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Indoor Agriculture: HVAC System Design Considerations

Indoor agriculture is a growing market, both literally and figuratively. All over the world, crops are cultivated indoors for a variety of reasons. In this EN, we will look at several HVAC considerations when dealing with indoor growing spaces.

Understanding Plant Biology

Plants are complex natural machines that need a variety of nutrients, minerals, vitamins, water, and gases like oxygen and carbon dioxide (CO_2) to grow. Plants also need light to provide energy for photosynthesis.

To gather these nutrients and support plant growth, the plant has several distinct parts:

- Shoot – the above-ground structure that support the plant's vertical growth, leaves, and fruit. The shoot collects light and carbon dioxide that is used to perform photosynthesis and create food in exchange for water and minerals. The shoot is negatively gravitropic and positively phototropic, meaning it grows away from gravity and toward light.
- Root – the below-ground structure that extracts water and minerals from the nearby soil in exchange for food. The root is positively gravitropic and negatively phototropic, meaning it grows toward gravity and away from light.

The leaf contains several layers of various cell types, each with its own unique function, to gather light and carbon dioxide. The leaves are covered with epidermal cells on the top and bottom, which secrete a waxy cuticle that serves to protect the leaf and prevent loss of water. Inside the leaf, the palisade mesophyll contains chloroplasts, which are largely responsible for the photosynthesis chemical reaction. The vascular bundles, commonly seen as veins in a leaf, contain the xylem and phloem, which allow water and nutrient flow throughout the plant. Finally, guard cells control and protect openings on the leaf, called stomata, which allow gas exchange. On most plants, the stomata are on the underside of the leaf.

When the plant is adequately watered and exposed to light, the guard cells swell, which opens the stomata allowing gas exchange between the plant and its environment. This allows air to freely enter the leaf and interact with the cells. The plant consumes the carbon dioxide and releases the oxygen through the open stomata alongside the water. The plant replaces evaporated water by drawing liquid water from the root to the shoot, through the xylem.

The plant balances carbon dioxide consumption and evaporated water loss through the stomata, which is controlled by guard cell operation.

Moreover, when plant water levels are low or there are low levels of light, the guard cells become flaccid and the stomata are closed.

Photosynthesis consists of two sets of reactions: light-dependent reactions to produce molecules (ATP and NADPH) later used, and light-independent reactions to produce glucose. The light-independent reactions produce chemical energy in the form of glucose from the carbon dioxide previously consumed by the plant. Plants use glucose for a variety of purposes, including: cellular respiration, fructose and sucrose production for fruits, stems, roots, and seeds; and stored in the form of starch.

Evapotranspiration

A plant uses water to grow for several purposes. First, water is used to circulate nutrients and vitamins from the root to the shoot. Second, the plant uses water as a component within photosynthesis, providing hydrogen atoms that are used to make glucose. Much, but not all, of the water taken up by the plant is released through evapotranspiration, which is a combination of evaporation and transpiration.

Liquid water found on the surface of the plant and soil evaporates to the surrounding air.

Transpiration is the movement of water within the plant, the resulting conversion to water vapor, and release from the stomata on the leaves. The plant evaporates water inside the leaves to increase solute concentration in the mesophyll cells. The reduced pressure within the upper areas of the xylem draws more water up through the xylem from the roots to the shoot (osmosis).

As a result of photosynthesis, plants add latent load to the space by evaporating water from the soil and plant surfaces and as they exhale water vapor into the space. In addition, as the plant evaporates water, there is a sensible cooling effect (negative sensible load). The amount of cooling can become substantial with a large number of plants in a single space.

Growing plants indoors

The grower can provide the components required for plant growth outside of a traditional, natural environment, one example is replacing sunlight with artificial lighting which can often add significant amount of heat to the space.

Some growers will choose to move plants to accommodate their growth cycle. Growers will start plants in one room with a unique set of lighting, temperature, and humidity conditions then move the plants to the next space with different conditions as the plant matures. Conversely, other growers will keep plants in a single space and adjust the conditions throughout the plant's life-cycle to optimize its growth.

Many growers have also developed proprietary methods for plant arrangement. For example, some vertical farms use rows of plant trays. This allows plants to grow in a traditional manner—from "ground" upward, though the growing medium may not actually be soil. This style allows many rows, or layers, of plants to be aligned side by side (see Figure 2), instead of a single layer as found in traditional outdoor agriculture. Alternatively, some companies have developed proprietary systems where plants are arranged within vertical columns. In this arrangement, the columns typically run from floor to ceiling, with the plants growing out of the vertical column toward the light source.

Figure 1. Plant evapotranspiration

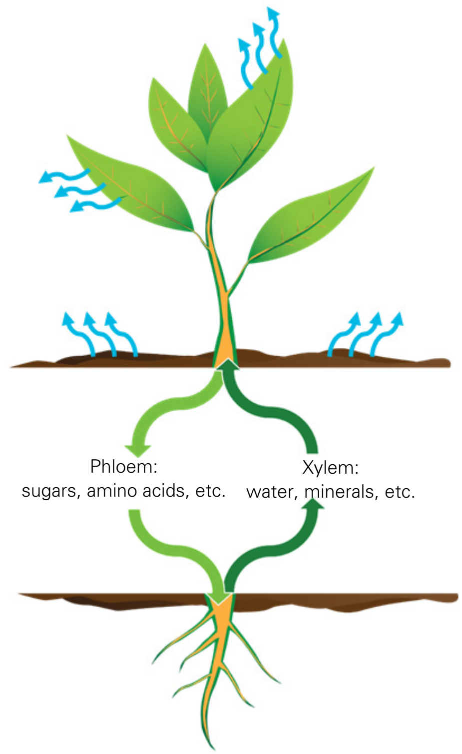


Figure 2. farming types

horizontal

vertical

Growers have replaced natural rainfall with a variety of clever irrigation techniques. In many cases, irrigation water is enriched with nutrients.

Understanding the grower's needs

The grower's needs are often dictated by producing a consistent, healthy crop as quickly as possible and at a reasonable cost.

Growers may specify a particular temperature and humidity condition for the indoor air surrounding their plant during the plant's growth phase.

Growers may use a phrase "vapor pressure deficit" or "vapor pressure difference" (VPD) to describe a specific growing condition. VPD can be expressed in different units, with kilopascals being very common. The VPD is the difference in vapor pressure of the boundary layer surrounding the plant leaf surfaces minus the vapor pressure of the surrounding air. Therefore, when a grower indicates a desired VPD, they're telling you there is a difference in vapor pressures between the leaf and air. The air conditions at the surface of the plant are assumed to be saturated because of the plant transpiration and water vapor release. Growers may reference a chart or table indicating appropriate VPD values for a given plant during a particular stage of growth. The designer can determine an adequate room humidity condition when the grower's desired VPD and indoor dry-bulb temperature preferences are known. See Vapor Pressure Difference sidebar for an example.

This isn't comfort cooling

In nature, plants experience periods of light and darkness throughout their growing season. Plants grown indoors are subjected to "daytime" periods where the sun-replacing lights are turned on to power photosynthesis. The lights are then later turned off to simulate "nighttime" periods. The amount, intensity, and color temperature of light provided to the plants can vary by species and growing phase. Some plants are photoperiod sensitive and subjected to varying time-periods of light per day when growing versus maturing, fruiting, or seeding. By controlling the amount of time a plant is subjected to light, growers can trigger different responses in photoperiod-sensitive plants, such as flowering.

Because of the lighting required, lighting power densities and resulting sensible heat are often significantly higher when compared to comfort cooling applications. It is common to see lighting power densities at 30 watts per square foot and higher—much higher than traditional comfort cooling applications.

Space temperatures can vary based upon plant species and growing phase. Some plant varieties grow well in cool spaces, such as 65°F, while others can grow in warm spaces, at 80°F and above. Similarly, plants are often more tolerant of higher relative humidity levels, so ranges often vary from 40 to 75 percent relative humidity.

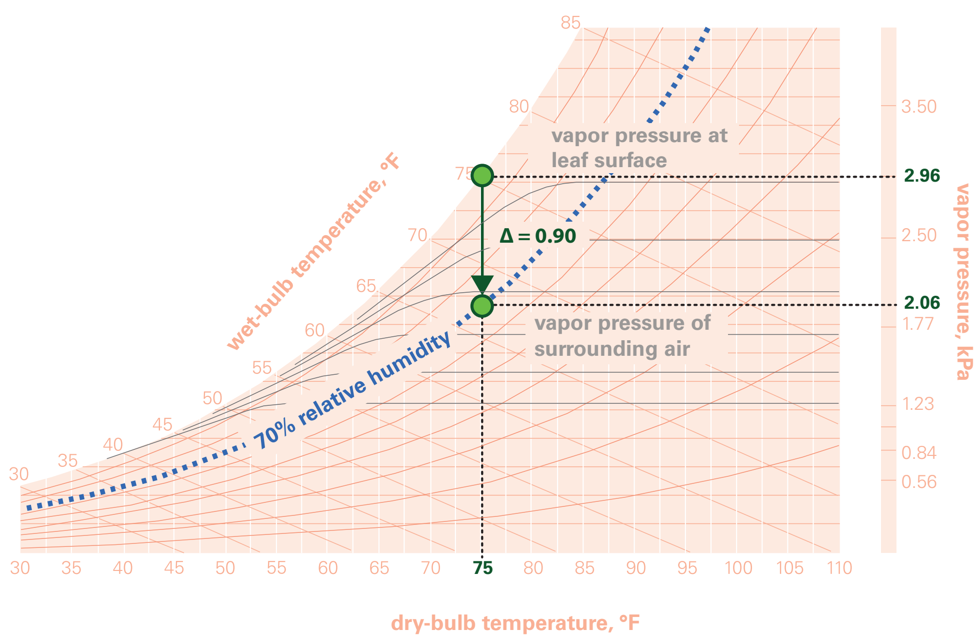
Vapor Pressure Difference

Here is a simple example that assumes the leaf and air dry-bulb temperatures are the same.

A grower has expressed a preference for an indoor dry-bulb temperature of 75°F. Using a psychrometric chart or psychrometric calculation tool, the vapor pressure at the leaf's surface is assumed to be at saturation (75°F/ 100% relative humidity), which equates to 2.96 kPa.

The grower has also said they would like a VPD of 0.90. The desired VPD value can be subtracted from the leaf conditions, yielding a desired vapor pressure of 2.06 kPa for the surrounding air.

So, to maintain the grower's preference of a space dry-bulb temperature of 75°F and VPD value of 0.90, the space can be controlled to 75°F dry-bulb and 70% relative humidity.



Many growers will choose to recirculate all of the supply air and not introduce any ventilation air. In fact, because the plants consume carbon dioxide, many growers will use a means to add carbon dioxide to the space to increase the concentration beyond ambient levels. Bringing in outdoor air, which has a relatively low concentration of carbon dioxide, can dilute the carbon dioxide-rich space.

There are often significant loads from the lights and plants during the "daytime" phase. Additional loads may be present from miscellaneous equipment like water pumps, air transfer fans, and other equipment. The evapotranspiration (latent) load from the plants is often very large and when combined with the various sensible loads, provides for a steep (low) space sensible heat ratio (SHR), which is the space sensible load divided by the sum of the space sensible and latent loads. It is common to see SHRs at or less than 50 percent, which indicate both large sensible *and* latent loads. HVAC equipment designed to maintain space temperature and humidity must then provide both sensible cooling *and* dehumidification.

During the "nighttime" phase, many of the sensible loads disappear (i.e., the lights turn off), but the plants continue to transpire. In many plants, the transpiration rate decreases slowly but it does not completely stop—the plant continues to add moisture to the space even when the lights are off. As a result, space SHRs are very steep, necessitating dehumidification without sensible cooling.

HVAC design considerations

Indoor agriculture HVAC systems must be designed for loads and operation that is very different when compared to comfort cooling for humans.

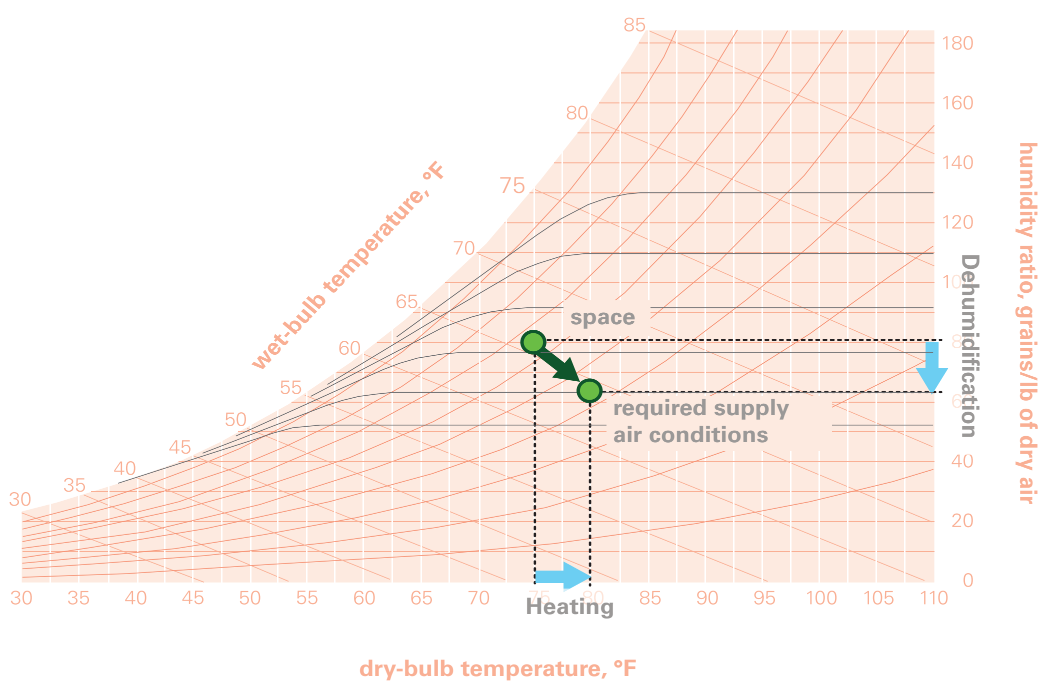
For example, during the "daytime" mode, there is a high sensible load from lighting, high latent load from the evapotranspiration, and a sensible cooling effect from the plant transpiration. This results in a need for both sensible cooling and dehumidification.

During the "nighttime" mode, there is very little sensible load, some latent load from evapotranspiration, and some sensible cooling from transpiration. This results in a need for dehumidification, but little or no sensible cooling.

As mentioned earlier, some specific growing conditions and plant types will create a situation often described as being a "negative SHR" where there are no sensible loads (lights off), but the plants continue to transpire and sensibly cool the space. Figure 3 shows a "nighttime" operation where the plants add latent load to the space, generating a need for dehumidification. The plants also cool the space. These two processes create the need for both heating and dehumidification to counteract the plant's cooling and humidification.

Because of these distinct sets of conditions, the HVAC system must be designed to handle the different modes of operation: cooling and dehumidification when the lights are on and primarily dehumidification (with the possibility of heating) when the lights are off. Heat must also be considered if plants are expected to add a significant cooling load and/or heat loss through the building envelope.

Figure 3. "negative" space sensible heat ratio (SHR)



Because the growing environment is controlled, indoor agriculture HVAC systems are designed and selected to facilitate year-round operation. In those regions where winters are cold, growers expect HVAC equipment to maintain desired space conditions, which will likely require dehumidification. In addition, because many growers choose to avoid bringing in outdoor air to help keep indoor concentration of carbon dioxide high, system designers must select equipment that can operate in cold ambient conditions without airside economizing.

In a traditional comfort cooling application, the desired cooling supply air temperature is determined using psychrometric analyses, often without much consideration about humidity level. In a system where dehumidification is critical, an additional analysis may be required to compute the required supply air temperature and humidity condition. See sidebar “Determining required supply air conditions” for an example.

Determining Required Supply Air Conditions

The supply airflow to the growing space and the corresponding supply air conditions are determined by the sensible and latent cooling loads within the boundaries of the conditioned space. This would include sensible heat gains from lights, equipment, and through the building envelope. Latent heat gains typically include evapotranspiration, evaporation from open water systems, people, infiltration, and any additional moisture-generating processes. Sensible and latent loads due to things outside of the space boundaries, such as ventilation and fan heat gains, are not included in the “space” loads used to determine supply-air conditions.

Continuing from the previous sidebar example, a grower has expressed a desire for an indoor dry-bulb temperature of 75°F and a VPD of 0.9, which resulted in a space setpoint of 75°F/70% relative humidity. These conditions correspond to a humidity ratio of 91.1 grains of moisture per pound of dry air (gr/lb).

The designer has computed the “daytime” space sensible and latent cooling loads to be 68 and 80 MBh respectively. The designer has selected a unit capable of delivering 3700 cfm. Using the space sensible cooling equation, the designer can compute the required supply air dry-bulb temperature:

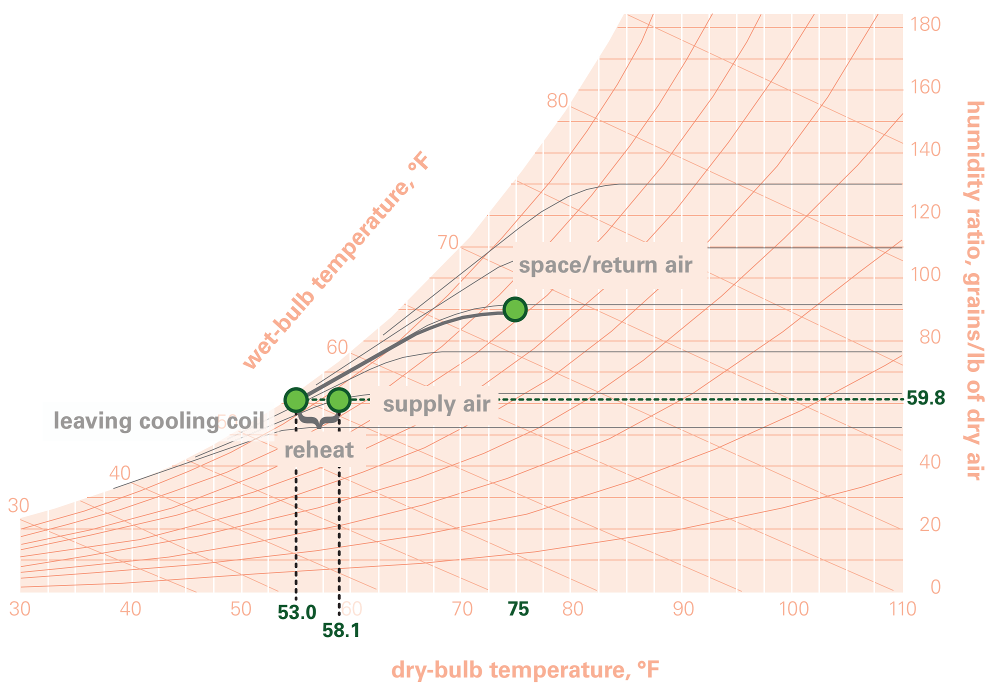
$$Q_{Sensible,space} = 1.085 \times cfm \times (DBT_{space} - DBT_{supply})$$
$$68{,}000 \text{ Btu/hr} = 1.085 \times 3700 \text{ cfm} \times (75°F - DBT_{supply})$$
$$DBT_{supply} = 58.1°F$$

Using the space latent cooling equation, the designer can compute the required supply air humidity condition:

$$Q_{Latent,space} = 0.69 \times cfm \times (W_{space} - W_{supply})$$
$$80{,}000 \text{ Btu/hr} = 0.69 \times 3700 \text{ cfm} \times (91.1 \text{ gr/lb} - W_{supply})$$
$$W_{supply} = 59.8 \text{ gr/lb}$$

Assuming the air leaves the coil near saturation, the dry-bulb temperature of the air leaving the coil will be 53.0°F (equates to 59.8 gr/lb and 98% RH), which is colder than the previously-calculated required supply air dry-bulb temperature (DBT_{supply}). The dehumidified air must then be reheated from 53.0°F to 58.1°F to prevent overcooling of the space.

Note: The 1.085 and 0.69 in the above equations are not constants; they are a function of the density and other properties of the air. At “standard air” conditions at sea level, these properties result in the values 1.085 and 0.69. Air at other conditions and other elevations will cause this factor to change.



Conclusion

Indoor agriculture is a unique market for HVAC. Growers operate the buildings twenty-four hours per day, seven days per week, three hundred and sixty five days per year and they expect to control the temperature and humidity for all hours. Because of the wide variation of the loads, many of the comfort cooling archetypes do not apply in these buildings. Designers must consider equipment that is able to cool, heat, and dehumidify the space to maintain the desired temperature and humidity.

By Eric Sturm, Trane. To subscribe or view previous issues of the Engineers Newsletter visit trane.com/EN. Send comments to ENL@trane.com.

References

[1] ASHRAE. *ASHRAE Handbook—HVAC Applications*, Chapter 25. 2019.

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