How to control humidity inside growth chambers and rooms for research and optimal plant growth

By Patrick Friesen, PhD
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The humidity inside your growth chamber can affect the growth rate and health of your plants. People often use relative humidity, but the vapor pressure deficit is more robust for assessing plant growth and health. Here we review how the vapor pressure deficit affects plant growth and transpiration, how to estimate water vapor loads from plants, and other factors that can change the vapor pressure deficit inside controlled environments. Seasonal and geographic differences can change the vapor pressure deficit by over 200% in growth chambers without formal humidity control, which could affect growth by 10 to 68% in some plants.

Part 1: How the vapor pressure deficit affects plants inside growth chambers

1.1 What is the vapor pressure deficit and how does it change?

The air inside plant growth chambers or rooms “holds” more or less water vapor depending on the air temperature. Water vapor, like all gases, exerts a partial pressure, termed vapor pressure (VP). As air temperature increases, the VP required to saturate the air with water vapor also increases. The saturation vapor pressure (SVP) is air at 100% relative humidity (RH), at which point water vapor will condense, forming dew or frost on solid objects. The temperature at which a given VP becomes the SVP is called the dew point temperature (DPT) (Figure 1). The VP deficit (vpd) is the difference between the VP of air and its SVP at a given temperature. The VP deficit based on leaf temperature (vpdL) is the difference between the SVP of leaves at leaf temperature and the VP of the surrounding air (Figures 1 & 2). The SVP is used to calculate the vpdL as intercellular air spaces inside leaves are assumed to be saturated with water vapor. Since leaves are most often the plant organ with the greatest surface area, the vpdL is most useful to infer how RH may affect plant growth: 

\[
\text{vpd} = \text{SVP}_{\text{air}} - \text{VP}_{\text{air}}
\]

\[
\text{vpdL} = \text{SVP}_{\text{leaf temp}} - \text{VP}_{\text{air}}
\]

\[
\text{RH} = \left(\frac{\text{VP}_{\text{air temp}}}{\text{SVP}_{\text{air temp}}}\right) \times 100\%
\]

Lower RH causes a higher vpdL, whereas higher RH causes a lower vpdL at a given temperature. Note that any temperature difference between a leaf and the surrounding air also affects the vpdL (Equation 2). Leaf temperature is largely determined by the energy balance of convective heat transfer with the surrounding air, absorption of radiative heat from the light source and surroundings, and evaporative cooling from transpiration (E). In growth chambers and rooms, the better the control and uniformity of air temperature, and the greater the air movement around plants, the closer leaf temperature will be to the air temperature set-point through convective heat transfer. Radiative heat from electric lights inside growth chambers generally causes leaf temperatures to be 1 to 3°C higher than air temperature and this will increase the vpdL (Equation 2, Appendix 1). The extent of radiative heating depends on the distance between the leaves and the lights and how much the lights radiate heat. In general, under a similar light intensity (Photosynthetic Photon Flux Density, PPFD), light emitting diode (LED) lighting fixtures will emit less radiant heat than high intensity discharge (high pressure sodium + metal halide) or fluorescent + halogen lighting fixtures. Lastly, anything that causes the temperature of the surrounding air (T_{air}) – 2kPa

\[
\text{DPT} = 17.5°C
\]

\[
\text{RH} = 30\%
\]

\[
\text{SVP}_{\text{leaf temp}} = 1.3kPa
\]

\[
\text{VP}_{\text{air temp}} = 2kPa
\]

\[
\text{VP}_{\text{air}} = 0.62kPa
\]

\[
\text{RH}_{\text{SVPTable.pdf}} = 100\%
\]

Figure 1: SVP curve with constant RH (%) lines over a range of temperatures. Here we illustrate how to estimate and interpret the vpdL. In this example, the growth chamber air temperature is 25°C and the leaf temperature is 26°C. The air has a VP of 2kPa, which means at 25°C it is at 62% RH, and becomes saturated (100% RH) at 17.5°C as DPT. The vpdL is 3.3kPa (SVP_{air temp}) – 2kPa (VP_{air}) = 1.3kPa. This SVP curve is available as a table, allowing you to easily calculate the vpdL when RH, leaf temperature, and air temperature are known (www.biochambers.com/knowledge/SVPTable.pdf).

Figure 2: Illustration of how the vpdL and boundary layer affect E and A. A) When the vpdL is high, the steeper gradient in water VP generally causes E to increase. A high vpdL can also reduce gs via guard cells to limit water loss, and this can reduce A and growth. When the vpdL is low, the gentle gradient in water VP reduces E and allows for greater gs and A. B) A thinner boundary layer increases gs, and acts to increase both E and A. A thicker boundary layer decreases gs, and acts to reduce E and A.
1.2 The vpdL affects plant growth and health

1.2.1 – Too high or low a vpdL can restrict plant growth

Plant leaves are covered with pores called stomata (singular stoma), surrounded by guard cells that control their size or aperture. Stomata are the site of gas exchange in plants, releasing water vapor through E while assimilating CO₂ for growth and development through photosynthesis (net CO₂ assimilation, A). 

\[ E = g_w \cdot (W_{al} - W_{a}) \]

Where \( W_{al} = \) amount of water vapor from leaves, and \( W_{a} = \) amount of water vapor in the air. Total conductance to water vapor (\( g_w \)) is a combination of stomatal (\( g_s \)) and boundary layer conductance (\( g_b \)) to water vapor, \( g_s \) determined by air temperature, air movement, and the length of the leaf vector across which air is moving. Greater air movement and a shorter vector across the leaf increases \( g_s \) (thinner boundary layer) whereas slower air movement and a longer vector across the leaf decreases \( g_s \) (thicker boundary layer). As \( g_s \) increases, \( E \) and the rate of convective heat transfer also increase. Stomatal aperture regulates stomatal conductance to water vapor (\( g_w \)) with greater stomatal opening leading to increased \( E \), and \( A \) would be only slightly diminished from \( E \) through lower mesophyll conductance to CO₂.

The mesophyll is the inner region of leaves beyond the stomata, and the flux of water vapor outwards reduces its ability to conduct CO₂ inwards towards the chloroplasts. Under a constant \( g_s \) however, the water loss and dehydration from \( E \) would be too much for most plants to handle. Plants have evolved to balance in a \( g_s \) between maintaining \( A \) and mitigating water loss through \( E \).

As the vpdL increases, flowering plants sense the increase in \( E \) or decline water status somewhere in the leaf or vasculature and close their stomata after an inherent threshold is reached. Reducing \( g_s \) is more difficult to pull from the soil, increasing demand through the leaves pulls at the water columns running throughout the vascular system. Gas bubbles (embolisms) can form and lead to disconnected water columns (cavitation). Because of the interconnectedness of whole-plant water status, high vpdL is often combined with drought (soil drying) experiments. In the effects to the contrast of plants, high vpdL potential limitations on plant growth from low vpdL are nutrient deficiency or impaired metabolism. Although it may be intuitive to think plants require some level of \( E \) to pull and maintain the flux of nutrients from the roots to the developing above-ground tissue, evidence is lacking to support this hypothesis; low \( E \) does not restrict nutrient uptake in sunflower (Helianthus annuus L.) or Arabidopsis. Regardless of whether low \( E \) is a contributing factor in tomato (Solanum lycopersicum L.), here a low vpdL can reduce the concentrations of calcium (Ca) and potassium (K) in the vegetative tissues. Reduced concentration of Ca and K can lead to some level of deficiency, which can lead to reduced growth. Hybrid aspen (Populus tremula x P. tremuloides) also shows nutrient deficiency and reduced growth compared to untreated plants after several years of chronically lower vpdL, and here the reduced growth was linked to impaired metabolism.

1.2.2 Traits that mitigate or exacerbate vpdL effects on plant growth

Plants can mitigate or exacerbate changes to \( g_s \) (and \( E \)) that may result from a high or low vpdL. The leaf surface area to volume ratio (SA:V) moderates how \( E \) can transiently affect leaf water status. If the vascular system cannot hydraulically support leaves (eg. roots dry out), leaf SA:V can affect how quickly leaves dry out. Plants that evolved in the tropics or humid understory of temperate forests tend to have broad thin leaves with a high SA:V. As a result, these plants are more susceptible to drying out at higher vpdL, and are more sensitive to closing their stomata and restricting their growth (eg. banana (Musa spp)). On the other end of the spectrum, plants that evolved in hot, arid environments tend to have leaves with a low SA:V, which are generally more resistant to drying out and have a greater water storage capacity (eg. cacti). Cacti and other succulents also tend to have stomata sunken into pits, having only small apertured pores exposed to the outside air, thereby chronically reducing \( g_s \). Plants that evolved in more temperate environments tend to have traits that fall somewhere between these two extremes.

Biochemical and anatomical modifications inside the leaf can also achieve greater rates of A at lower \( g_s \), again mitigating the tradeoff between water loss through \( E \) and carbon gain through \( A \). These biochemical and anatomical modifications are termed CO₂ concentrating mechanisms (CCMs), and include C₃ and C₄ plant photosynthesis (net CO₂ assimilation, A).

1.2.3 A low vpdL may be beneficial or essential to your plant growth objectives

Through the same process that can cause nutrient deficiency, a low vpdL (low \( E \)) can also alleviate salt stress by reducing the uptake of toxic salts.

Maintaining a low vpdL is frequently required to grow vegetative cuttings, as often their underdeveloped root system cannot hydraulically support high rates of \( E \) from their relatively large leaf area. For Cannabis (Cannabis sp), a recommended vpdL is 0.8 kPa for vegetative cuttings, steadily increasing with plant growth to 1.5 kPa for maturing flower buds.

A low vpdL can also increase leaf extension rate from improved leaf water status, thereby increasing light interception capacity and growth. In sweet potato (Ipomoea batatas (L.) Lam.) and potato (Solanum tuberosum L.), reducing the vpdL from 1.2 to 0.4 or 1.9 to 0.6 kPa shifts biomass allocation to the edible tubers with little or no effect on overall growth (dry biomass).

If plants grown at low vpdL are to be moved to an area of higher vpdL, take care to avoid humidity shock. Stomata of plants grown at low vpdL are acclimated to the humid air, and often cannot properly close in response to higher vpdL. As a result, leaf and plant water status decline, which can lead to more severe dehydration in some cases. If plants are to be moved from areas of low to high vpdL, gradually increase exposure to higher vpdL (over days) if possible to mitigate humidity shock.

1.2.4 A low vpdL can encourage infection from pathogens

Although growth at low vpdL may benefit to your goals, low vpdL can also encourage the infection and severity of fungal and bacterial pathogens. The incidence and severity of powdery mildew (Uncinula necator (Schwein.) Burt) infection on grape seedlings (Vitis vinifera L. cv ‘Riesling’) increases with decreasing vpdL until 0.5 kPa (85% RH at 25°C), where it plateaus or marginally decreases. For other fungi such as Cercospora carotae (Pass.) Solheim, a pathogen of carrots (Daucus carota L. var. sativa Hoffm.), and Magnaportha oryzae (B.C.) Couch, a pathogen of perennial ryegrass (Lolium perenne L.), a threshold vpdL must be achieved before infection occurs. For C. carotae this threshold is a range from 0.3 to 0.8 kPa (84% RH at temperatures from 16 to 32°C), and for M. oryzae the threshold is 0.3 kPa (92% RH at 28°C).
**Part 2: Factors that add or remove water vapor inside growth chambers or rooms**

Now that you’ve determined an acceptable vpdl range for plant growth, how do you determine whether you can achieve this? The following sections discuss how to estimate water vapor loads from plants (whole-plant $E$), how to adjust the vpdl in growth chambers without formal humidity control, factors that affect the ambient humidity of growth chambers, and how to interpret humidity control specifications.

2.1 - How to estimate water vapor loads from plants and their pots on a whole-plant or growth area basis

Potted plants and their wet soil emit vapor water into growth chambers and rooms. Estimating $E$ on a whole-plant or growth area basis ($E_{w}$ or $E_{p}$) may be desirable for scheduling the frequency of watering, estimating how much water to use for hydroponic systems, and estimating the flow rates of aeroponic misting systems.

Estimates of $E$ rely on estimates of $g$, for a given set of conditions (Equations 5 & 6). Because there is a tradeoff between carbon gain through $A$ and water loss through $E$, there is a strong relationship between $A$ and $g$. This relationship has been empirically determined and modelled for a number of species, the Ball-Berry model (BBM) being one model that is widely used. The BBM also incorporates RH and ambient CO$_2$ in addition to $A$ to determine $g$. At this point it is also important to calculate gas exchange parameters based on whether stomata are located on both the top and bottom of leaves (amphistomatous), only on the bottom of leaves (hypostomatous), or rarely only on the top of leaves (hyperstomatous). To extend $g$, to total leaf conductance to water vapor ($g_{c}$), the average boundary layer conductance ($g_{b}$) of leaves must be approximated (Figure 2). Estimates of $g_{c}$ can then be used to calculate $E$ (Equations 5 & 6). Next $E$ can be scaled to $E_{w}$ or $E_{p}$, the latter based on the average leaf area per unit ground area, often referred to as the leaf area index (LAI, m$^2$ leaf area m$^{-2}$ ground area). For large plants, if values of $A$ for the BBM are from upper-most fully expanded leaves (which they often are), a scaling factor is also required to account for shading, leaf age, and light attenuation. Finally to model $E$, certain assumptions are required about the VP of the air inside the growth chamber that is interacting with the plants.

In one scenario, $E$ for sunflower is modelled with an ambient VP of 1.24 kPa (21°C, 50% RH) across a range of temperatures (Figure 3). In Figure 4 the ambient RH is held at 50% across a range of temperatures, showing how $E$ increases at lower temperatures, but is markedly reduced at warmer temperatures compared to Figure 3 (Figure 4 vs Figure 3). Herein lies a central challenge in estimating $E$ and how many plants affect the VP inside growth chambers or rooms; more $E$ increases the VP but a higher VP reduces $E$. This same effect occurs for lettuce (Lactuca sativa L.), but note the lower values of $E$ due to lower $g$ (Figures 5 & 6). To estimate the upper limits of whole-plant $E$ and water vapor loads inside growth chambers, we modelled sunflower under a max LAI of 3.5. This hypothetical growth room is filled with large sunflower plants under high light intensities. Here removing water vapor via dehumidification will be the challenge and we assumed RHs of 70% at 15°C, 65% at 20°C, 60% at 25°C, 55% at 30°C, and 50% at 35°C. Finally we can convert $E$ to water vapor load units of kg h$^{-1}$ m$^{-2}$ which are more readily used to size de-humidification equipment (Figure 7). This process can...
be applied to other crops such as lettuce, here assuming 50% RH across a range of temperatures (Figure 8). The water vapor loads are again lower with lettuce compared with sunflower, again due to lower $g_s$ but also from a lower modelled LAI of 1 which is likely close to the upper limit for lettuce (Figure 8).

Another way to estimate $E$ is to calculate the energy load from the light canopy and assume projected leaf area = floor/growth area. Here we converted light spectra and intensities (PPFD) to watts m$^{-2}$ (not lamp watts) and used the heat of vaporization (at leaf temperature) to determine water vapor loads (Figure 9). This method assumes leaves behave like exposed water and does not consider $g_wv$.

Pot volume is an important determinant of overall plant size, and affects $E$ through its overall effects on plant growth and leaf area$^{68,98}$ Pot volume and soil surface area also affect evaporation from the soil ($S_{\text{soil}}$). For recently watered pots with soil that conducts water well, evaporation rates may be similar to a dish of water, with only boundary layer constraints, and can be estimated by: $^{6,31}$

$$S_{\text{soil}} = g_{aw}(W_{\text{soil}} - W_{\text{air}}) \quad \text{(Equation 9)}$$

$$g_{aw} = g_{ai} \quad \text{(Equation 10)}$$

As soil dries, it behaves less and less like a dish of water and rates of evaporation may be better estimated by:

$$S_{\text{soil}} = st^{0.5} + bt \quad \text{(Equation 11)}$$

Where $s$ is sorptivity, $t$ is time, and $b$ is a constant ($< 0$)$^{30,106}$.

**Figure 4:** Modeled transpiration ($E$, m$^{-2}$ of leaf area) of sunflower across changing leaf temperatures and $vpd_L$. In this example, the air inside the growth chamber has a constant RH of 50% across all temperatures. All other models, values, equations, and assumptions are the same as Figure 3.

**Figure 5:** Modeled transpiration ($E$, m$^{-2}$ of leaf area) of lettuce across changing leaf temperatures and $vpd_L$. In this example, the air inside the growth chamber has a constant VP of 1.24 kPa and leaf temperature is 1°C higher than air temperature. Values of net CO$_2$ assimilation rates ($A$) to estimate stomatal conductance ($g_s$) with the Ball-Berry Model$^{11}$ were taken from Kim et al. 2004.$^{34}$ Here $A$ was measured at 400 PPFD light intensity, 20°C, and an ambient [CO$_2$] of 600 µmol mol$^{-1}$ (ppm).$^{34}$ Next, the relative change in $A$ was estimated across leaf temperatures higher and lower than 20°C based on the average $C_5$ response of $A$ to temperature from Yamori et al. 2014.$^{35}$ Slope ($m$) and intercept ($g_0$) values for the BBM were taken from Jung et al. 2016$^{100}$ and Kim et al. 2004$^{11}$ respectively. Estimates of boundary layer conductance assumed an average leaf path vector of 5 cm (0.05 m) and air movement of 0.7 m s$^{-1}$. $g_{aw}$, and $E$ were calculated from Equations 6 & 5.$^{10,11}$

**Figure 6:** Modeled $E$ (m$^{-2}$ of leaf area) of lettuce across changing leaf temperatures and $vpd_L$. In this example, the air inside the growth chamber has a constant RH of 50% across all temperatures. All other models, values, equations, and assumptions are the same as Figure 5.

### 2.2 How to adjust the $vpd_L$ in growth chambers without formal humidity control

Temperature and RH both indirectly and directly affect $E$ through their effects on $g_s$ and the $vpd_L$. Temperature control in growth chambers and rooms is standard. Humidity control includes several options, and depends on the application and where the equipment will be installed. In growth chambers without formal humidity control, the $vpd_L$ can be manipulated by changing the temperature, adding or removing sources of water vapor, and/or adjusting the fresh air flow rate. Lowering the temperature or adding more plants are two options to lower the $vpd_L$. Overwatering, wetting a cloth with a large surface area, or installing a household humidifier are other ways to add sources of water vapor inside your existing growth chamber and lower the $vpd_L$. Without formal humidity control, however, care must be taken to adjust the fresh air flow too much, as the [CO$_2$] can potentially be reduced below ambient and slow plant growth. Ethylene and other volatiles can also build up with little fresh air flow, potentially causing undesirable growth effects, especially if chambers are filled with plants (Figure 10). $^{10}$ With only a few small plants, the fresh air flow rate can often be reduced to lower the $vpd_L$ without appreciably affecting the [CO$_2$] inside a growth chamber or room. To increase the $vpd_L$, increase the temperature, or in most situations with plants inside your growth chamber, increase the fresh air flow rate (Figure 10).

How fresh air flow affects the $vpd_L$ inside a growth chamber depends on the VP difference between the fresh air coming in and the air inside. The greater the difference in VP, the more fresh air will either decrease or increase the $vpd_L$. In growth chambers filled with plants, in most cases fresh air will increase the $vpd_L$, as the water vapor load from plants will raise the VP higher than the fresh air coming in. How much fresh air changes the $vpd_L$ also depends on its flow rate; the greater the fresh air flow rate the more fresh air will change (in most cases increase) the $vpd_L$ (Figure 10).
Figure 7: Estimated water vapor loads from sunflower (m$^{-2}$ of growth area), assuming an LAI of 3.5. In this example, the air inside the growth chamber has RHs of 70% at 15°C, 65% at 20°C, 60% at 25°C, 55% at 30°C, and 50% at 35°C. E values were reduced by 50% after multiplying by 3.5 to account for shading and leaf age effects before conversion to kg hr$^{-1}$ m$^{-2}$. All other models, values, equations, and assumptions are the same as Figure 4.

Figure 8: Estimated water vapor loads from lettuce (m$^{-2}$ of growth area), assuming an LAI of 1. In this example, the air inside the growth chamber has a constant RH of 50% across all temperatures. This is a direct conversion of E values from Figure 6 to kg hr$^{-1}$ m$^{-2}$.

Figure 9: Calculated water vapor load from E as a function of leaf temperature. Here we converted light spectra and intensities (PPFD) to watts m$^{-2}$ and used the heat of vaporization (at leaf temperature) to estimate water vapor loads. This method assumes projected leaf area = floor/growth area, that leaves behave like exposed water, and does not consider $g_{\text{w}}$. Blue lines = 500 PPFD. Green lines = 1000 PPFD. Red lines = 1500 PPFD. Circles = white LED fixture. Diamonds = white, red, and far-red LED fixture. Squares = high-pressure sodium + metal halide bulbs. Triangles = fluorescent tubes + halogen bulbs.

Figure 10: Drawdown of CO$_2$ concentration and change in the vpdL as a function of fresh air flow inside a BioChambers SPC-37. Here the growth chamber was filled with well-watered and fertilized maize and soybean plants. Leaf temperatures ranged from 25.5 to 26.5°C (chamber set-point 25°C) and PPFD averaged 430 μmol m$^{-2}$ s$^{-1}$ across the upper leaves. The LAI of all plants was 0.48. Flow rates were decreased by manually closing the fresh air intake valve from fully open (arrow). After each flow rate change, at least 45 minutes passed before measurements were recorded to allow for steady state conditions. The air outside the BioChambers building was an average of 2.5°C at 95% RH (0.69 kPa VP) over the course of measurements. Mean ±SE.
The VP of the fresh air flowing into your growth chambers depends on the characteristics of the building(s) where the chambers are installed. How is the air conditioned and circulated inside your building? What are the sources of water vapor and how well is your building sealed? Where in the world are you located? What time of year is it? In buildings without humidity control, geographic location and time of year can be the prevailing factors in determining the VP of the ambient fresh air. 

Lattitudinally, the greatest average (annual) VPVs occur near the equator and follow a bell-curve toward the poles. There is also significant variation in VPVs longitudinally, for example from east of the Sierra Nevada mountain range to the east coast of the USA. Time of year also changes the VP of air, with summers generally having higher VPVs than winters. For example, if we compare the average VP of Winnipeg, Manitoba, Canada in January (0.16 kPa) with Tallahassee, Florida, USA in July (2.76 kPa) and bring them both to 21°C, we see a vpdL of 2.37 kPa (6% RH) for Winnipeg and vpdL of 0 (100% RH) for Tallahassee. If we compare average VPs of Winnipeg in summer (July) (1.61 kPa) with winter (January) (0.16 kPa) at 21°C, we see a vpdL of 1.24 kPa (65% RH) for July and 2.37 kPa (6% RH) for January. Here without additive humidity in your chamber, during the winter, there could be significantly different seasonal growth responses. Figure 11 shows how dry the air can be in Winnipeg in winter when warmed up to 30°C inside a BioChambers TPC-19. Here, adding four maize plants linearly reduces the vpdL from 4.2 to 3.9 kPa. However, a 3.9 kPa vpdL will reduce A and growth to some degree in the majority of plants compared to lower vpdL. Compare Figure 11 with a BioChambers SPC-37 filled with maize and soybean (Glycine max (L.) Merr) plants at 25°C, also in Winnipeg in late fall (Figure 10). Here, the vpdL ranges from 1.5 to 0.8 kPa as the fresh air flow is reduced. The differences between these tests (at full fresh air flow) are the amount of plant material, a 5°C temperature difference, and the greater VP of the ambient fresh air coming into the SPC-37 (Figures 10 & 11).

2.3 Formal options to control humidity and the vpdL inside growth chambers

2.3.1 Additive humidity

Spray nozzle additive humidity is the most popular and cost-effective option to lower the vpdL. Spray nozzle additive humidity increases the RH by running pressurized water through a spray nozzle, emitting small water droplets that evaporate into the air. Remember that increasing the RH (reducing the vpdL) is more challenging at higher temperatures, as warmer air “holds” more and more moisture (Figure 1). A typical specification for spray nozzle additive humidity may look something like this: “Up to 75% RH with all lights on, up to 90% RH with all lights off, and limited by a 25°C DPT. Based on ambient fresh air of 21°C at 50% RH (1.24 kPa VP).”

The specification states that the equipment can maintain 75% RH (lights on) or 90% RH (lights off) or higher, at temperatures equal to or lower than a 25°C DPT (ie. the SVP of 25°C). This means at around 27°C or lower you can maintain 90% RH and at 30°C or lower you can maintain 75% RH. Keep in mind this specification assumes ambient fresh air enters the growth chamber at 21°C at 50% RH (1.24 kPa VP) at full fresh air flow. The realized performance of the equipment will depend on the condition of the actual ambient fresh air and how much plant material is inside. Plant material adds water vapor, so if the ambient air is at 21°C at 50% RH (1.24 kPa VP), adding plant material may increase the additive humidity capabilities of your equipment.

Ultrasonic additive humidity is more expensive but uses water more efficiently and does not require a high pressure water supply. Ultrasonic additive humidity works by generating ultrasonic pulses through water columns to generate very small micro droplets (<1 micrometer diameter) which rapidly evaporate into the air. A specification for ultrasonic additive humidity is interpreted the same way as spray nozzle additive humidity. To prevent build-up of mineral deposits that can clog the spray heads, ultrasonic additive humidity works by generating ultrasonic pulses through water columns to generate very small micro droplets (<1 micrometer diameter) which rapidly evaporate into the air. Ultrasonic additive humidity is more expensive but uses water more efficiently and does not require a high pressure water supply. Ultrasonic additive humidity works by generating ultrasonic pulses through water columns to generate very small micro droplets (<1 micrometer diameter) which rapidly evaporate into the air. Ultrasonic additive humidity is more expensive but uses water more efficiently and does not require a high pressure water supply. Ultrasonic additive humidity works by generating ultrasonic pulses through water columns to generate very small micro droplets (<1 micrometer diameter) which rapidly evaporate into the air. Ultrasonic additive humidity is more expensive but uses water more efficiently and does not require a high pressure water supply. Ultrasonic additive humidity works by generating ultrasonic pulses through water columns to generate very small micro droplets (<1 micrometer diameter) which rapidly evaporate into the air. Ultrasonic additive humidity is more expensive but uses water more efficiently and does not require a high pressure water supply.

2.3.2 De-humidification

De-humidification by refrigeration is a popular and cost-effective way to add some de-humidification capacity to equipment. With this option, the conditioned air inside the chamber is run over the cold evaporator coil of the refrigeration equipment to condense out some water vapor before re-entering the growth area. This is the same principle as the condensation drip often seen on the back of window air conditioners. In contrast to additive humidity, reducing the RH or increasing the vpdL is more challenging at lower temperatures, which “hold” less water vapor and saturate at lower VPs. A typical specification for de-humidification by refrigeration looks like this: “Down to 45% RH with all lights on or off and limited by an 8°C DPT. Based on ambient fresh air of 21°C at 50% RH (1.24 kPa VP).”

This specification means that this equipment can maintain 45% RH or lower at temperatures equal to or greater than an 8°C DPT (ie. the SVP of 8°C), which is around 21°C or higher. Again, this specification assumes a water vapor load of ambient fresh air entering the equipment at 21°C at 50% RH (1.24 kPa VP) at full fresh air flow. In contrast to additive humidity, adding plants and other sources of water vapor will decrease de-humidification capacity. De-humidification through desiccant drying is more expensive than by refrigeration, but achieves appreciably greater de-humidification capacities. Here, the conditioned air inside the chamber passes through a drying wheel with a chemical desiccant that is continually regenerated with heat. Because desiccant dryers come in several sizes/capacities, estimating the water vapor load from fresh air and plants is important to help size the desiccant dryer only to the specification you need, as the cost differences between drying units are significant. A specification for de-humidification through desiccant drying is interpreted the same way as de-humidification by refrigeration, where a lower limiting DPT means a greater capacity to de-humidify.
Appendix 1

<table>
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Appendix 2 - List of abbreviations:

- VP: Vapor pressure, kPa
- SVP: Saturation vapor pressure, kPa
- RH: Relative humidity, %
- DPT: Dew point temperature, °C, corresponds to a SVP
- vpd: Vapor pressure deficit of the air, kPa
- vpdL: Vapor pressure deficit between leaves and the air, kPa
- E: Transpiration rate, mmol H2O m⁻² (leaf area) s⁻¹
- A: Net CO₂ assimilation rate, µmol CO₂ m⁻² s⁻¹
- Eₚₚₚ: Total leaf/plant conductance to water vapor, mmol H₂O m⁻² (leaf area) s⁻¹
- gₛₒₜ: Stomatal conductance to water vapor, mmol H₂O m⁻² (leaf area) s⁻¹
- gₑₑₑ: Boundary layer conductance to water vapor, mmol H₂O m⁻² (leaf area) s⁻¹
- PPFD: Photosynthetic photon flux density, µmol photons (400-700nm) m⁻² s⁻¹
- SA:V: Surface area to volume ratio
- CAM: Crassulacean acid metabolism
- Eₑₑₑ: Whole-plant transpiration rate, mmol H₂O m⁻² (leaf area) s⁻¹
- Eₑₑₑₑₑ: Whole-plant transpiration rate, mmol H₂O m⁻² (growth area) s⁻¹ (with a given LAI)
- Or, kg H₂O hr⁻¹ m⁻² (growth area, with a given LAI)
- LAI: Leaf area index, m² leaf area m⁻² growth area
- BBM: Ball-Berry model of stomatal conductance
- CCM: CO₂ concentrating mechanism
- Sₑₑₑₑₑₑₑ: Evaporation rate from the surfaces of soil in pots, mmol H₂O m⁻² s⁻¹
References
