one for dehumidification and the other for temperature control. This provides modulated control by passing a fraction of the conditioned air through the humidity control system while the remainder passes through the temperature control exchanger. The fraction of air passing over the dehumidification exchanger is adjusted to achieve the desired final humidity when the two streams are blended. The other fraction is then cooled to restore the desired chamber air temperature. To prevent condensed water from freezing, coil surface temperature must be maintained above 2°C. Thus, at an air temperature of 15°C, for example, the lowest relative humidity possible is about 45%. For lower humidity, the refrigerant exchanger must be isolated and periodically defrosted. This is accomplished by constructing parallel humidity coils; one maintains control while the other is being defrosted.

Physical adsorption of liquids on solid desiccants is one of the oldest known methods of reducing moisture from gas streams and is occasionally used in growth chambers. This technique offers the advantage of producing very low humidities in gas streams over a wide temperature span without interfering with temperature control. It permits independent latent and sensible load control, thereby eliminating costly reheat or bypass. The desiccant requires periodic dehydration, usually by oven drying. So two desiccant containers are required. Some systems have built-in provision for automatic desiccant dehydration. Chemical dehumidification generally is feasible only in chambers containing a small amount of transpiring plant tissue (Asker, 1965; Brown et al., 1965; Harter, 1965). Desiccants are sometimes used to improve control precision of other dehumidification systems where a high degree of precision is required. Chemical desiccants also are often used in systems having low humidity load to eliminate dampness on cooling coils, thereby avoiding problems due to the biological growth on coils common to all mechanically refrigerated systems, or to minimize frost formation on coils where the refrigerant is below 0°C.

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