System Catalog

Indoor Agriculture

A technology-based approach to growing crops indoors

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Trane® Indoor Agriculture

Why grow plants indoors?

Indoor agriculture is a technology-based approach to growing crops indoors. This allows growers to specify and control the ideal environment to achieve the optimal harvest. Growers can do this by controlling temperature, humidity, carbon dioxide, lighting, irrigation, and fertilization. There are several advantages to growing indoors:

- **Water use reduction.** By recycling water that results from dehumidifying the air, indoor farms can reduce the amount of water consumed. In addition to this, excess water is not drained into the soil.
- **Increased crop yields.** Because the conditions are controlled, growers can harvest more crop per square foot compared to traditional farms.
- **Consistent, reliable yields.** Controlling the environment allows growers to replicate ideal growing conditions crop after crop, allowing consistent and reliable production.
- **Year-round growing season.** Crops can be grown year-round, regardless of climate, enabling locally produced crops that do not require lengthy periods of transport from farm to consumer.
- **Reduced or eliminated use of herbicides and pesticides.** Some farms forgo the use of herbicides and pesticides because the growing environment is controlled and isolated.

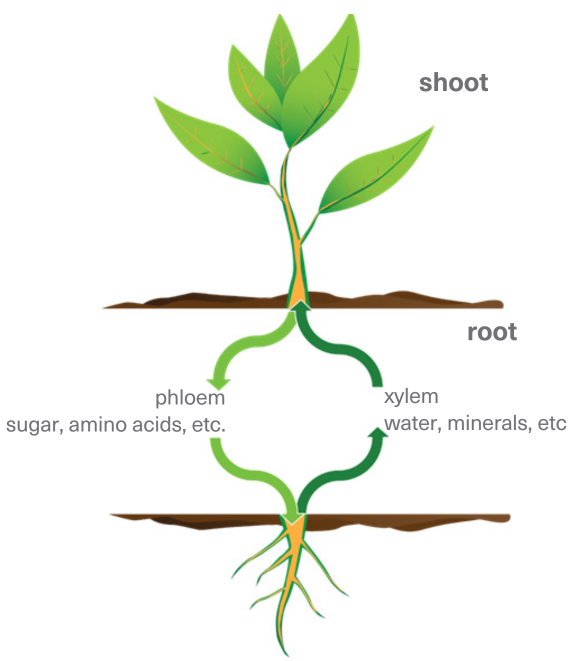
Indoor agriculture can be an energy-intensive operation. This catalog strives to illustrate the requirements for indoor agriculture environmental control, the differences compared to traditional comfort cooling, and highlighting best practices.

Plant Biology

To gather nutrients and support plant growth, the plant is divided into several systems:

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

Plants have a circulatory system. The phloem is used to transport sugars and amino acids from the shoot to the root. The xylem is used to transport water and minerals from the root to the shoot.



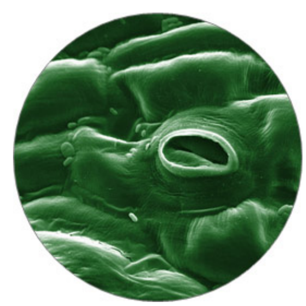
Plants need a variety of nutrients, minerals, and gases from several sources:

- Light. Outside, this comes from the sun; inside, this is provided by lighting fixtures
- Gases. Carbon dioxide (CO_2) and oxygen (O_2)
- Minerals and vitamins. From the soil: phosphorus, potassium, nitrogen, magnesium, calcium, and sulfur
- Water. From ground water, rain, and/or irrigation

When water is freely available or the plant is adequately watered, and the plant is exposed to light, the guard cells found on the leaves become swollen, opening the stomatal pore to its largest size. Conversely, when water levels are low or there are low levels of light, the guard cells become flaccid and the stomatal pore is closed.

When the stomata are open, air can freely enter the leaf and interact with the spongy mesophyll. Carbon dioxide, contained within the air, is consumed during photosynthesis within the leaf and oxygen is released. This oxygen also exits the leaf through the stomata.

Water evaporates within the leaf and exits through the open stomata to allow carbon dioxide entry. The evaporated water must be replaced through transpiration, using water that is introduced through irrigation.



The plant balances carbon dioxide consumption and evaporated water loss through guard cell control and the resulting stomatal pore opening.

Evapotranspiration

A plant requires water to grow. Water is also used within the plant structure to move nutrients from the root system to the shoots through the xylem. Much, but not all, of this water is eventually released by the plant through evapotranspiration, which is a combination of evaporation and transpiration.

Evaporation

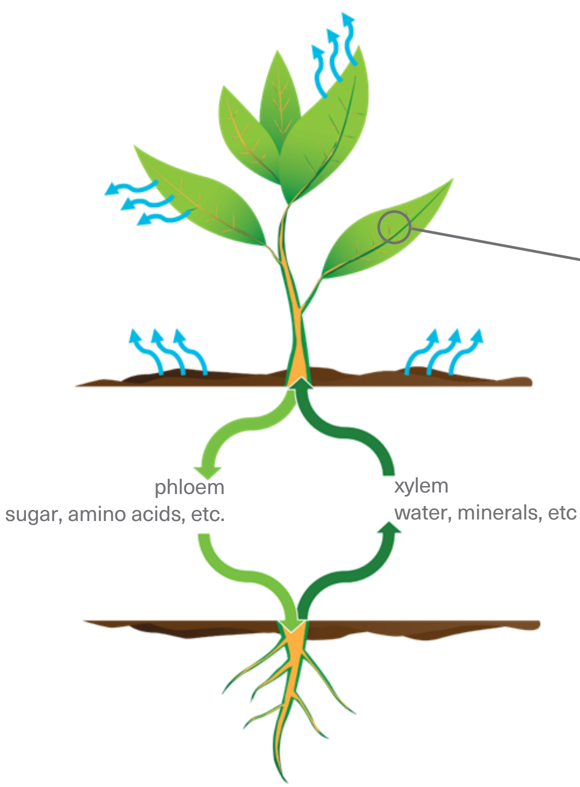
Evaporation is from the movement of water from the soil and plant leaves to the surrounding air.

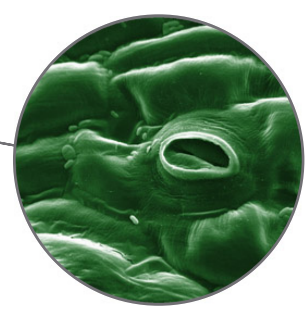
Transpiration

Transpiration is the movement of water within the plant and the resulting conversion to water vapor and release from the stomata on the leaves. This transpiration of water increases the solute concentration in the mesophyll cells of the leaves.

Through osmosis (the diffusion of water), water moves from the xylem to the mesophyll cells within the leaf. The reduced pressure within the upper areas of the xylem draws water up through the shoot xylem. Water molecules tend to stick to one another because of cohesion. They also tend to stick to other polar molecules, like cellulose, due to adhesion. Capillarity, the tendency of a liquid in a capillary tube or absorbent material to rise or fall as a result of surface tension, is a consequence of adhesion. The adhesive forces counteract gravity, which allows the water to move upwards.

As a result of this process, 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.





Transpiration
Water movement within the plant and eventual release from leaf stomata.

Indoor Growing

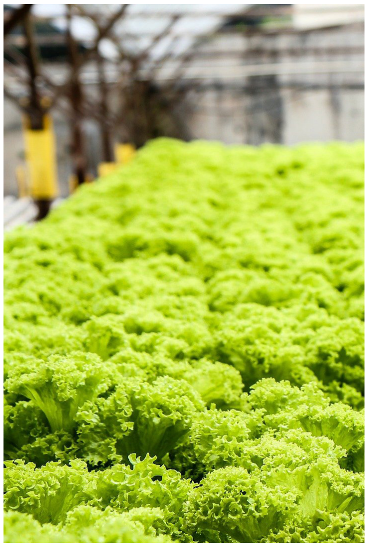
Grow Rooms

Some plants experience a growth cycle that lasts several seasons—spring to summer to autumn. As a result, growers reproduce these conditions with altered lighting, temperature, and humidity conditions. Other plants grow and produce fruit quickly, so growers only provide a single set of conditions. In either case, to grow plants indoors, growers must provide lighting, irrigation, minerals, nutrients, and carbon dioxide. Lighting fixtures are used to replace sunlight. Minerals and nutrients may be provided through the use of fertilizer. Alternatively, growers may mix irrigation water with minerals and nutrients and provide this enriched solution—commonly called "fertigation"—to the plants.

Crop growth rates, duration of growing period, plant sizes, and other variables are used to determine whether plants are kept in a single space from seed/seedling to harvest or if they're moved from room to room. In those facilities where plants are moved, there are often several types of growing spaces with unique lighting, temperature, and humidity conditions. This allows spaces to be specifically designed for the growth phase with some crops necessitating several different spaces (e.g. clone rooms, mother rooms, vegetation rooms, flowering rooms, and drying rooms). It's important for the HVAC designer to understand the specific conditions that must be maintained in each space, and whether the grower intends to change these for future crops.

For those plants which are not moved, growers may expect the operating conditions be varied throughout the plant's life cycle. Because of this, the HVAC designer must have a clear understanding of the expected conditions at each stage of the plant's life, whether they're expected to change for future crops, and loads to ensure adequate equipment sizing.

The plant shoot is phototropic, which means the above-ground portion of the plant grows toward the light source and the root is gravitropic, meaning the root system grows toward gravity. Many growers take advantage of this with proprietary methods to arrange their plants. Some growers have their plants arranged on tables or trays or suspended horizontally in the irrigation water. Alternatively, some "vertical" growers arrange the plants horizontally in trays layered on top of one another, allowing more plants to be placed per square foot than a traditional outdoor agricultural operation. Finally, some companies have developed systems that allow the plants to be placed in vertical systems that allow the plant to grow outward, even from a vertical tube.



Grow rooms—types and sizes

Plant growth may be contained in a single large growing space, or separated into two or more individual grow rooms for a variety of reasons:

Growing all plants in a single large room:

- Keeps all plants in a single space
- Allows for greater use of floor area
- Lighting schedules cannot be staggered
- Allows easier worker access to the plants
- Plants will be subjected to uniform temperature and humidity conditions

image source: MaxLite®, www.maxlite.com

Separating all plants into two or more individual grow rooms:

- Allows plants to be isolated from one another
- Allows lighting schedules and durations to be staggered
- Allows the plants to be subjected to different temperature, humidity, and CO_2 conditions by grow room

Some crops with longer growth cycles are moved from room to room as they mature. This allows each room to be purpose-built and designed for the specific growth cycle. Alternatively, growers may prefer to keep the plants in a single space and change the indoor conditions to suit the specific growth cycle. For load-design purposes, it's important to understand how each room will be used, what the expected loads will be, and if the grower intends to change space temperature and humidity setpoints.

Grow room conditions—temperature, humidity, and VPD

The grower's actions are often driven by the need to produce a consistent, healthy crop as quickly as possible and at the lowest cost. Growers may specify a particular temperature and humidity condition for the indoor air surrounding their plant during the plant's growth phase or they may use a phrase "vapor pressure deficit" or "vapor pressure difference" (VPD) to describe a specific growing condition. 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. VPD can be expressed in different units, with kilopascals being very common.

Plant transpiration and growth are dependent on an appropriate VPD:

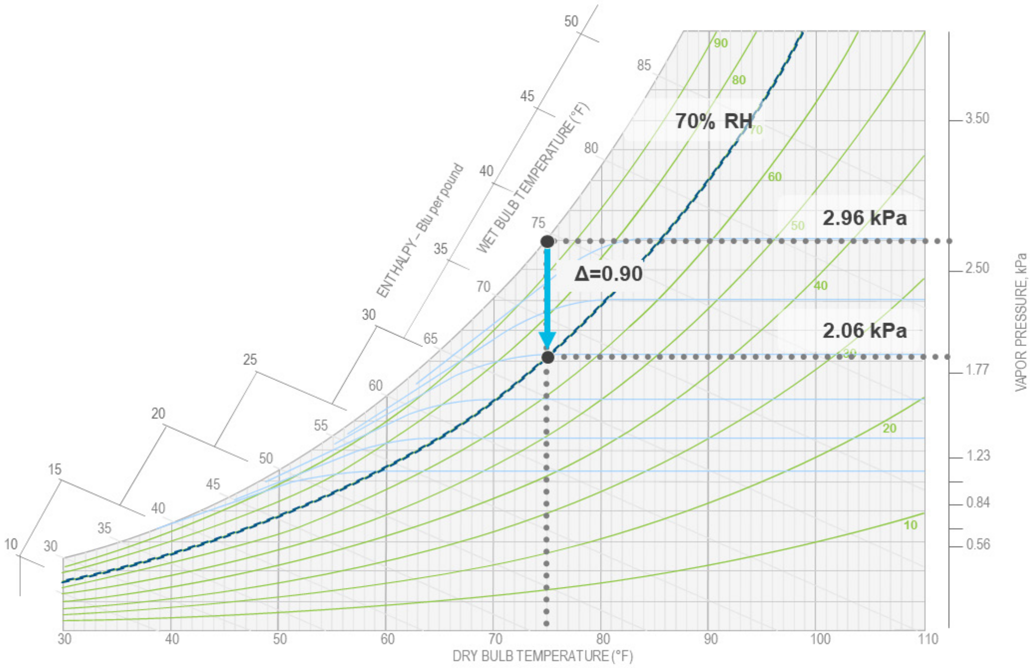
- When the plant is in a dry environment with low humidity, the vapor pressure difference between the plant and surrounding air is large. As a result, the plant's rate of transpiration will increase due to the higher rate of evaporation from the stomata in the leaves. An insufficiently watered plant experiencing large VPDs will begin to wilt.
- Conversely, when the surrounding air has high humidity, the vapor pressure difference between the plant and surrounding air is small. As a result, the plant's rate of transpiration will decrease due to less evaporation from the leaves.

The grower should be able to provide the desired dry-bulb temperature and VPD. When a grower indicates a desired VPD, they're telling you how much difference is required in vapor pressures between the leaf and air.

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 on "Using Vapor Pressure Difference (VPD) to determine growing space control setpoints" on page 8. Achieving a desired VPD at a higher temperature and subsequent higher relative humidity will significantly reduce the HVAC component design capacity and energy required to achieve the desired conditions (see sidebar on "HVAC and VPD" on page 9).

Several sample VPD charts are provided at the end of this publication. The first chart is a standard chart, which assumes the leaf temperature and surrounding air temperature are the same. The next chart assumes the leaf is 1°F colder than the surrounding air temperature. The final chart assumes the leaf temperature is 3°F colder than the surrounding air.

Using Vapor Pressure Difference (VPD) to determine growing space control setpoints



Growers often specify a vapor pressure difference or vapor pressure deficit (VPD) to describe a specific set of growing space conditions needed. In North America, expressing this difference is often accomplished with the kilopascal unit of measure. VPD is the difference in vapor pressure between the leaf boundary layer and the surrounding air. The leaf boundary layer is assumed to be saturated because this is where the plant releases water vapor through the stomata. In some cases, the grower might assume the temperature of the leaf to be cooler than the surrounding air dry-bulb temperature because of the cooling effect produced by the leaves converting liquid water to water vapor.

Consider the following example: a grower prefers a VPD of 0.90 kPa with a dry-bulb temperature setpoint of 75°F. The leaf surface temperature is also 75°F.

Step 1: The leaf boundary layer conditions can be plotted on a psychrometric chart. The boundary layer is assumed to be saturated, therefore 100 percent relative humidity, and the corresponding vapor pressure at 75°F is determined to be 2.96 kPa.

Step 2: Subtract the required VPD to determine the desired vapor pressure of the surrounding air.
Surrounding air vapor pressure = leaf vapor pressure – desired VPD = 2.96 – 0.90 = 2.06 kPa

Step 3: Determine space relative humidity or dew point temperature setpoint from the surrounding air vapor pressure. This can be read from the psychrometric chart. To maintain the grower's preference of a space dry-bulb temperature of 75°F and VPD value of 0.90, the space must be controlled to 75°F dry-bulb and 70 percent relative humidity (or a dew point temperature of 64.6°F).

HVAC and VPD

The choice of growing space dry-bulb temperature and humidity setpoints can affect HVAC equipment sizing and energy consumption. Growing spaces with lower dry bulb temperature setpoints and drier relative humidity setpoints often require more cooling and dehumidification capacity. As a result, larger equipment must be provided, and the equipment uses more energy.

Consider an example with two different growing space dry-bulb temperature setpoints: 75°F and 80°F. To maintain a VPD of 0.90 kPa, the following space dry bulb temperature and relative humidity setpoints would be required:

	Condition 1: 75°F	Condition 2: 80°F
VPD	0.90 kPa	0.90 kPa
Dry bulb temperature setpoint	75°F	80°F
Resulting relative humidity setpoint	70%	74%
Resulting dew point temperature setpoint	64.6°F	71°F

HVAC energy consumption increases when there is a larger differential between the space conditions and the ambient air conditions used for heat rejection. Cooling equipment will operate at a lower suction temperature to maintain the cooler space temperature (75°F), which will be less efficient than the equipment maintaining 80°F. As a result, it may be advantageous to use "warmer" conditions if the plants are tolerant to these conditions.

Common irrigation types

Growers may use a variety of methods to irrigate plants. In addition to this, growers often mix fertilizer with irrigation water, which is often referred to as "fertigation." This nutrient-rich solution is then applied to the plants. Fertigation may include:

1. Providing a properly treated source of water. This water may be new, reclaimed, filtered, and treated.
2. Mixing the water with nutrients, commonly in a tank, either manually or with automated controls.
3. Distributing the solution to the plants–pumping and timing to control the amount applied to plants to allow for absorption, while also providing optional rotation between zones to maintain system pumping pressure.

In many cases, indoor agricultural facilities will use a separate room to store and mix fertilizer into the irrigation water. In addition, pumping and distribution equipment is needed to circulate and distribute the solution. Depending on the application, the nutrient-rich solution can be continuously circulated, or remain static.

Some growers choose to use hydroponics or aquaponics. As long as plants receive the nutrients needed, soil is not required in an indoor environment for plant growth. Instead, some growers will suspend the roots of the plants in nutrient-rich water, where the roots absorb water and nutrients.

Aquaponics is the combination of two types of farming, aquaculture and hydroponics. Aquaculture is the farming of aquatic organisms such as fish, crustaceans, or mollusks.

Hydroponics is the cultivation of plants in a nutrient solution. In aquaponics, the fish waste is processed by bacteria, which becomes dissolved nutrients for the plants to consume. The plants, as they consume nutrients, act as a filter system for the water that the fish live in.

Regardless of irrigation type, special consideration should be given for water evaporation loads if hydroponics or aquaponics are used and there are large amounts of water exposed to the conditioned air.

Lighting

Lights are the primary source of energy for the indoor plant growing process. This growth is primarily in the day cycle (lights on means "daytime", lights off means "nighttime"). The lighting radiation provides energy to the plants for photosynthesis. The spectrum of the light produced includes beneficial light called photosynthetically active radiation (PAR). The intensity of the light can also increase the process of photosynthesis, within limits. Excessive intensity can be detrimental to optimum growth and may also provide too much heat directly to the plants. Lighting intensity and placement is an important consideration for optimum growth.

The lights are a large part of the electrical energy consumption of the facility. The lights also generate a significant amount of heat, which requires the HVAC system to provide cooling to offset this heat. In most indoor growing applications, the lights are the largest source of heat and tend to dominate the sensible cooling load requirements. There is a correlation between electrical energy consumption and heat generation. For these reasons, the efficiency of the fixtures is an important consideration when selecting the lighting fixtures.

There are various types of lighting fixtures available for indoor growing applications. Some common types include high pressure sodium (HPS), metal halide (MH), ceramic metal halide (CMH) and light emitting diodes (LED). Each type of light has a specific spectrum of light that they produce. LED lights can have variable spectra available for the grower to select from. The spectrum selection of LED fixtures is typically a manual setting at the time of installation and is not changed afterward. The spectrum and intensity of light produced will impact the effectiveness of the growing cycle and is therefore an important consideration when selecting lighting fixtures.

High pressure sodium, metal halide, and ceramic metal halide fixtures have been in use indoor growing applications for many years. These types of lights are typically controlled either "on" or "off." These types of lights use electronic ballasts to drive the bulbs (similar to fluorescent lights) and operate at a constant level. Variable levels of light intensity can be achieved by

operating a portion of the lights, if they are appropriately located for this purpose. In many cases, the practical result is two levels of light – low (partial fixtures on) and high (all fixtures on). This allows the grower to vary the intensity at different phases of growth, or to simulate dawn and dusk transitions.

LED light fixtures are newer to the indoor growing market, compared to other types of lights. One of the main advantages of LED lights is that they typically consume less electrical power and therefore also produce less heat – which reduces the requirement for cooling. LED light fixtures typically have dimmer controls to allow the grower to vary the light level to optimize growth and minimize excess heat. With LED fixtures that have dimming controls, it is possible to use PAR sensors to measure light levels and adjust the level of the fixtures. This can be a manual PAR reading and adjustment of the light level, or it can be an automated control process including real-time measurement with PAR sensors. Either method allows the grower to vary the intensity at different phases of growth, or to simulate dawn and dusk transitions. It also provides a high limit on the intensity, to compensate for light placement and help prevent undesired effects from the excessive intensity.

Regardless of the type and manufacturer of the grow lights, a Trane® control system will be able to control the lighting to the grower's specification. Refer to the Controls section of this catalog for more information (page 38).

Trane's industry experts can provide high-value lighting systems as part of a construction or renovation project. Contact your local Trane representative to discuss lighting options. www.trane.com/lighting

HVAC Systems

Consider staggering "daytime" periods

The use of a controlled environment permits the growers and operators to determine when plants are illuminated for the "daytime" period. In those buildings with multiple, separated growing spaces, operators may consider staggering the "daytime" periods for several reasons:

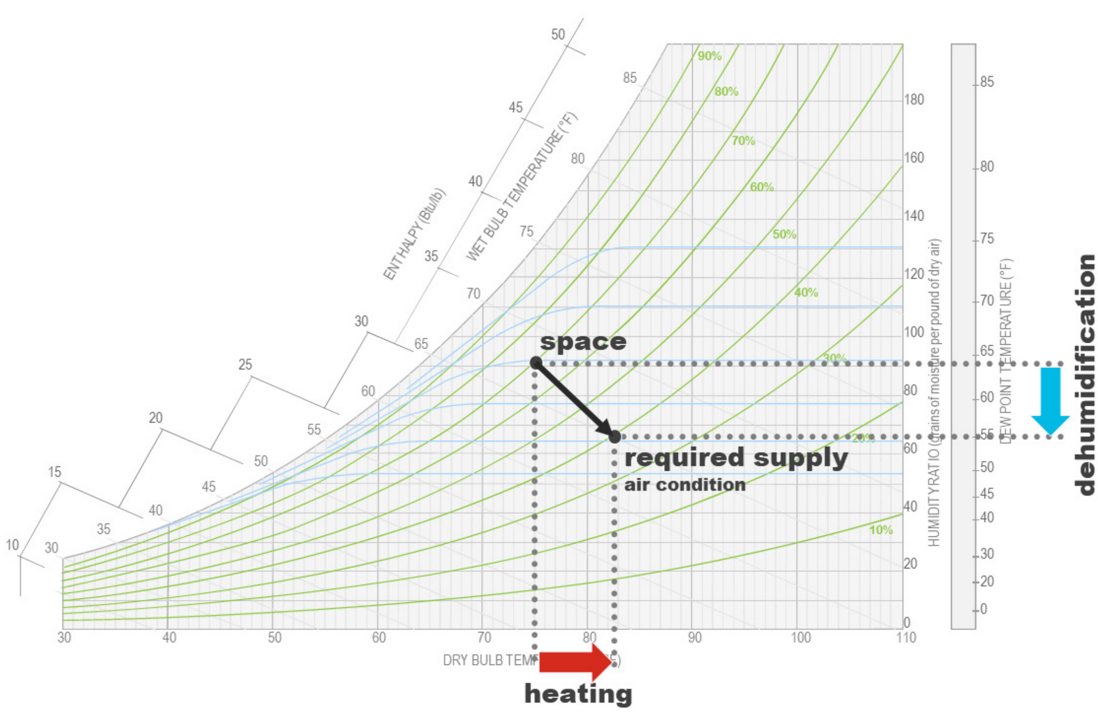
- **Reduced peak load.** Reducing the peak load reduces the infrastructure requirements for electrical and mechanical systems. Staggering room operation can reduce the cumulative peak cooling load for the entire building. If the grow rooms are served by a single cooling source, such as a chilled water system, this can reduce the largest block load, allowing for smaller equipment to be installed, along with reduced peak energy usage.
- **Reduced peak electrical demand.** Shifting operation allows the grow lights and HVAC peak electrical demands to also be staggered. This also serves to reduce the peak electrical demand, which may be used as a component in electrical utility billing.
- **Reduced load swings.** When the lights are turned on, sensible load is added to the space and plants increase their evapotranspiration, which results in an increase of latent load. By staggering the times when the lights turn on and off, the total load remains steadier when compared to turning all the room lights on at a single time and slamming the chiller plant with an immediate cooling load. Similarly, turning lights off reduces the space load quickly.

Dehumidifying systems with reheat

To maintain space temperature and humidity, systems will very likely need to be equipped with both temperature control and humidity control. During the "daytime" mode when grow lights are on, HVAC systems must provide enough cooling to offset the sensible loads (likely from grow lights and some envelope loads). At the same time, the systems must also offset the space latent loads from plant evapotranspiration necessitating dehumidification.

During the "nighttime" mode when grow lights are turned off, systems often need to provide dehumidification to offset some space latent loads from the plants, however there is little sensible cooling to offset.

In fact, there may be times when the space requires both dehumidification to offset the plant's water vapor contribution and heat to offset the cooling effect from the plants. Some call this operation "negative SHR" because plotting the space sensible heat ratio is opposite to the traditional comfort cooling plot (see figure below).



Ventilation with outdoor air

In a comfort cooling application, outdoor air is introduced into the occupied spaces to dilute indoor contaminants and increase indoor air quality. In an indoor agriculture application, carbon dioxide may be added to the growing space to increase concentrations beyond ambient levels, for increased plant growth rates. As a result, the introduction of outdoor air would dilute the carbon dioxide-rich space, so many growers decide to forgo ventilation in the growing spaces.

Airside economizers

Airside economizers can be used to reduce the mechanical cooling load by using mild outdoor air to offset space cooling loads. This is accomplished by opening the outdoor (economizer) air damper and increasing the amount of outdoor air circulation beyond minimum ventilation requirements. Some growers may choose to not use airside economizers for several reasons:

- **Loss of carbon dioxide.** To maintain space pressure, additional air must be exhausted during economizer operation, resulting in the loss of CO_2 that has been added to the growing space.
- **Impact on odor mitigation.** Exhausted air due to economizing may need to be filtered or cleaned to alleviate odors from growing and processing which may require additional exhaust fans and communicating controls. See "Filtration, odor mitigation, and air cleaning" on page 15 for more information.
- **Increased risk of introducing foreign organisms.** During economizer operation, there is an increased risk of foreign organisms, such as molds and pollens, to be brought in from outdoors. This also introduces an opportunity for cross contamination between adjacent HVAC units and facilities. Some of these risks can be mitigated with filtration.

Airside economizer control should be based upon both outdoor air dry-bulb temperature and dew-point temperature to ensure the supply air is both cold enough and dry enough to offset space sensible and latent loads.

Determining supply air conditions

The procedure for determining the proper supply air conditions—dry bulb temperature and humidity ratio—may be different due to the fact that the load can be dominated by plant latent loads. As a result, the proper supply air conditions may not conform to traditional comfort cooling methods. The following procedure establishes the required dry-bulb temperature and humidity ratio for the supply air.

Step 1: determine the entering air conditions. The entering air may be 100 percent recirculated air, or it may be a mixture of recirculated air with outdoor air for ventilation. If the air is 100 percent recirculated air, the entering conditions are likely the same as the space conditions with minimal additional heat gains.

If outdoor air is being introduced for ventilation, climactic data may be used to determine peak dry-bulb and humidity ratios of the return-outdoor air mixture.

Using a psychrometric chart or calculator, determine the entering air dry-bulb temperature and humidity ratio.

Consider an example growing space whose return air dry-bulb temperature is 75°F and relative humidity is 70 percent, corresponding to a VPD of 0.90 kPa (see "Grow room conditions – temperature, humidity, and VPD," page 7). No outdoor air is being introduced; therefore, a mixed air temperature will not need to be computed. These conditions equate to a humidity ratio of 91.1 grains per pound of dry air (gr/lb).

Step 2: determine the space sensible and latent loads. Common sources of indoor space loads include:

- Sensible load due to growing lights
- Sensible load due to additional equipment in the space (e.g. dehumidifiers, circulation fans, fluid pumps)
- Sensible load due to the cooling effect of plant evapotranspiration
- Latent load due to plant evapotranspiration
- Use of a load analysis software program, such as TRACE® 3D Plus, may be used to estimate total sensible and latent loads

In the example growing space, the design "daytime" loads have been computed:

	Sensible (Btu/hr)	Latent (Btu/hr)
Lighting	98,300	0
Evapotranspiration	-52,800	58,700
Total	45,500	58,700

Step 3: determine the total airflow that the unit must deliver. The supply air volume may be determined based upon equipment minimum and maximum limitations or required supply air velocity within the growing space.

In the example, a 2000-cfm constant volume unit will be used to supply conditioned air to the growing space.

Step 4: determine the supply air humidity ratio. Using the space latent heat equation, the supply air humidity ratio can be computed.

$$Q_{space,\ latent} = 0.69 \times \text{airflow} \times (W_{space} - W_{SA})$$

$$58{,}700 \text{ Btu/hr} = 0.69 \times 2000 \text{ cfm} \times (91.1 \text{ gr/lb} - W_{SA}) \therefore W_{SA} = 48.6 \text{ gr/lb}$$

In the Q_{space}, latent equation, 0.69 is derived from the properties of air; it is not a constant. At the "standard" air condition, which is 69°F dry air at sea level, the product of density, the latent heat of water vapor, and conversion factors for units—7,000 grains/lb and 60 min/hr—equals 0.69. A different air condition or elevation will result in a different value.

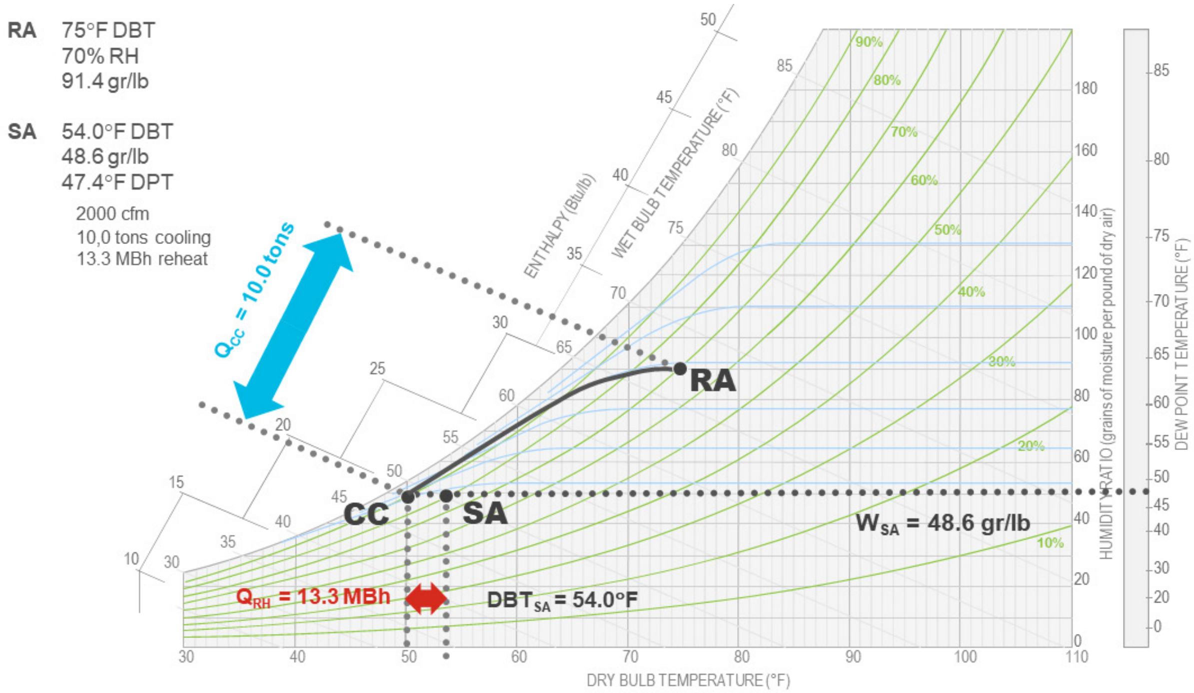
Step 5: determine the supply air dry-bulb temperature. Using the space sensible heat equation, the supply air dry-bulb temperature can be computed.

$$Q_{space,\ sensible} = 1.085 \times \text{airflow} \times (DBT_{space} - DBT_{SA})$$

$$45{,}500 \text{ Btu/hr} = 1.085 \times 2000 \text{ cfm} \times (75°F - DBT_{SA}) \therefore DBT_{SA} = 54.0°F$$

In the Q_{space}, sensible equation, 1.085 is derived from the properties of air; it is not a constant. At the "standard" air condition, which is 69°F dry air at sea level, the product of density, the specific heat of air, and a conversion factor for units—60 min/hr—equals 1.085. A different air condition or elevation will result in a different value.

The example shows the supply air must be dehumidified to a humidity ratio of 48.6 grains per pound to offset the space latent loads, and then must also be delivered at a dry-bulb temperature of 54.0°F to offset the space sensible loads. Plotting these conditions on a psychrometric chart helps visualize the required process.



Recirculated air from the growing space enters the unit and is cooled to a humidity ratio of 48.6 grains per pound, representing 10 tons of cooling. The supply air is then heated from the cooling coil leaving air temperature of 50.0°F to 54.0°F, representing 13.3 MBh of heat.

The procedure may be repeated using the expected design “nighttime” loads. Evaluating both conditions helps ensure equipment components, such as cooling and heating coils, are adequately sized. Given the reduced sensible and latent loads during “nighttime,” some designers might choose to use a Variable Air Volume (VAV) system to reduce supply airflow during those times that experience lower loads.

Variable air volume in growing spaces

At times when loads are less than design, VAV systems will reduce the supply air volume to match the current demand. Typically, this is accomplished with the use of a variable speed fan. During periods of low loads, the unit will continue provided a constant supply air discharge condition, while reducing the volume of supply air. Some units, such as packaged rooftop and split systems, may encounter a minimum fan speed limitation. If the load continues to decrease, the unit may automatically use supply air temperature reset to then increase the discharge air condition to continue offsetting the load.

In a dehumidification application, the use of supply air temperature reset is generally discouraged because the amount of dehumidification performed by the unit is also reduced. Instead, consider using reheat to allow the unit to continue dehumidifying the supply air to the appropriate discharge air condition. Reheat is used to raise the supply air dry-bulb temperature to ensure no overcooling occurs.

If the HVAC units are expected to provide high velocity air movement throughout the growing spaces, the use of VAV may not make sense since the air velocity would be reduced at part-load conditions.

Common supply air distribution configurations

Overhead ductwork may be used to ensure conditioned supply air is delivered to the growing space, atop the plant canopy. Advantages include ductwork being out of the way however maintenance and cleaning may be difficult due to its height and location. Underfloor ductwork may be used, but care must be taken to ensure irrigation water and debris do not enter the underfloor duct system.

Duct material considerations

Supply and return air ductwork can be assembled from a variety of materials, both rigid and flexible. Rigid ductwork is often permanently installed and may be cleaned periodically. Some growers prefer to use flexible fabric duct materials because the ductwork can be disconnected, laundered, and replaced. While there are several options available, growing spaces may provide some additional challenges.

The presence of airborne chemicals from the growing process, such as fertilizers or chemical fumigation, may also inform duct material decisions. Finally, if condensation is expected on cold surfaces, consideration should be made for corrosion resistance and/or thermal insulation and a vapor barrier.

Air filtration

Air filtration is used for several reasons: ensuring HVAC components remain relatively clean and ensuring foreign contaminants and particles are kept out of the growing environment. Clean HVAC components help ensure system performance and helps to keep the air distribution system clean.

Airborne particles vary in size and as a result, many filter types are available. The minimum efficiency reporting value (MERV) system is used to describe a filter's ability to capture particles ranging from 0.3 to 1.0 µm. Filters with a larger MERV rating are able to capture smaller particles more efficiently. These filters often have a large footprint and impose a greater airside pressure drop in the air stream. This results in increased fan energy use.

ASHRAE®'s ventilation standard, Standard 62.1, requires MERV 8 filtration upstream of any dehumidifying device, such as a cooling coil. Some designers choose to select a filter with a higher MERV rating to capture smaller particles.

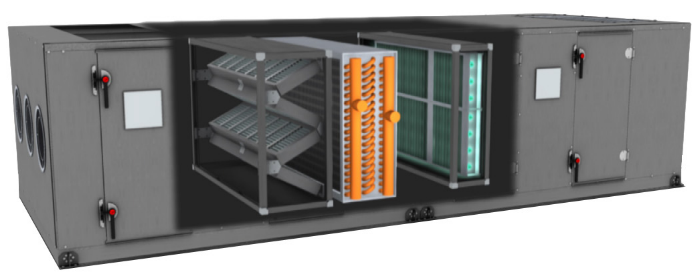
Some equipment accommodates a pre-filter and post-filter. In many cases, a MERV 8 pre-filter is used to ensure components remain clean and a post-filter with a higher MERV rating is used to reduce particulates in the supplied air. The use of a pre-filter also helps prolong the life of the often-more-expensive post-filter.

Filters do require maintenance. They should be inspected and replaced at regular intervals, as recommended by the equipment manufacturer. Filters may be replaced based upon a length of time they've been in use, or a differential pressure sensor may be used to indicate when the filters are dirty and must be replaced. During replacement, the filter assembly should be carefully inspected to identify areas that are not sealed, allowing air to bypass the filter. These areas can be sealed to minimize airflow bypassing the filters.

Odor mitigation and air cleaning

Some applications require additional consideration for odor mitigation. Often, gas phase filtration is used to reduce odors. Alternatively, devices using photocatalytic oxidation may be used to reduce odors. Consult specific odor mitigation device manufacturers for sizing and application guidance.

Other air cleaning technologies, such as ultraviolet germicidal irradiation (UVGI) and dry hydrogen peroxide can be used to inactivate microbiologicals. Sometimes, UVGI devices are used to constantly treat interior surfaces within HVAC equipment. Alternatively, higher doses of UVGI can be used to treat the supply air in a "fly-by" configuration. Consult air cleaning device manufacturers for sizing and application guidance.



Airside Systems

There are a variety of systems that can serve indoor agricultural spaces, and each has its own set of advantages and drawbacks.

Conventional DX Systems Paired with Dehumidifiers

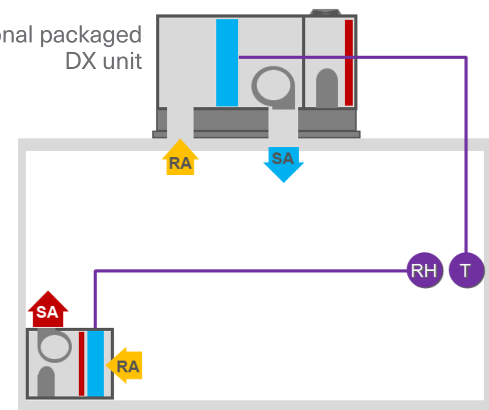
Conventional direct expansion (DX) equipment, which is designed for comfort cooling applications, is sometimes used in growing spaces. Examples of commonly applied equipment includes packaged DX rooftop units, DX split systems, and VRF systems.

This equipment is not designed for the large latent loads found in indoor agricultural settings. As a result, the conventional system is used to primarily offset the space sensible cooling load and control space temperature while coincidentally offsetting some of the latent load. To offset the balance of the latent load and maintain space humidity, one or more dehumidifiers must be located within the growing space.

Standalone dehumidifiers use a vapor compression refrigeration cycle to remove humidity from circulated air. The dehumidifier then rejects the heat removed by the evaporator plus the heat of compression into the space as sensible heat resulting in the air leaving the dehumidifier drier and warmer compared to entering the unit. For sizing purposes, the conventional DX system might need to be sized to remove the heat produced by the additional dehumidifiers. During some operating modes, this additional heat may be useful to maintain space temperature. Some dehumidifier manufacturers offer a split system, allowing heat produced to be rejected elsewhere.

Advantages

- **Quick installation.** Conventional DX equipment and dehumidifiers have short lead times and can be easily procured. Installation is relatively straightforward.
- **Simple controls.** Conventional DX equipment can be controlled by a temperature sensor installed in the space. Dehumidifiers are often controlled by a relative humidity sensor mounted in the entering airstream.
- **Easy to install and service.** Both types of equipment are easy to install and typically easy to service by qualified personnel. Replacement parts are readily available.



Drawbacks

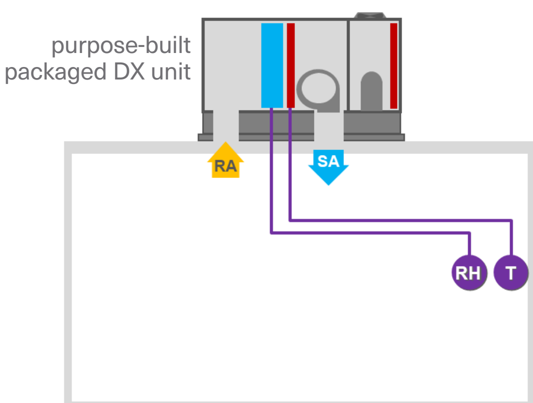
- **Precise space temperature and humidity control can be difficult.** Precise temperature and humidity control can be difficult when using separate, disconnected systems.
- **Challenge of operating in cooling mode during cold weather.** The DX equipment likely needs to operate in cooling mode during all seasons, which may be difficult in cold climates. In a comfort cooling application, if the space needs cooling when it's cold outside, airside economizing is typically used. This allows all of the cooling to be done with cold outdoor air, while the unit's compressors are off. For a variety of reasons, airside economizers are often not used in an indoor agricultural setting (see Airside economizers, page 12). Because heat and moisture loads are present year-round, mechanical refrigeration systems must be designed and controlled to operate in all ambient conditions.
- **Higher energy usage compared to other options.** This configuration likely consumes more energy compared to other HVAC options.
- **Limited controls integration.** Standalone controls are typically used, often with limited integration between components.

Purpose-Built Packaged Units or Split Systems with Dehumidification

Purpose-built systems are available in several configurations—packaged units or split systems—and are designed with sufficient dehumidification to handle plant evapotranspiration loads. This allows both space temperature and humidity to be maintained by a single system. To prevent overcooling during periods of reduced sensible cooling load, like "nighttime" modes, reheat is typically provided. Often, heat is recovered from the refrigeration system, using hot gas reheat, and used as the first stage of reheat rather than rejecting the heat outside.

Advantages

- **Integrated operating modes (dehumidification, cooling, heating).** This equipment is designed to support dehumidification, cooling, and heating operation modes.
- **Packaged controls.** Operational mode control is typically pre-installed in the unit controller.
- **Easy to install and service.** Both types of equipment are easy to install and typically easy to service by qualified personnel. Replacement parts are readily available.
- **More efficient than conventional DX and standalone dehumidifiers.** Purpose-built units typically have higher efficiencies compared to conventional DX equipment paired with standalone dehumidifiers in the space.



Drawbacks

- **Challenge of operating in cooling mode during cold weather.** The DX equipment likely needs to operate in cooling mode during all seasons, which may be difficult in cold climates. In a comfort cooling application, if the space needs cooling when it's cold outside, airside economizing is typically used. This allows all of the cooling to be done with cold outdoor air, while the unit's compressors are off. For a variety of reasons, airside economizers are often not used in an indoor agricultural setting (see Airside economizers, page 12). Because heat and moisture loads are present year-round, mechanical refrigeration systems must be designed and controlled to operate in all ambient conditions.
- **Higher energy usage compared to other options.** This configuration likely consumes more energy as compared to applied/chilled water systems.
- **Spaces with "negative sensible heat ratios" require supplemental or recovered source of heat.** An additional source of heat may need to be provided on systems that serve spaces that experience "negative sensible heat ratios" where the supply air must be dehumidified to offset space latent loads, then heated above the space cooling setpoint temperature to offset the plant cooling effect. This enables simultaneous dehumidification and heating. See "Dehumidifying systems with reheat" on page 11 for more information.
- **Higher equipment cost compared to conventional DX systems.** Purpose-built packaged or split DX equipment is typically more expensive than conventional DX equipment.

Trane Thrive™ Packaged Rooftop Unit

Trane's Thrive packaged rooftop unit is a purpose-built packaged rooftop unit specifically engineered to meet the requirements of indoor agriculture. Units range in capacities from 3 to 80 tons, with up to 600 pounds of water removal per hour. Modulating hot gas reheat is available, along with natural gas and electric heat options. Units are designed to operate in ambient conditions as low as 0°F.

Thrive features

	Trane Thrive Packaged Rooftop Unit
Capacity range	3-80 tons
Dehumidification capacity	Up to 600 pounds of water per hour
Airflow range	500-25,000 cfm
Refrigeration options	DX, air-source heat pump, and water-source heat pump design options
Compressor modulation	Variable capacity scroll compressors
Fan modulation	ECM and VFD-controlled direct drive fan options
Air filtration options	Multiple air filters supported and UVGI options
Controls	BACnet-enabled TRACER® UC600

For additional information on Thrive, and other Trane solutions, visit www.trane.com/indoorag.

Air Handling Units

Air handling units (AHUs) may be purpose-built or configured for specific applications. Air handlers are often more configurable and include more options for casing types and insulations, supply fan static pressure capabilities, and air-to-air heat recovery or desiccant dehumidification for improved efficiency. Cooling can be provided by chilled water, DX using a split system, or even VRF with a linear expansion valve kit. Heat can be provided by recovered heat, hot water, steam, natural gas, or electricity.

Air handlers can be specified with a variety of air-to-air heat recovery options and desiccant dehumidification. Several common configurations include cool and reheat, series heat exchangers, series coil loops, and series desiccant wheels.

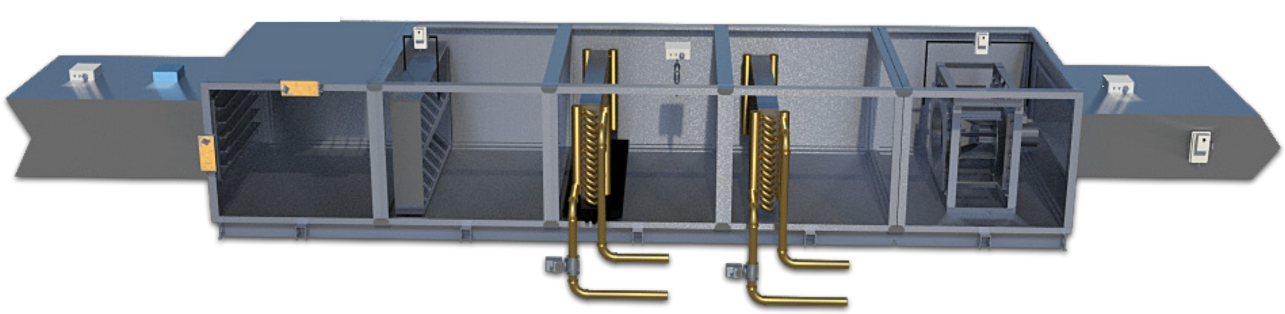
Insulation is important in those applications where air handlers are installed outside in cold climates. When units are dehumidifying during cold weather, there is a risk of moisture condensing on the inside surfaces of the air handler casing. If the air handler cannot be installed indoors, then consider the use of low-leak construction and improved insulation.

Advantages

- **Greatest flexibility (heat recovery, materials, casing materials and insulation).** Air handlers can be configured in a wide variety of ways. Many are available with a range of air-to-air heat recovery technologies or desiccant dehumidification. Units can be constructed with a variety of materials and insulations.
- **Range of cooling options (chilled water, DX).** Chilled water is commonly used as a source of cooling. The chilled water is sourced from air- or water-cooled chillers and those chillers may include heat recovery or free cooling. Remote condensing units or VRF units can be used to provide cooling through refrigeration (DX) coils.
- **Integrated operating modes, precise control.** Like the purpose-built DX equipment, air handlers can be designed to support the needed operating modes. And, when paired with chilled water, this approach can deliver precise control of both temperature and humidity.
- **Likely lowest energy use.** Air handlers and efficient chillers with heat recovery likely offer the most efficient combination resulting in the lowest energy use.

Drawbacks

- **Likely highest installed cost.** The combination of air handlers and chillers or DX condensing units likely carries the highest installed cost.
- **May require more skilled service personnel.** The use of chillers may require more skilled service personnel with a higher degree of training.

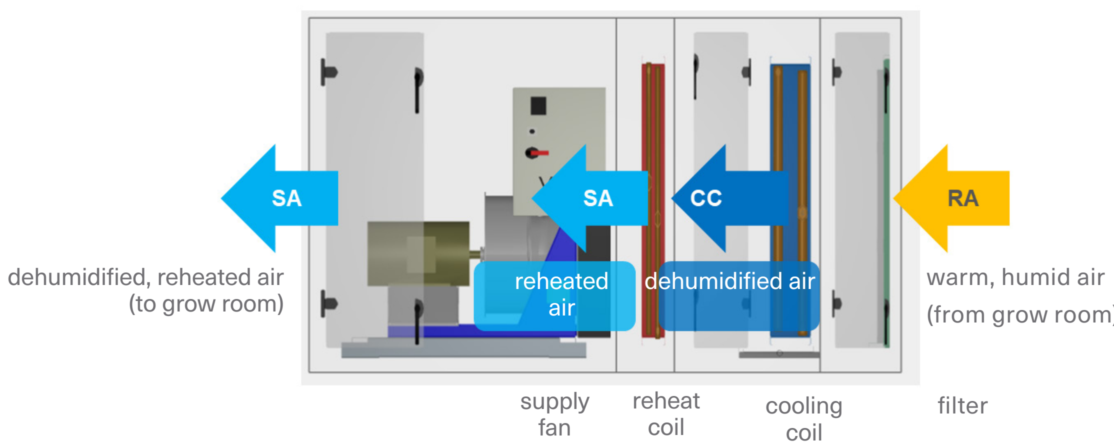


Cool and reheat

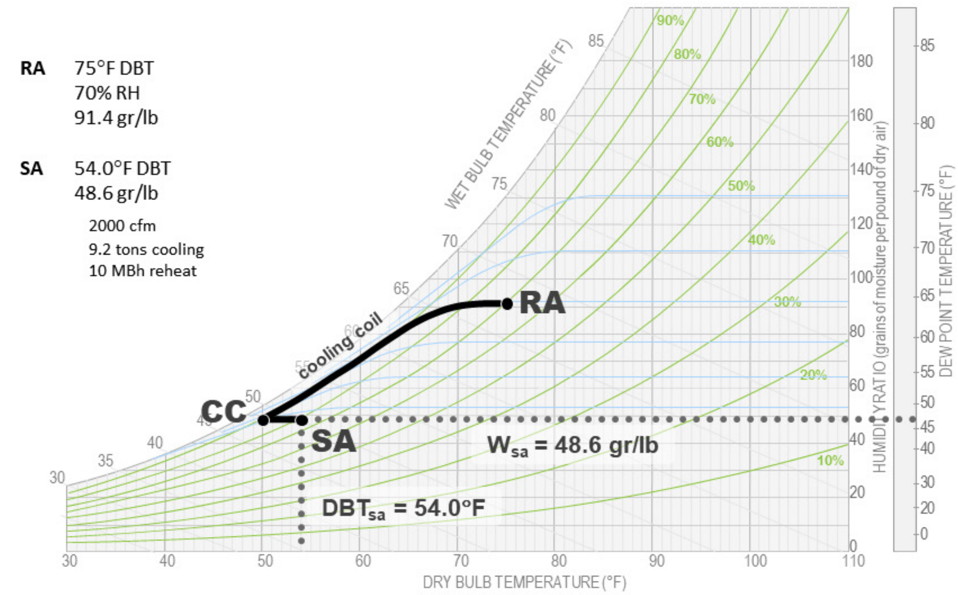
A basic air handling configuration is often called "cool and reheat." In this configuration, warm and humid air from the grow room enters the air handler, passes through the cooling coil and is dehumidified dry enough to offset the space latent load. The cool, dry air then passes through a reheat coil, where it is warmed up to avoid overcooling the grow room.

To help illustrate, example "daytime" and "nighttime" psychrometric charts are provided for each configuration (page 21). The example assumes a constant-volume 2000-cfm air handler serving a "daytime" cooling load of 45,500 Btu/hr sensible, 58,700 Btu/hr latent. Using the procedure shown in Determining supply air conditions, page 12, a "daytime" supply air temperature of 54.0°F dry bulb is needed to offset the space sensible loads. A humidity ratio of 48.6 gr/lb is needed to offset the space latent loads.

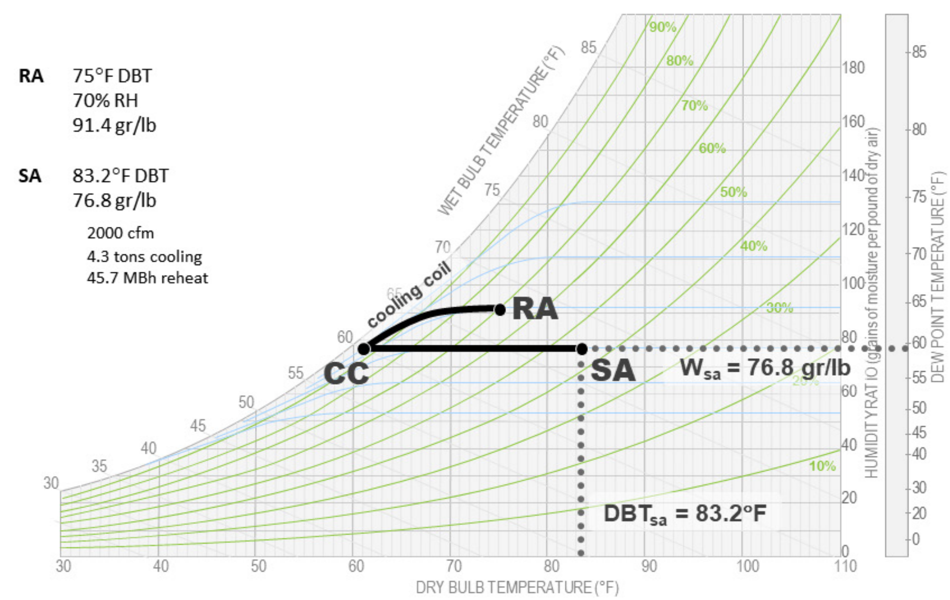
During "nighttime," the space experiences a load of -17,600 Btu/hr sensible, 19,600 Btu/hr latent. As a result, the supply air temperature must be 83.1°F dry bulb and the humidity ratio must be 76.9 gr/lb to offset the space sensible and latent loads, respectively.



Cool and reheat psychrometric chart—daytime



Cool and reheat psychrometric chart—nighttime



Series heat exchanger

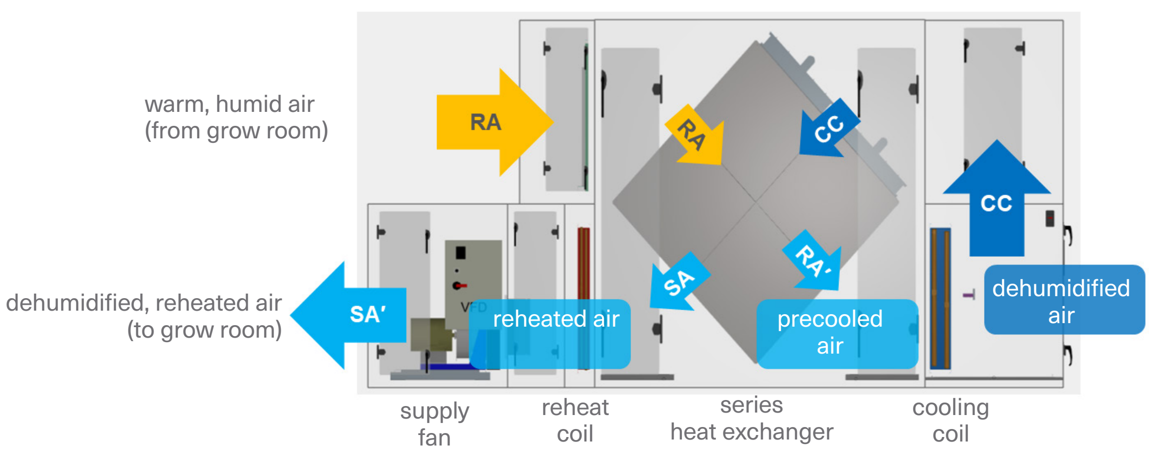
It may be advantageous to add air-to-air heat recovery to reduce the total system energy usage. When the heat exchanger is placed in the series or "wraparound" configuration, it removes heat from the air upstream of the cooling coil and transfers it to downstream of the coil to serve as reheat.

During the "daytime" mode, when the warm, humid recirculated air passes through the upstream side of the heat exchanger, it is pre-cooled several degrees. Then, the air passes through the cooling coil where it is dehumidified to the appropriate condition. Finally, the dry air passes through the downstream side of the heat exchanger, where heat removed from the warm air upstream is now used to reheat the air downstream of the cooling coil. An additional reheat coil may be used if more capacity is needed.

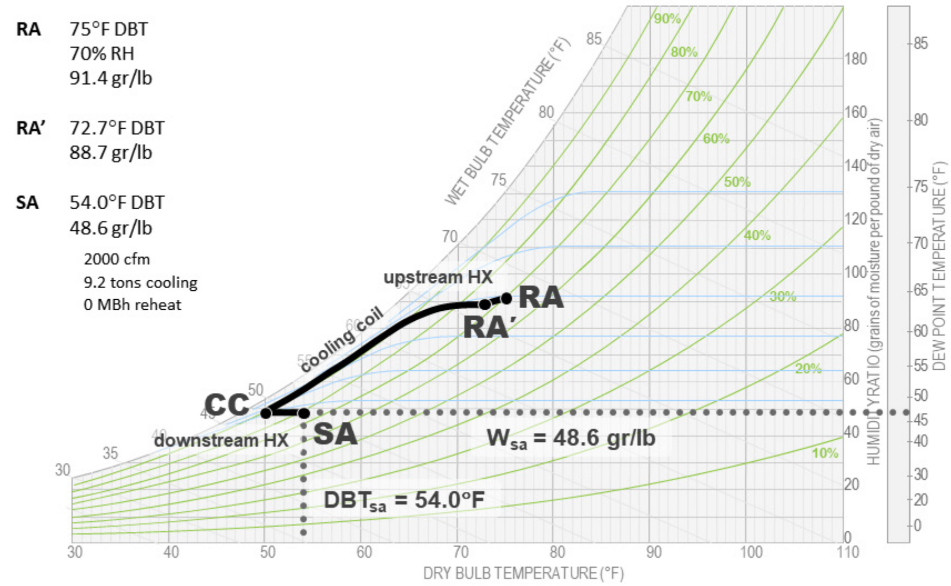
The pre-cooling effect reduces the cooling energy, while the reheating effect provides some or all of the needed reheat energy.

During the "nighttime" mode, more reheat is often needed, so more pre-cooling can be used. The heat exchanger pre-cools the air further. After it's dehumidified, the air is reheated as it passes through the downstream side of the heat exchanger.

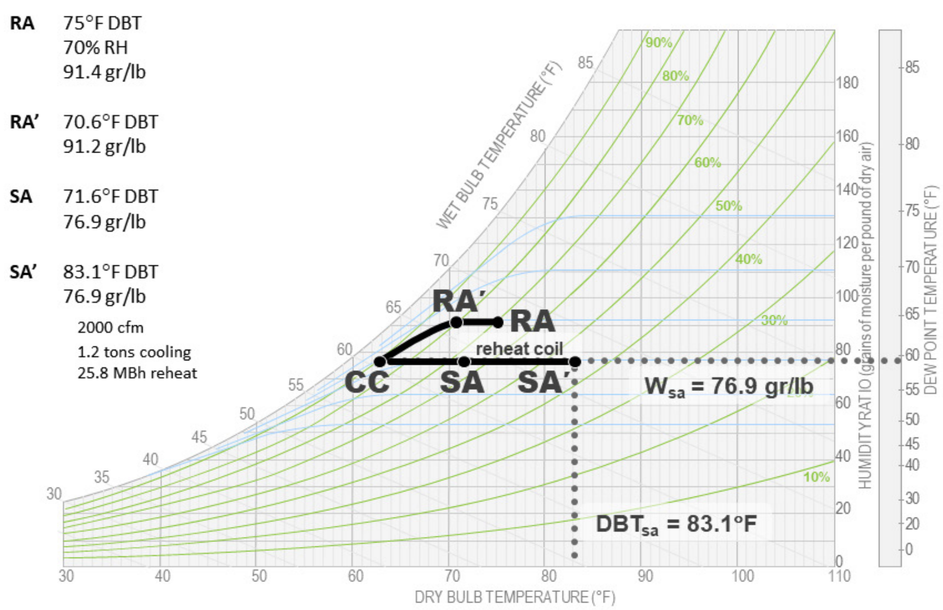
To control heat exchanger capacity, face-and-bypass dampers are often used. In a series/wrap-around configuration, the amount of reheat provided by the heat exchanger is modulated by varying the airflow.



Series heat exchanger psychrometric chart—daytime

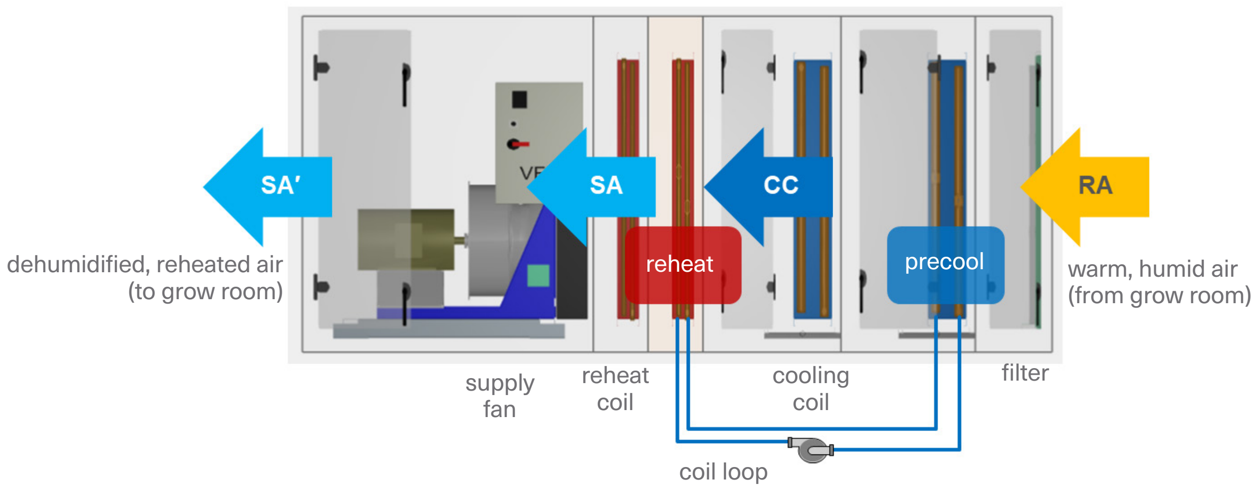


Series heat exchanger psychrometric chart—nighttime



Series coil loop

Alternatively, a coil runaround loop or heat pipe may be used in a series configuration. In the example, the upstream coil pre-cools the entering warm, humid air while the downstream coil reheats the dehumidified supply air. A pump is used to circulate the fluid used for heat recovery. Coil runaround loops and heat pipes do not transfer as much heat as a plate heat exchanger, but these devices are more compact. As a result, the air handler may not be as tall or long.



Series desiccant wheel (Trane CDQ®)

A series desiccant wheel is configured in series with the cooling coil, rotating between the air upstream of the cooling coil and the air downstream of the coil. The wheel is constructed of a desiccant, which adsorbs water vapor from the air downstream of the coil and then releases it into the air upstream of the coil.

During the “daytime” mode, the warm, humid air passes through the upstream side of the desiccant wheel, where water vapor is released from the desiccant resulting in a higher air humidity ratio. Then, the air passes through the cooling coil where the air is partially dehumidified. When the air passes through the downstream side of the wheel, the desiccant will adsorb water vapor from the air, further dehumidifying it to the required condition. This adsorption process does release some sensible heat, so the air also warms as it passes through the downstream side of the wheel. Cooling energy is reduced, while the wheel provides some or all of the reheat needed.

The cooling coil operates at a warmer temperature compared to other configurations because some of the dehumidification is performed by the desiccant wheel. This is illustrated in the example psychrometric analysis. During “daytime” operation, the fixed plate heat exchanger requires a cooling coil supply temperature of 48.0°F compared to 51.0°F when using the desiccant wheel. This allows for some additional energy savings by operating the chiller or DX system at a warmer suction temperature.

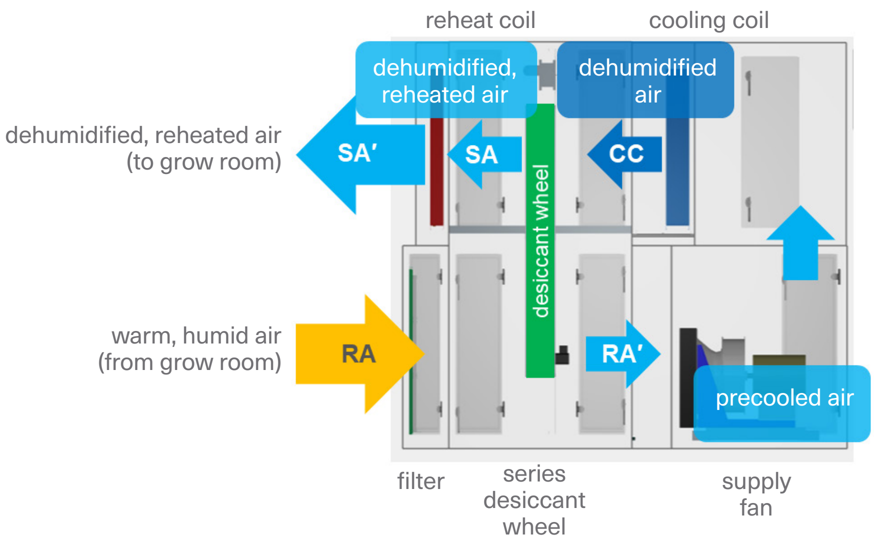
During the “nighttime” mode, the process is the same. The cooling coil partially dehumidifies the air and the desiccant wheel dehumidifies the rest of the way while also warming the air up. A supplemental heating coil may be needed to reheat the air.

Trane CDQ desiccant wheels can greatly improve the dehumidification capabilities of an air conditioning system. Features include:

- **Increased cooling coil dehumidification capacity**
- **Lower achievable supply air dew point temperature**
- **Improved energy efficiency for dehumidification**
- **Decreased cooling capacity when dehumidifying**
- **Decreased need for reheat**
- **Lower unit cooling sensible heat ratios**
- **Warmer chilled water supply temperatures or DX suction temperatures**

Trane CDQ wheels are available on Trane Performance Climate Changer air handling units.

Note: carefully evaluate the use of CDQ wheels in applications where airborne oils may be present. While surface dirt and debris have a minor impact on wheel performance, oils can coat and seal the pores within the wheel reducing its ability to adsorb water vapor.



Series desiccant wheel psychrometric chart—daytime

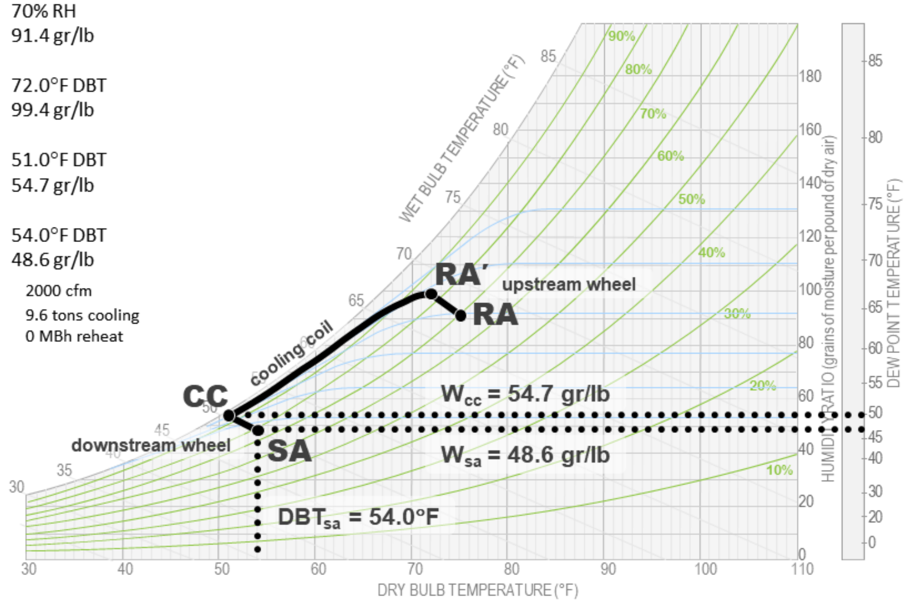
RA 75°F DBT
70% RH
91.4 gr/lb

RA' 72.0°F DBT
99.4 gr/lb

CC 51.0°F DBT
54.7 gr/lb

SA 54.0°F DBT
48.6 gr/lb

2000 cfm
9.6 tons cooling
0 MBh reheat



Series desiccant wheel psychrometric chart—nighttime

RA 75°F DBT
70% RH
91.4 gr/lb

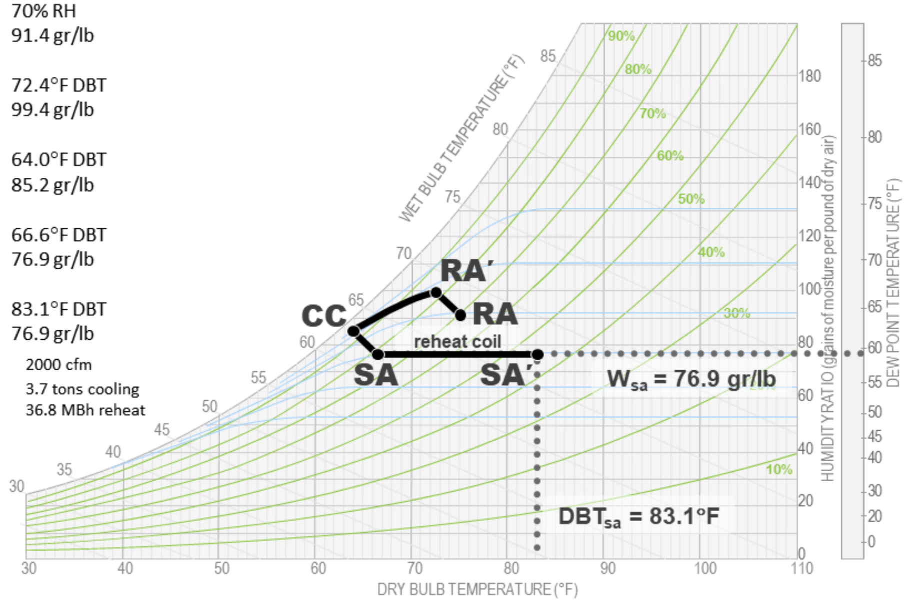
RA' 72.4°F DBT
99.4 gr/lb

CC 64.0°F DBT
85.2 gr/lb

SA 66.6°F DBT
76.9 gr/lb

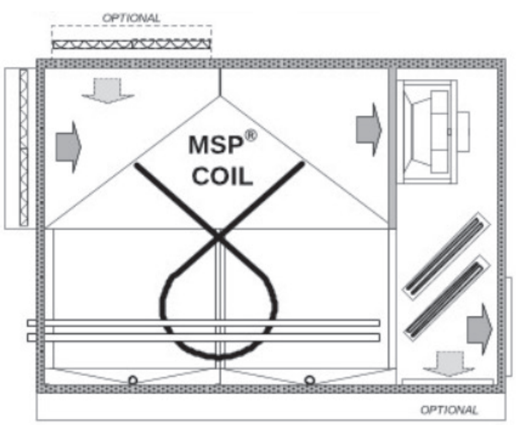
SA' 83.1°F DBT
76.9 gr/lb

2000 cfm
3.7 tons cooling
36.8 MBh reheat

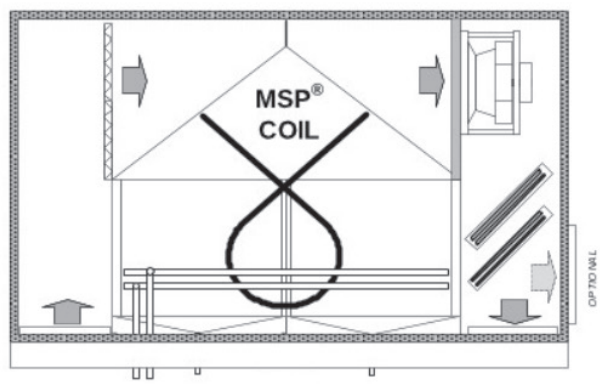


MSP Air Handlers

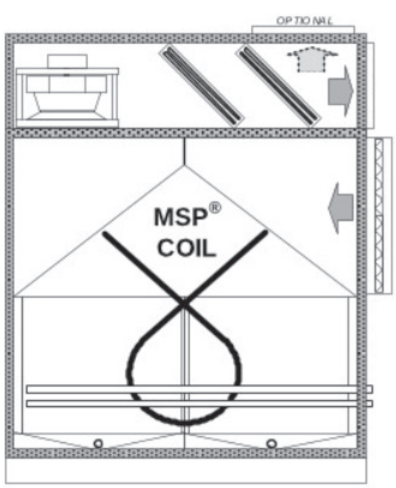
Trane offers MSP air handlers for this application in four configurations: dehumidifier-vertical (DV), dehumidifier-universal (DU), dehumidifier-horizontal (DH), or dehumidifier-downflow (DD). The air handlers are built around a large fixed-plate heat exchanger in series with a chilled water cooling coil that pre-cools and pre-dehumidifies the warm, humid return air from the growing space. The air then passes through a dehumidification coil to ensure it is sufficiently dried. Next, the air passes through the fixed plate again absorbing heat. Finally, after passing through the fan, optional cooling and heating coils are used to temper the supply air.



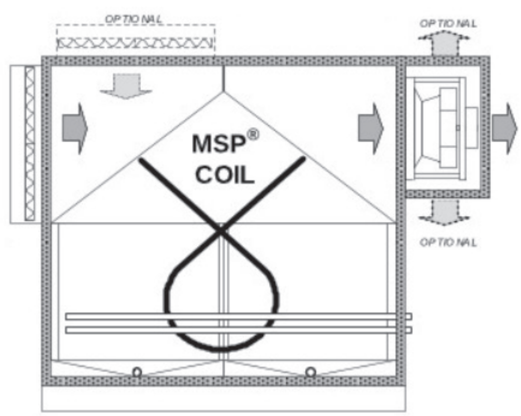
dehumidifier, horizontal (DH)



dehumidifier, downflow (DD)



dehumidifier, vertical (DV)



dehumidifier, universal (DU)

Trane Air Handling Portfolio

Trane Performance Climate Changer® is the most comprehensive air handling portfolio in the industry. In addition to this, Trane also offers the MSP air handler, which is built around a fixed-plate heat exchanger.

			Trane Performance Climate Changer		
		MSP	Catalog	Semi-custom	Custom
Airflow	up to 15,000 cfm	x	x	x	x
	15,000 to 60,000 cfm			x	x
	60,000 to 130,000 cfm				x
	130,000 to 200,000+ cfm				x
Insulation thickness	2-inch foam doublewall	x	x	x	x
	3-inch foam doublewall			x	x
	4-inch foam doublewall				x
Air cleaning	2-inch filters	x	x	x	x
	4-inch filters		x	x	x
	18-inch/30-inch bag			x	x
	12-inch cartridge			x	x
	HEPA			x	x
	gas phase filtration			x	x
	UVGI			x	x
	TCACS			x	x
Cooling and heating coils	hydronic	x	x	x	x
	refrigerant		x	x	x
	electric	x	x	x	x
	gas			x	x
	IFB			x	x
Fans	direct drive plenum (DDP)		x	x	x
	motorized impellers	x	x	x	x
	housed		x	x	x
Energy recovery	energy wheel			x	x
	fixed plate heat exchanger	x		x	x
	enthalpy core			x	x
Dehumidification	CDQ®			x	x

Chilled Water Systems

Chilled water systems can be used to serve one or many air handlers and provide the necessary cooling for dehumidification. In addition, chilled water systems can be used to provide recovered heat and serve reheat loads. Properly designed and sized chilled water systems can provide all of the reheat necessary, eliminating the need for separate hot water systems. Because the dehumidification loads are present year-round, chilled water systems need to operate accordingly. As a result, consideration must be given to the type of system, system configuration, installation and system control to ensure reliable operation in all conditions.

Air-Cooled and Water-Cooled Chiller Considerations

A variety of factors should be considered when selecting air- or water-cooled chillers.

- **Capacity.** Individual air-cooled chillers are typically available from 7.5 to over 500 tons of cooling capacity. Water-cooled chillers are typically available from 10 to 4,000 tons of cooling capacity.
- **Maintenance.** A major advantage to using an air-cooled chiller is the elimination of the cooling tower. This eliminates the concerns and maintenance requirements associated with water treatment, chiller condenser-tube cleaning, cooling tower mechanical maintenance, tower freeze protection, and the availability and quality of make-up water. Systems that use an open cooling tower must have a water treatment program. Lack of treatment results in contaminants, such as bacteria and algae. Fouled or corroded tubes can reduce water-cooled chiller efficiency and lead to premature equipment failure. The condensers of air-cooled chillers can become clogged with debris, for example cottonwood, or corrode if near a body of salt water. Both reducing efficiency and reliability.
- **Low ambient operation.** Air-cooled chillers are often selected for use in systems that have year-round cooling requirements that cannot be met with an airside economizer. Air-cooled condensers have the ability to operate in below freezing weather and can do so without the problems associated with operating the cooling tower in these conditions. Cooling towers may require special control sequences, basin heaters, or even an indoor sump for safe operation in freezing weather.
- **Efficiency.** Water-cooled chillers are typically more energy efficient than air-cooled chillers. The refrigerant condensing temperature in an air-cooled chiller is dependent on the ambient dry-bulb temperature. The condensing temperature in a water-cooled chiller is dependent on the condenser-water temperature, which is dependent on the ambient wet-bulb temperature. Since the wet-bulb temperature is often significantly lower than the dry-bulb temperature, the refrigerant condensing temperature (and pressure) in a water-cooled chiller can be lower than in an air-cooled chiller. A lower condensing temperature, and therefore a lower condensing pressure, means that the compressor needs to do less work and subsequently the compressor consumes less energy. This efficiency advantage may lessen at part-load conditions because the dry-bulb temperature tends to drop faster than the wet-bulb temperature. As a result, the air-cooled chiller may benefit from greater condenser relief. Additionally, the efficiency advantage of a water-cooled chiller system is less when the additional cooling tower and condenser pump energy are considered.
- **Heat recovery.** Air- and water-cooled chillers can provide heat recovery, allowing heat produced to be used. Typically, water-cooled chillers can provide a greater degree of heat recovery flexibility and capacity. Heat recovery capacity in some air-cooled chillers may be limited.
- **Budget and lifecycle.** Air-cooled chilled water systems typically have a lower first cost, however a higher operational cost compared to water-cooled systems. Water-cooled chillers typically have a longer expected lifespan compared to air-cooled chillers.

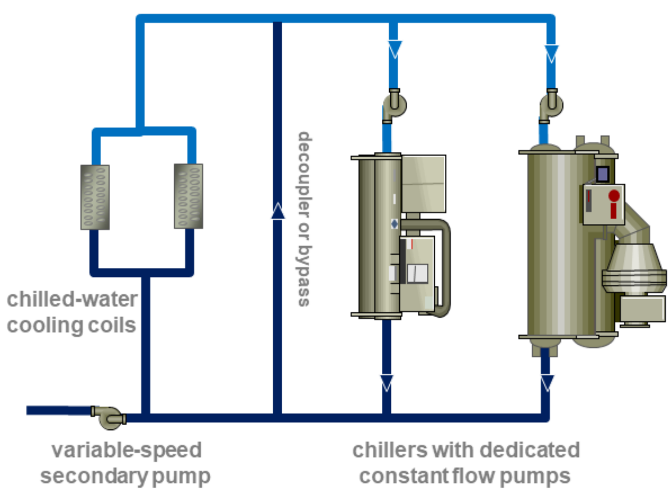
Common Configurations

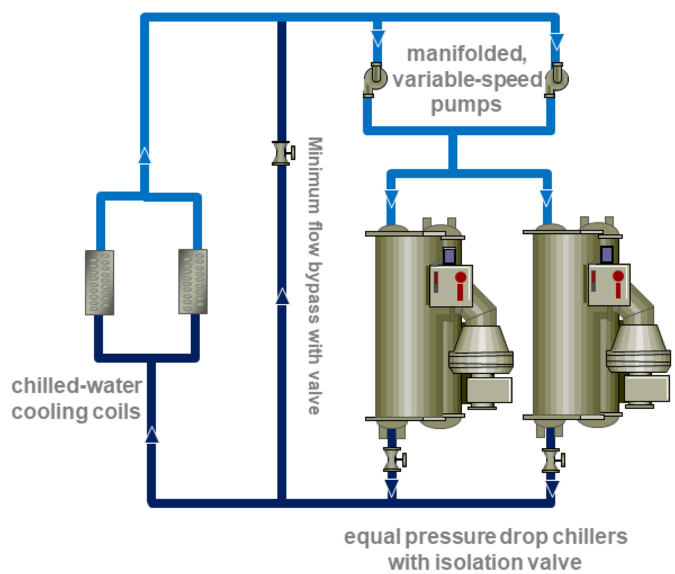
Often, the chillers are arranged in a primary-secondary configuration. This configuration, also called decoupled, places the chillers on a primary loop with constant speed pumps. A secondary loop, served with variable speed pumps, provides chilled water to the air handlers. A bypass line between the primary and secondary loops provides a path for the flow difference between the two loops.

An alternate configuration, called variable primary flow, uses a single chilled water loop with variable speed pumps providing water flow through the chillers and coils. A bypass pipe with a control valve ensure chiller flow stays above the minimum required for proper chiller operation. Unlike the primary-secondary configuration, the chiller evaporator water flow is variable.

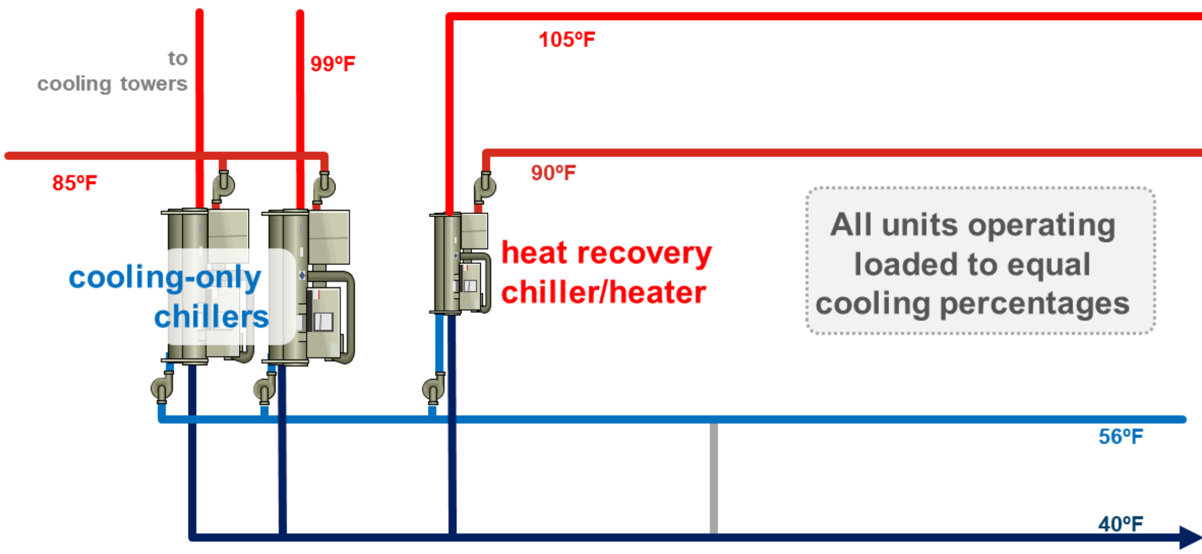
Separate Chilled Water and Hot Water Systems

A separate chilled water system consisting of air- or water-cooled chillers, pumps, and heat rejection equipment (if needed) serves chilled water coils in air handlers. Another system, producing hot water through a boiler, is provided to serve reheat coils within the air handlers. Heat rejected from the chilled water system is not reused.





Heat Recovery Configurations



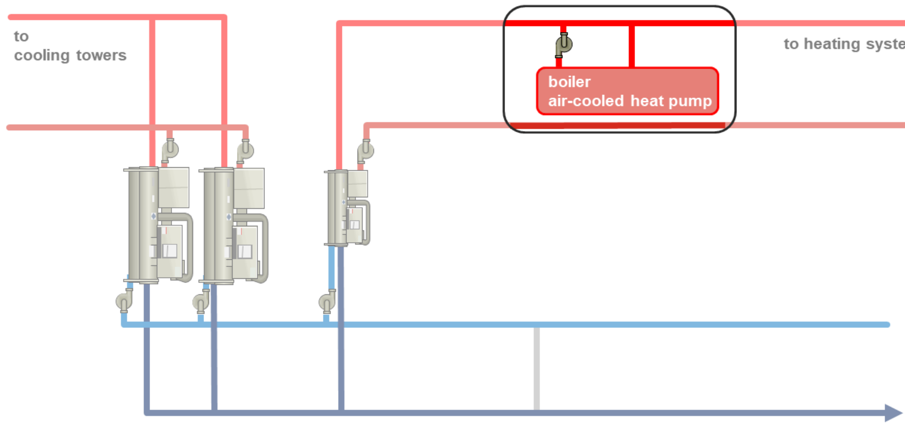
Chillers in parallel

In a parallel configuration, the chillers are placed in a primary-secondary piping layout. The chillers all receive the same return chilled water condition and make the same supply chilled water temperature, so they are loaded to equal percentages.

The chiller condensers may be separated allowing cooling-only chillers to reject their heat via cooling towers, while heat recovery chillers supply heat for the air handler reheat coils. Often the cooling-only chillers are selected at about 99°F leaving condenser water temperature, where the heat recovery units make 105°F to 110°F. This difference in leaving condenser water temperature allows the cooling-only chillers to be more efficient than the heat recovery chiller-heaters.

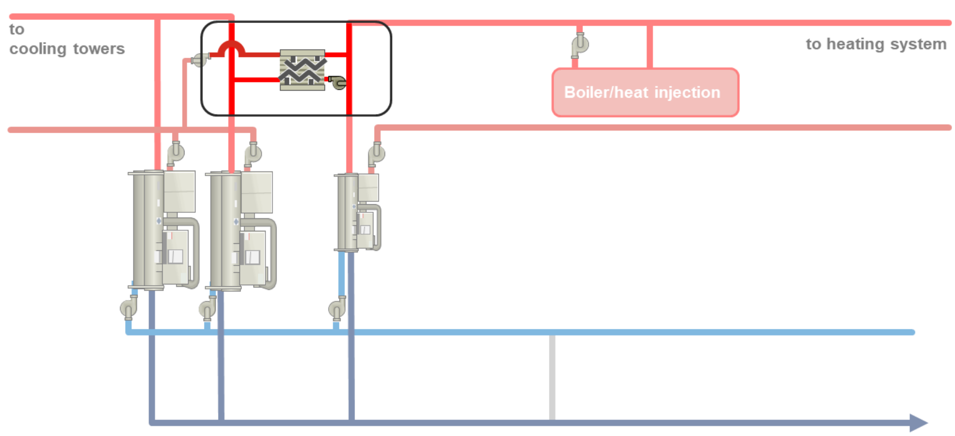
In this example, there are two cooling-only chillers and one heat recovery chiller-heater. All chillers are controlled to make 40°F water, with a 16°F delta-T at design conditions. The cooling-only chillers reject their heat to cooling towers, while the chiller-heater rejects its heat to the heating water load in this example at 105°F.

As previously mentioned, when evaporators are piped in parallel all units are loaded to equal cooling percentages. The heat recovery chiller is sized for the heating load, while the cooling-only chillers are sized for the balance of the cooling load minus the chiller/heater cooling capacity.



Chillers in parallel—backup heat

Designers might wish to include a backup heating source, such as a boiler or air-cooled heat pump to augment hot water production, or when the heat recovery chiller leaving hot water temperature is not high enough. At part cooling load, there is a reduced return water temperature, meaning the heat recovery chiller cannot make its design heating and cooling capacity. This means an auxiliary heating device may be needed.

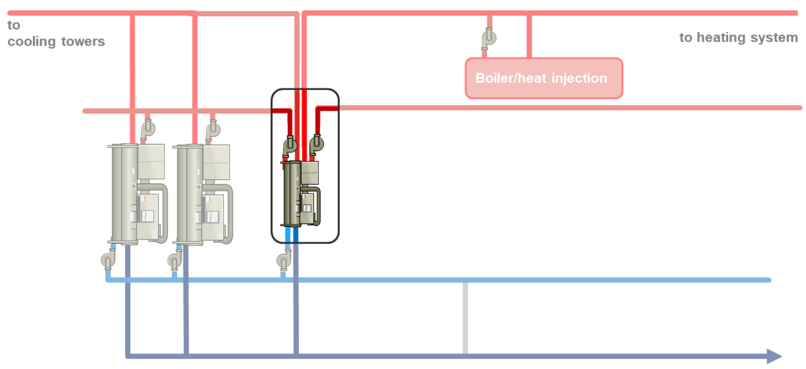


Chillers in parallel—alternate: heat exchanger to reject excess heat

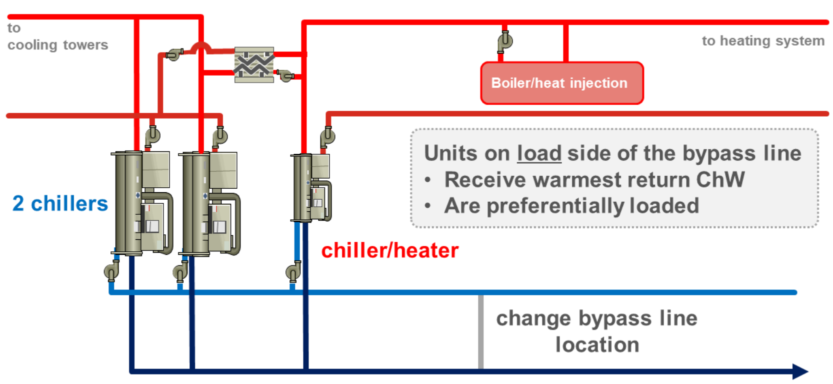
There may be times when heat recovery is not needed, or some heat must be rejected. If that occurs and there is no way to reject the heat, then that unit's cooling load must be reduced. This affects the chilled water supply temperature. In the worst case, if there is no heating load, no cooling can be provided by the heat recovery chiller. To prevent this from occurring, a heat exchanger to reject heat to the cooling tower loop may be provided.

There may be times when the chiller-heater is producing too much heat for the heating system. In this case, the excess heat can be rejected through the cooling tower using a plate and frame heat exchanger. This maintains separate heat and cooling tower water loops.

Double bundle condensers instead of a fixed plate heat exchanger



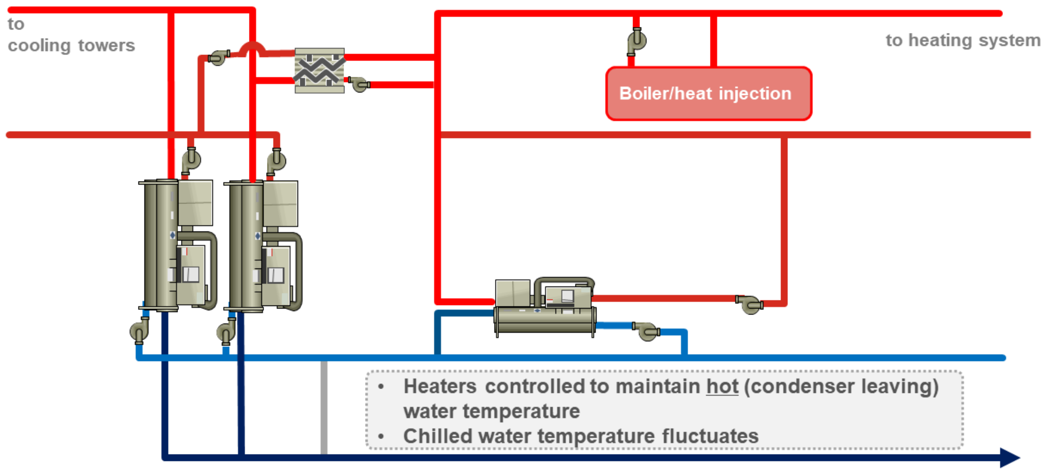
Chillers in parallel—alternate: double bundle condenser to reject excess heat
Some chiller manufacturers make chillers with two condenser bundles allowing some heat to be rejected to the heating water system, and the remaining heat to be rejected via cooling towers. Instead of using a separate heat exchanger, one or more chillers with "double bundle" condensers are used. As the heating demand decreases, the cooling condenser is enabled—allowing excess heat to be rejected to the cooling tower. A double bundle design also reduces the required footprint and is easier to maintain.



"Heaters" preferentially loaded

Preferentially loading allows the heat recovery chillers to be loaded as necessary–up to full capacity. In the "normal" parallel configuration, the bypass line is located between the chillers and coils. In the preferential primary-second configuration, the chilled water bypass line has been "moved," with the heat recovery chiller between the coils and bypass line. On the chilled water load (coil) side of the bypass, the return chilled water is now the system return water. This means the chiller-heater receives warmer return chilled water. This reduces the overall lift of the chiller-heater, so it can operate more efficiently. The heat recovery chiller is still controlled to make the system chilled water temperature.

If the system return chilled water temperature is at its design temperature, the heat recovery chiller will be fully loaded. With a properly sized heat recovery chiller, there is always enough heat to satisfy the heating load. If more heat is recovered than is needed, additional heat is rejected to the condenser-side heat exchanger or through the use of a double-bundle condenser. Preferential loading ensures there is always enough heat available, and it's simple to control.

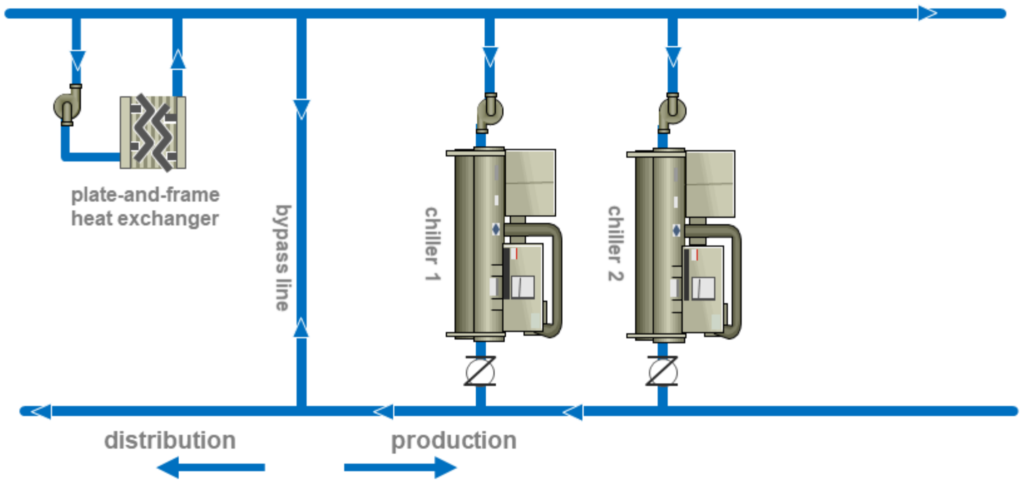


"Heaters" in sidestream position

The sidestream configuration allows the heat recovery chillers to satisfy the reheat load by becoming a "heater" with the primary duty of providing heat. The chiller is operated to maintain the heating water temperature by controlling the leaving condenser water temperature. The heat recovery unit's chilled water pre-cools the return chilled water. This chilled water is then passed through the cooling-only chillers to ensure the leaving system chilled water is at its design leaving chilled water temperature.

The sidestream configuration exactly satisfies the heating, makes system controls very simple and reduces the heat recovery compressor power. A drawback is that the cooling-only chiller pumps need to be a little larger.

Waterside Economizing



A plate and frame heat exchanger may be used to perform free cooling through waterside economizing. A plate and frame heat exchanger is used with a cooling tower to provide cooling during very low wet-bulb temperature conditions. To increase the number of economizing hours, designers often specify a cooling tower larger than necessary.

Water from the cooling tower is kept separate from the chilled water loop by a plate-and-frame heat exchanger. Keeping the loops separate prevents cross-contamination between the free cooling loop and the chilled water loop. This also allows the free cooling loop to use a freeze inhibitor that is separated from the chilled water loop. With the addition of a second condenser-water pump and proper piping modifications, this heat exchanger can operate simultaneously with the chiller, provided the chiller is placed downstream of the heat exchanger. As much heat as possible is rejected through the heat exchanger while the chiller handles the rest of the cooling load. Plate-and-frame heat exchangers isolate the building loop from the water in the open cooling tower loop, but they must be cleaned, typically annually.

The use of waterside economizing and heat recovery chillers should be carefully considered. When the plate-and-frame heat exchanger offsets the cooling load, the amount of heat that can be recovered from the chillers is reduced. Consider performing a whole building energy analysis to evaluate the use of free cooling and heat recovery chillers.

Trane Chiller Portfolio

The Trane® chiller portfolio includes centrifugal, helical rotary and scroll compressor models, ranging in capacities from 20 to over 4,000 tons. Regardless of the chiller you choose, you'll benefit from the reliable performance that has made Trane chillers the industry standard for decades. Trane's portfolio has a wide range of air and water-cooled chiller solutions that can meet various efficiency and systems needs enabling them to reduce energy consumption based on their budget.

- Air-cooled, water-cooled heat rejection options
- Modular chillers to provide scalability
- Compressor types (scroll, helical rotary, centrifugal)
- Heat exchanger types (plate and frame, shell and tube)
- Variety of refrigerant types
- Low voltage, medium voltage, and high voltage options
- Heat recovery capabilities
- Free cooling options

Air-Cooled Chillers

Trane air-cooled chillers utilize positive displacement (scroll and helical rotary) compressors to create chilled water. Chillers can be packaged or use remote evaporators.
Models include:

- CGAM – 20-130 tons
- Series R RTAC – 140-500 tons
- Sintesis RTAF – 115-520 tons
- Ascend® ACS – 140-230 tons
- Ascend® ACR – 140-550 tons
- TACA – 40-440 tons

Water-Cooled Chillers

Water-cooled chillers from Trane feature both helical rotary and centrifugal compressors to make chilled water.
Models include:

- Series R® RTWD/RTUD – 60-250 tons
- Series R® Optimus – 150-430 tons
- Agility® HDWA – 150-450 tons
- Series S CenTraVac CVHM– 170-390 tons
- CenTraVac® CVHE/CVHF/CVHH – 150 -2,000+ tons
- CenTraVac® Duplex® CDHF/CDHH – 1,450-4,000 tons
- TACW – 60-1400 tons

Modular Air- and Water-Cooled Chillers

Trane air- and water-cooled modular chillers by Thermafit™ utilize scroll and oil free centrifugal compressors to make chilled water. Models can include heat recovery and simultaneous heat and cooling to produce both heating- and chilled-water.
Models include:

- AMC (air-cooled chiller) – 15 to 80 tons
  (max of 12 modules, up to 960 tons per chiller bank)
- MWC (water-cooled chiller) – 15 to 80 tons
  (max of 12 modules, up to 960 tons per chiller bank)
- AXM (air-to-water heat pump) – 30 tons
  (max of 10 modules, up to 300 tons per chiller bank)
- WXM (water-to-water heat pump) – 20 to 80 tons
  (max of 12 modules, up to 960 tons per chiller bank)
- MAS (air-source multipipe) – 30 tons
  (max of 12 modules, up to 300 tons per chiller bank)
- MWS (water-source multipipe) – 30 to 60 tons
  (max of 10 modules, up to 600 tons per chiller bank)

Controls

Automatic controls are essential to maintain optimum growing conditions and crop output. Single point management can be beneficial due to the number of systems, changing operation schedules, and complex processes occurring within the growing space. There are several key benefits to fully automated growing environments.

Automate — Make more efficient use of resources and your workforce. Control the quality of your crops.

Efficient workforce — Design the control system to enable the productivity of your workforce. Easy to monitor and manage from various locations. Alerts to notify of unexpected conditions. Provide easy manual intervention for real-time adjustments.

Integrate — Temperature, humidity, lighting and CO_2 can all be controlled to provide the optimum growing environment.

Optimize growth — Maintain optimum conditions over the various phases of the grow cycle.

Optimize energy — Manage HVAC and lighting to minimize energy usage.

Data to validate and improve — Gather and store data to record growing conditions, including long-term storage for historical analysis. View the performance over the grow cycle. Analyze the data to identify improvements and control your processes.

Managing the Grow Room Environment

Proper control and optimization of the growing environment requires the control of all environmental conditions including - temperature, relative humidity, the resulting vapor pressure deficit (VPD), CO_2, and lighting levels.

Lighting

Lights are typically controlled to either ON ("daytime" mode) or OFF ("nighttime" mode). This designation of day and night correlating to lights ON/OFF is critical to coordinating the other elements of environmental control. The desired levels of temperature, humidity and CO_2 will vary based on day versus night. It is recommended to stagger the day and night cycles for the various grow rooms, to reduce overall capacity requirements and electrical demand charges (see Consider staggering "daytime" periods sidebar on page 11).

If variable lighting is used (such as LED lights), the control strategy may take advantage of the variable levels. Typically, the variable lighting is controlled to a certain photosynthetically active radiation level (PAR) during the day mode and OFF during the night mode. The PAR level can be manually set at the time of commissioning (typically using a hand-held PAR meter) or can be dynamically controlled by the control system based on a PAR sensor input. More sophisticated lighting strategies can be implemented at the grower's discretion, such as phasing in sunrise and sunset conditions.

Temperature, humidity and VPD

The control of grow room temperature, relative humidity and VPD are all closely interrelated. See page 7 for more information on VPD. VPD is a critical parameter for growing, and desired VPD levels are achieved by controlling temperature and humidity accordingly. Different combinations of temperature and humidity can provide the desired VPD level. It is most efficient to maintain the desired VPD at the highest possible temperature that is still suitable for both plant growth and human occupants.

Image source: MaxLite®, www.maxlite.com

During "daytime" mode when plants are actively growing, dry-bulb temperature is maintained at a high limit. Relative humidity is controlled to a suitable level to maintain the desired VPD. For example, for a VPD of 1.0, a combination of 77°F and 68 percent relative humidity will provide the desired VPD.

During "nighttime" mode, temperature is controlled to a low limit (i.e. 70°F) as there is no heat generated from the lights and the plants typically have a slight evaporative cooling effect. The relative humidity (i.e. 65 percent) needs to be maintained at a level that will prevent condensation and minimize microbial growth.

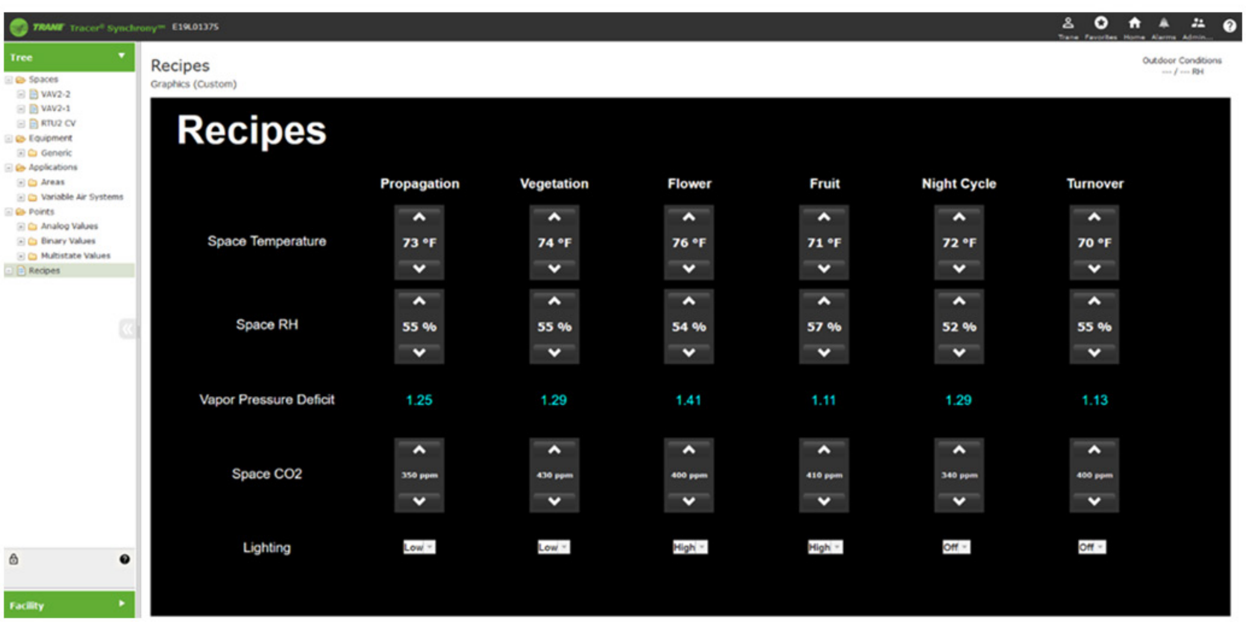
Carbon dioxide (CO_2)

Because plants consume CO_2 and produce O_2 when they are actively growing, additional CO_2 is often added to the growing space. During the "daytime" mode, CO_2 is injected to maintain a level higher than ambient outdoor conditions because it is beneficial to plant growth. CO_2 is typically controlled between 1000 and 1800 parts per million (PPM) in the grow room, compared to 350-450 PPM outdoors. During "nighttime" mode, CO_2 injection is not required. To ensure the CO_2 is not exhausted, HVAC systems are designed to not ventilate or perform airside economizing.

Grow room environmental recipes

As plants go through various growing cycles, the requirements for temperature, relative humidity, VPD and CO_2 concentration can vary significantly. It can be very challenging and cumbersome to try to make manual adjustments constantly throughout growing cycles, and across many grow rooms. It can also be difficult to maintain consistency and levels of quality with manual processes.

Grow room environmental recipes is a concept that allows for various stages of plant growth to be scheduled, and for the environmental conditions to be preset for each stage of growth. The grower can specify the number of stages, the number of days in each stage, and the environmental conditions in each stage. Manual adjustments to schedules and environmental recipes can easily be made to fine tune for variations as needed. Automated system control using pre-programmed recipes significantly reduces labor costs and the chance of operator error, and provides a repeatable and precise grow cycle.

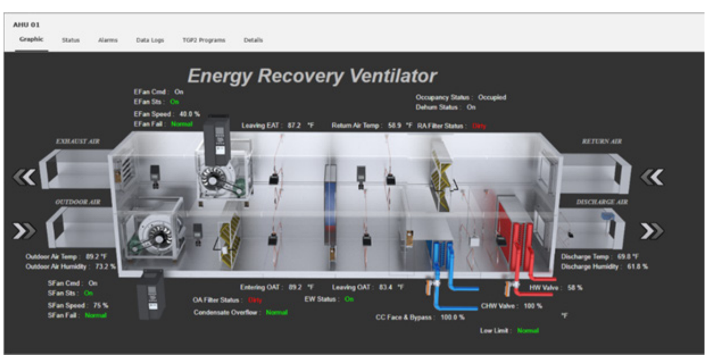


Other types of rooms

Growing facilities will have additional rooms for cloning, drying plants, processing product, etc. The types of rooms, configurations and processes can vary by the grower, the crop and other factors. The HVAC systems in these rooms, if properly designed for the task, can be controlled to the required sequence by the control system. Some of these rooms have more typical environmental conditioning needs while others may have more specialized needs. For example, a drying room will need to be able to remove the excess humidity as the plant materials dry. A control sequence might include controlling relative humidity to slowly decreasingly space humidity as plant materials dry.

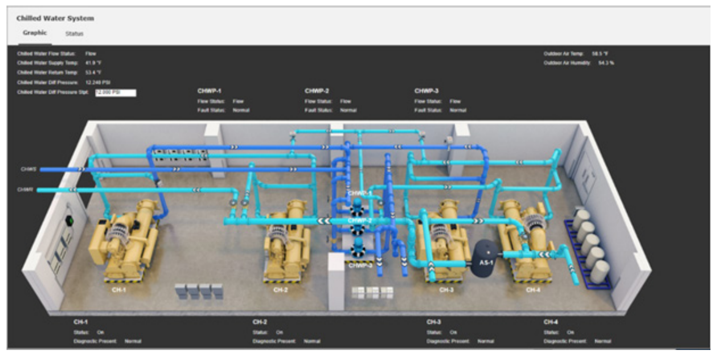
Purpose-built equipment

Grow room temperature and humidity conditions can be maintained by either packaged equipment with DX cooling and reheat, or air handling units with chilled water cooling and hot water reheat. This equipment requires local controllers for each piece of equipment, and each controller needs to be integrated into the central control system for the facility. The central system sends commands and setpoints to the equipment controllers, monitors system performance, and gathers historical data.



Central plant control

Larger growing facilities may have central cooling and heating plants that provide both chilled water and hot water to the air handling units that control room temperature and humidity. These systems need to be managed for efficiency and for stability as rooms change modes and loads change accordingly.



Managing energy

Indoor grow facilities can be very energy intensive. There are a number of strategies that can be deployed to reduce the total energy consumption, peak capacity and demand charges.

- Daytime modes are much higher energy usage than nighttime modes.
- The mechanical and electrical systems need to have adequate capacity to handle the maximum number of rooms in a daytime mode at any time.
- Staggering daytime modes between grow rooms can dramatically reduce peak demand and the system capacity required.

Peak demand charges and time-of-day electricity rates should be considered when determining daytime and nighttime schedules.

Time of day	Rooms 1-5	Rooms 6-10
7:00 a.m. to 7:00 p.m.	daytime	nighttime
7:00 p.m. to 7:00 a.m.	nighttime	daytime

Tracer® Control Systems

Trane® Tracer controls can provide a variety of benefits when applied to indoor grow facilities. Trane delivers fully functional and commissioned control systems, with easy-to-use human interfaces. Some of the benefits include:

- **Integration —** Tie various systems together for coordinated control of the growing environment
- **Automation —** Improve productivity by automating growing processes
- **Customizable —** To meet the needs of each job and each grower
- **Open —** Built on a foundation of open, industry-standard protocols – to facilitate future expansions and integrations
- **Multiple User Interface options —** To give your staff the flexibility it needs
- **Secure Remote Connectivity —** To manage your facility from wherever you are.

Tracer controls – equipment

Trane provides a full line of programmable equipment controllers for various applications. These can be used for both Trane and other equipment. These controllers can be factory installed and programmed on Trane HVAC equipment, or can be field-mounted and programmed for other applications.

Trane Air-Fi® wireless sensors

Trane has a variety of Air-Fi Wireless sensors that can be used in grow facility. The most common sensor types include temperature and relative humidity. For CO_2 measurement, use a hardwired sensor that is suitable to this application. Some of the features of Trane Air-Fi Wireless sensors include:

- Mobility to facilitate locating and relocating sensors as needed. Air-Fi sensors can be wall mounted or affixed to grow racks with magnets for easy removal and relocation.
- Combined temperature and relative humidity in a single sensor.
- Ability to average up to six sensors in a room, to provide multiple points of sensing.
- Lifetime batteries to reduce maintenance requirements.

Tracer® SC+ system controller

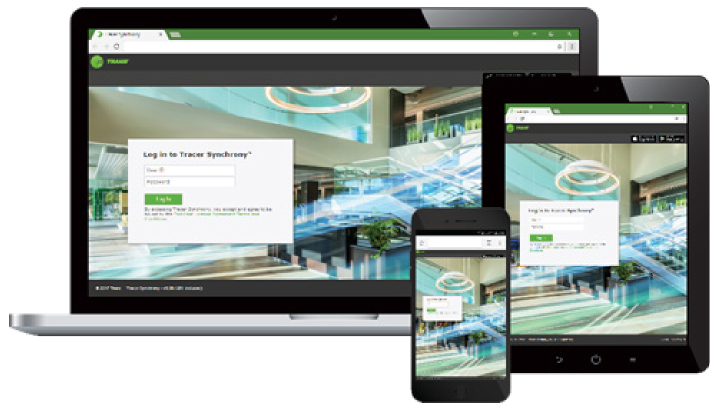
The Tracer SC+ is the heart of the Trane control system and is ideal for automated control and monitoring of single site grow facilities. The Tracer SC+ coordinates all aspects of control, tying together room sensors and equipment controls, central plants, and other control needs within the facility. It has a number of features and functions, including:

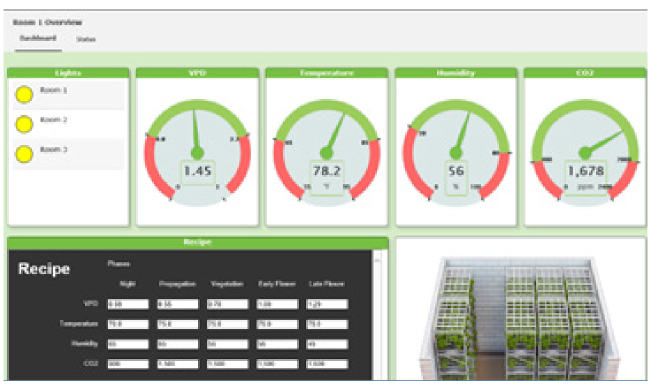
- Easy to use user interface provides simple navigation to standardized equipment pages and graphics.
- Coordinates HVAC equipment and systems to provide accurate room control with minimized energy usage.
- Allows integration with third party devices using BACnet®, LonTalk®, and Modbus® without gateways.
- Data logging to monitor system parameters over time and real-time data log visualization.
- Alarm and event collection with remote alarm notification via email and SMS.
- Enables Internet secure data transfer to the Tracer® Ensemble™ building management system.
- Secure remote access via Trane Connect™, eliminating the need for VPN connections.
- Compatible with Trane mobile apps to enable user access to the site at anytime from anywhere.

Tracer Ensemble® Building Management System

Tracer Ensemble is a web-based building management system (BMS) that provides a robust, easy to use, user interface. It is a fully scalable enterprise BMS solution and can be installed on a customer's computer server or hosted by Trane and purchased as a service (Tracer Ensemble Cloud). It has a number of features, including:

- User created dashboards allow easy data visualization to understand the real-time performance of the facility.
- User created reports enable repeatable facility analysis to manage quality and improve growing techniques.
- Long term data logging with unlimited storage allows year over year performance benchmarking.
- Alarm and event collection with remote alarm notification via Email and SMS.
- Integrated maintenance management and work order creation.
- Secure remote access to every site via Trane Connect, eliminating the need for VPN connections.





Trane Intelligent Services

Building performance – Trane's cloud-based HVAC analytics software that continuously looks for sequence of operation anomalies to improve the comfort, reliability and energy savings performance of the building. For indoor agriculture applications, this offering can track metrics that optimize the growing environment such as temperature and humidity.

Energy performance – Trane's cloud-based energy management software that continuously reads utility interval meter data. This service helps visualize how the facility is using energy and provides tools and reports to reduce the intensity and usage of energy in buildings. By taking into account peak demand and utility rates, Trane can help make recommendations on load shifting and other curtailment strategies.

Active monitoring – Trane's 24/7 service to monitor, triage, and dispatch Trane service technicians based on alarms generated from BAS systems. Automated reports give visibility to the quantity and frequency of alarms worked by the Active Monitoring team. This risk mitigation strategy is ideal for sites that require consistent uptime.

Energy assessment (energy optics) – Trane's "non-connected" reporting tool that helps visualize the usage of energy from the facility's interval meter data. This is an excellent way to identify areas of opportunity–whether it be a simple schedule change–or a more complex implementation of energy conservation measures. Optics can also be used to validate changes and track the impact of actions taken.

Trane Rental Services

HVAC system operation is critical for process dehumidification and cooling, and disruptions can occur when you least expect it. Portable equipment can be used to serve temporary needs to overcome system failures or power losses, keeping your business operational while you repair, replace, or upgrade your existing systems. With our large fleet of equipment and wide network of highly trained service staff, Trane Rental Services is well positioned to help; delivering fast, reliable and cost-effective solutions when you need them.

Trane Rental Services is available 24/7 for technical support, quotes, and inquiries regarding availability. With our round-the-clock support, we can also offer shipments on weekends, holidays, and after normal business hours.

Rental offerings include:

Remote power generation

- Diesel generators – 150 kW – 1.0 MW
  - All sizes are Prime rating
  - Dedicated trailers, on-board fuel storage
  - Models available which are switchable between 208V and 460V

Chilled water systems

- Air-cooled chillers – 25-500 tons
  - Supply chilled water temperature: 0°F – 65°F
  - Integral pumps, circuit breaker or fused disconnect
- Water-cooled chillers – 250 – 1000 tons
  - Unit-mounted starter, circuit breaker or fused disconnect
- Cooling towers – 270, 500, and 1000 tons
  - Induced draft open-loop towers on trailers with basic manifold
- Pumps – 14 – 4,800 gpm
  - Skid-mounted with throttling valves, disconnect, and starter

Air handling units

- Air handling units: 5,000 – 25,000 cfm
  - Fused disconnect, flexible duct connectors
  - Variable speed supply fans, high static pressure capabilities
  - Hot water capability on most units
- Desiccant dehumidifiers – 5,000 cfm
  - Moisture removal up to 102 pounds per hour
  - Indoor/outdoor installation
  - Chilled water connection

Packaged unitary equipment

- Packaged Voyager units with electric heat – 25, 35, and 50 tons
  - Horizontal discharge
  - Variable speed supply airflow
  - Hot gas reheat
  - Airside economizer
  - High static pressure capability in 35- and 50-ton units

For more information visit www.trane.com/rentalservices or contact Trane's 24-hour customer service at 800-755-5115.

Additional Tools from Trane

Trane® Select Assist™

Used to select Trane air conditioning equipment, including air- and water-cooled chillers, air handlers, and direct expansion rooftops and split systems. For more information visit www.traneselectassist.com.

TRACE® 3D Plus

Trane's TRACE 3D Plus load design and energy analysis software program can be used to properly size equipment and simulate operation to determine annual energy usage and operating expenses. The program includes default libraries to simulate plant evapotranspiration and the resulting cooling effect. The program is able to simulate direct expansion systems, chilled water systems, air-to-air energy recovery, hot gas reheat, and heat recovery chilled water systems. Standard utilization schedules are included to model "daytime" and "nighttime" modes.

Glossary of Terms

Aeroponics. A combination of Aquaculture and Hydroponics where the hydroponic medium functions as a filter for the aquaculture farm and the aquaculture farm effluent turns to nutrients for the hydroponic portion. This system typically has many open water tanks so be aware of surface evaporation.

Canopy. In forest ecology, canopy refers to the upper layer of a tree, formed by mature tree crowns. In indoor agriculture, the canopy or plant canopy is the plan view or area in square feet of mature leaf matter. This area is used to predict the transpiration of the crops. A plant canopy typically varies by crop type and growing method where in the canopy can from plan view may be thin or thick.

Clones. An asexual propagation technique for plants. A piece of the stem or root of a parent plant is placed in a suitable medium where it can grow new roots, stems, or both, becoming a genetic copy of the parent.

Crop. A plant or organism that is cultivated. Typically for food especially a grain, fruit, or vegetable; however also for aesthetics, pharmaceuticals, or fuels such as cut flowers and algae.

Cultivation. Any of the actions associated with 'growing'. For indoor agriculture, it is the actions associated with growing, preparing, raising, and training crops up to but not including harvesting.

Cure (curing room). A room designed to ripen qualities of flowers over a controlled period of time, under specific conditions. Humidification or dehumidification may be required.

Daytime. A period of time when grow lights are on, providing energy to the plants. The "daytime" period may, or may not, correlate with the position of the sun and actual daytime period outdoors.

Drying (drying room). A room designed to reduce the moisture content of fresh cut flower over a controlled period of time under specific conditions. Humidification and dehumidification may be required.

Evaporation. The movement of water and water vapor from the soil and plant leaves to the surrounding air.

Evapotranspiration. The combined effect of evaporation and transpiration. See page 4.

Fertigation. The system and method of delivering fertilizer and irrigation. Can include pumps, tanks, piping, sensors, logic, controls, etc.

Flowering (flower room). Flowering spaces are areas that can have the light period or photoperiod augmented to force photoperiod sensitive plants to begin setting fruit or entering their fruiting stage of growth.

Greenhouse. Typically, a building with opaque to transparent covering most of the surfaces to allow sunlight penetration.

Horticulture. the art or practice of garden cultivation and management.

Hydroponics. Using a nutrient solution to grow plants in an inert media.

Microclimate. A localized variation in environmental conditions within a larger space.

Nighttime. A period of time when grow lights are off. The "nighttime" period may, or may not, correlate with the position of the sun and actual nighttime period outdoors.

Photosynthesis. The method by which plants produce sugar to grow.

PAR. Photosynthetically Active Radiation.

PPFD. Photosynthetic Photon Flux Density.

Propagation. reproducing plants by seed, cutting, clone, graft, or tissue.

Root rot. Plant diseases characterized by decay of the roots and caused especially by fungi.

Transpiration. The movement of water within the plant and the resulting conversion to water vapor which is then released from the stomata on the leaves to the environment.
See page 4.

Vapor pressure deficit/difference (VPD). 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. VPD can be expressed in different units, with kilopascals being very common. See page 7.

Vertical garden/farm. Methods used to increase a farm's productivity per square foot. Often employed indoors or in urban environments where the footprint value is high or limited.

Vegetative (Veg Room). Veg room is an area dedicated to vegetative growth of the plants. Lettuce growing facilities are always vegetative.

Resources

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Sample VPD Chart

(T_{leaf} equals $T_{surrounding\ air}$, barometric pressure = 14.7 psi)

Dry-bulb temperature, °F (leaf temperature is 0°F cooler than surrounding air)	Relative Humidity, %																
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%	30%	25%	20%
60°F	0.00	0.09	0.18	0.27	0.35	0.44	0.53	0.62	0.71	0.80	0.88	0.97	1.06	1.15	1.24	1.32	1.41
61°F	0.00	0.09	0.18	0.27	0.37	0.46	0.55	0.64	0.73	0.82	0.92	1.01	1.10	1.19	1.28	1.37	1.46
62°F	0.00	0.09	0.19	0.28	0.38	0.47	0.57	0.66	0.76	0.85	0.95	1.04	1.14	1.23	1.33	1.42	1.52
63°F	0.00	0.10	0.20	0.29	0.39	0.49	0.59	0.69	0.79	0.88	0.98	1.08	1.18	1.28	1.38	1.47	1.57
64°F	0.00	0.10	0.20	0.31	0.41	0.51	0.61	0.71	0.81	0.92	1.02	1.12	1.22	1.32	1.42	1.53	1.63
65°F	0.00	0.11	0.21	0.32	0.42	0.53	0.63	0.74	0.84	0.95	1.05	1.16	1.26	1.37	1.48	1.58	1.69
66°F	0.00	0.11	0.22	0.33	0.44	0.55	0.65	0.76	0.87	0.98	1.09	1.20	1.31	1.42	1.53	1.64	1.75
67°F	0.00	0.11	0.23	0.34	0.45	0.56	0.68	0.79	0.90	1.02	1.13	1.24	1.36	1.47	1.58	1.69	1.81
68°F	0.00	0.12	0.23	0.35	0.47	0.58	0.70	0.82	0.94	1.05	1.17	1.29	1.40	1.52	1.64	1.75	1.87
69°F	0.00	0.12	0.24	0.36	0.48	0.60	0.73	0.85	0.97	1.09	1.21	1.33	1.45	1.57	1.69	1.81	1.94
70°F	0.00	0.12	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25	1.38	1.50	1.63	1.75	1.88	2.00
71°F	0.00	0.13	0.26	0.39	0.52	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.55	1.68	1.81	1.94	2.07
72°F	0.00	0.13	0.27	0.40	0.54	0.67	0.80	0.94	1.07	1.21	1.34	1.47	1.61	1.74	1.88	2.01	2.14
73°F	0.00	0.14	0.28	0.42	0.55	0.69	0.83	0.97	1.11	1.25	1.39	1.52	1.66	1.80	1.94	2.08	2.22
74°F	0.00	0.14	0.29	0.43	0.57	0.72	0.86	1.00	1.15	1.29	1.43	1.58	1.72	1.86	2.01	2.15	2.29
75°F	0.00	0.15	0.30	0.44	0.59	0.74	0.89	1.04	1.19	1.33	1.48	1.63	1.78	1.93	2.08	2.22	2.37
76°F	0.00	0.15	0.31	0.46	0.61	0.77	0.92	1.07	1.23	1.38	1.53	1.69	1.84	1.99	2.15	2.30	2.45
77°F	0.00	0.16	0.32	0.48	0.63	0.79	0.95	1.11	1.27	1.43	1.58	1.74	1.90	2.06	2.22	2.38	2.54
78°F	0.00	0.16	0.33	0.49	0.65	0.82	0.98	1.15	1.31	1.47	1.64	1.80	1.97	2.13	2.29	2.46	2.62
79°F	0.00	0.17	0.34	0.51	0.68	0.85	1.02	1.18	1.35	1.52	1.69	1.86	2.03	2.20	2.37	2.54	2.71
80°F	0.00	0.17	0.35	0.52	0.70	0.87	1.05	1.22	1.40	1.57	1.75	1.92	2.10	2.27	2.45	2.62	2.80
81°F	0.00	0.18	0.36	0.54	0.72	0.90	1.08	1.26	1.45	1.63	1.81	1.99	2.17	2.35	2.53	2.71	2.89
82°F	0.00	0.19	0.37	0.56	0.75	0.93	1.12	1.31	1.49	1.68	1.87	2.05	2.24	2.43	2.61	2.80	2.99
83°F	0.00	0.19	0.39	0.58	0.77	0.96	1.16	1.35	1.54	1.73	1.93	2.12	2.31	2.51	2.70	2.89	3.08
84°F	0.00	0.20	0.40	0.60	0.80	1.00	1.19	1.39	1.59	1.79	1.99	2.19	2.39	2.59	2.79	2.99	3.19
85°F	0.00	0.21	0.41	0.62	0.82	1.03	1.23	1.44	1.64	1.85	2.06	2.26	2.47	2.67	2.88	3.08	3.29
86°F	0.00	0.21	0.42	0.64	0.85	1.06	1.27	1.49	1.70	1.91	2.12	2.33	2.55	2.76	2.97	3.18	3.40
87°F	0.00	0.22	0.44	0.66	0.88	1.10	1.31	1.53	1.75	1.97	2.19	2.41	2.63	2.85	3.07	3.29	3.51

Sample VPD Chart, continued

(T_{leaf} is 1°F colder than surrounding air, barometric pressure = 14.7 psi)

Dry-bulb temperature, °F (leaf temperature is 1°F cooler than surrounding air)	Relative Humidity, %																
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%	30%	25%	20%
60°F	-0.06	0.03	0.11	0.20	0.29	0.38	0.47	0.56	0.64	0.73	0.82	0.91	1.00	1.09	1.17	1.26	1.35
61°F	-0.06	0.03	0.12	0.21	0.30	0.39	0.49	0.58	0.67	0.76	0.85	0.94	1.03	1.13	1.22	1.31	1.40
62°F	-0.07	0.03	0.12	0.22	0.31	0.41	0.50	0.60	0.69	0.79	0.88	0.98	1.07	1.17	1.26	1.36	1.45
63°F	-0.07	0.03	0.13	0.23	0.32	0.42	0.52	0.62	0.72	0.82	0.91	1.01	1.11	1.21	1.31	1.41	1.50
64°F	-0.07	0.03	0.13	0.24	0.34	0.44	0.54	0.64	0.74	0.85	0.95	1.05	1.15	1.25	1.35	1.46	1.56
65°F	-0.07	0.03	0.14	0.24	0.35	0.45	0.56	0.67	0.77	0.88	0.98	1.09	1.19	1.30	1.40	1.51	1.61
66°F	-0.07	0.03	0.14	0.25	0.36	0.47	0.58	0.69	0.80	0.91	1.02	1.13	1.23	1.34	1.45	1.56	1.67
67°F	-0.08	0.04	0.15	0.26	0.37	0.49	0.60	0.71	0.83	0.94	1.05	1.17	1.28	1.39	1.50	1.62	1.73
68°F	-0.08	0.04	0.15	0.27	0.39	0.51	0.62	0.74	0.86	0.97	1.09	1.21	1.32	1.44	1.56	1.67	1.79
69°F	-0.08	0.04	0.16	0.28	0.40	0.52	0.64	0.77	0.89	1.01	1.13	1.25	1.37	1.49	1.61	1.73	1.85
70°F	-0.08	0.04	0.17	0.29	0.42	0.54	0.67	0.79	0.92	1.04	1.17	1.29	1.42	1.54	1.67	1.79	1.92
71°F	-0.09	0.04	0.17	0.30	0.43	0.56	0.69	0.82	0.95	1.08	1.21	1.34	1.47	1.60	1.73	1.86	1.99
72°F	-0.09	0.04	0.18	0.31	0.45	0.58	0.71	0.85	0.98	1.12	1.25	1.38	1.52	1.65	1.79	1.92	2.05
73°F	-0.09	0.05	0.19	0.32	0.46	0.60	0.74	0.88	1.02	1.16	1.29	1.43	1.57	1.71	1.85	1.99	2.13
74°F	-0.09	0.05	0.19	0.34	0.48	0.62	0.77	0.91	1.05	1.20	1.34	1.48	1.63	1.77	1.91	2.06	2.20
75°F	-0.10	0.05	0.20	0.35	0.50	0.64	0.79	0.94	1.09	1.24	1.38	1.53	1.68	1.83	1.98	2.13	2.27
76°F	-0.10	0.05	0.21	0.36	0.51	0.67	0.82	0.97	1.13	1.28	1.43	1.59	1.74	1.89	2.05	2.20	2.35
77°F	-0.10	0.05	0.21	0.37	0.53	0.69	0.85	1.01	1.16	1.32	1.48	1.64	1.80	1.96	2.11	2.27	2.43
78°F	-0.11	0.06	0.22	0.38	0.55	0.71	0.88	1.04	1.20	1.37	1.53	1.69	1.86	2.02	2.19	2.35	2.51
79°F	-0.11	0.06	0.23	0.40	0.57	0.74	0.91	1.07	1.24	1.41	1.58	1.75	1.92	2.09	2.26	2.43	2.60
80°F	-0.11	0.06	0.24	0.41	0.59	0.76	0.94	1.11	1.29	1.46	1.64	1.81	1.99	2.16	2.34	2.51	2.69
81°F	-0.12	0.06	0.25	0.43	0.61	0.79	0.97	1.15	1.33	1.51	1.69	1.87	2.05	2.23	2.41	2.59	2.78
82°F	-0.12	0.07	0.25	0.44	0.63	0.81	1.00	1.19	1.37	1.56	1.75	1.93	2.12	2.31	2.49	2.68	2.87
83°F	-0.12	0.07	0.26	0.46	0.65	0.84	1.03	1.23	1.42	1.61	1.80	2.00	2.19	2.38	2.58	2.77	2.96
84°F	-0.13	0.07	0.27	0.47	0.67	0.87	1.07	1.27	1.47	1.67	1.86	2.06	2.26	2.46	2.66	2.86	3.06
85°F	-0.13	0.08	0.28	0.49	0.69	0.90	1.10	1.31	1.51	1.72	1.93	2.13	2.34	2.54	2.75	2.95	3.16
86°F	-0.13	0.08	0.29	0.50	0.72	0.93	1.14	1.35	1.56	1.78	1.99	2.20	2.41	2.63	2.84	3.05	3.26
87°F	-0.14	0.08	0.30	0.52	0.74	0.96	1.18	1.40	1.62	1.83	2.05	2.27	2.49	2.71	2.93	3.15	3.37

Sample VPD Chart, continued

(T_{leaf} is 3°F colder than surrounding air, barometric pressure = 14.7 psi)

Dry-bulb temperature, °F (leaf temperature is 3°F cooler than surrounding air)	Relative Humidity, %																
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%	30%	25%	20%
60°F	-0.18	-0.09	0.00	0.08	0.17	0.26	0.35	0.44	0.53	0.61	0.70	0.79	0.88	0.97	1.06	1.14	1.23
61°F	-0.19	-0.09	0.00	0.09	0.18	0.27	0.36	0.45	0.55	0.64	0.73	0.82	0.91	1.00	1.10	1.19	1.28
62°F	-0.19	-0.10	0.00	0.09	0.19	0.28	0.38	0.47	0.57	0.66	0.76	0.85	0.95	1.04	1.14	1.23	1.33
63°F	-0.20	-0.10	0.00	0.10	0.19	0.29	0.39	0.49	0.59	0.69	0.78	0.88	0.98	1.08	1.18	1.28	1.37
64°F	-0.20	-0.10	0.00	0.10	0.20	0.30	0.41	0.51	0.61	0.71	0.81	0.92	1.02	1.12	1.22	1.32	1.42
65°F	-0.21	-0.11	0.00	0.11	0.21	0.32	0.42	0.53	0.63	0.74	0.84	0.95	1.05	1.16	1.26	1.37	1.48
66°F	-0.22	-0.11	0.00	0.11	0.22	0.33	0.44	0.55	0.66	0.76	0.87	0.98	1.09	1.20	1.31	1.42	1.53
67°F	-0.22	-0.11	0.00	0.11	0.23	0.34	0.45	0.57	0.68	0.79	0.91	1.02	1.13	1.24	1.36	1.47	1.58
68°F	-0.23	-0.11	0.00	0.12	0.24	0.35	0.47	0.59	0.70	0.82	0.94	1.06	1.17	1.29	1.41	1.52	1.64
69°F	-0.24	-0.12	0.00	0.12	0.25	0.37	0.49	0.61	0.73	0.85	0.97	1.09	1.21	1.34	1.46	1.58	1.70
70°F	-0.25	-0.12	0.01	0.13	0.26	0.38	0.51	0.63	0.76	0.88	1.01	1.13	1.26	1.38	1.51	1.63	1.76
71°F	-0.25	-0.12	0.01	0.14	0.27	0.39	0.52	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.56	1.69	1.82
72°F	-0.26	-0.13	0.01	0.14	0.28	0.41	0.54	0.68	0.81	0.95	1.08	1.21	1.35	1.48	1.62	1.75	1.88
73°F	-0.27	-0.13	0.01	0.15	0.29	0.42	0.56	0.70	0.84	0.98	1.12	1.26	1.40	1.53	1.67	1.81	1.95
74°F	-0.28	-0.13	0.01	0.15	0.30	0.44	0.58	0.73	0.87	1.01	1.16	1.30	1.44	1.59	1.73	1.87	2.02
75°F	-0.28	-0.14	0.01	0.16	0.31	0.46	0.60	0.75	0.90	1.05	1.20	1.35	1.49	1.64	1.79	1.94	2.09
76°F	-0.29	-0.14	0.01	0.17	0.32	0.47	0.63	0.78	0.93	1.09	1.24	1.39	1.55	1.70	1.85	2.01	2.16
77°F	-0.30	-0.14	0.02	0.17	0.33	0.49	0.65	0.81	0.97	1.12	1.28	1.44	1.60	1.76	1.92	2.08	2.23
78°F	-0.31	-0.15	0.02	0.18	0.34	0.51	0.67	0.84	1.00	1.16	1.33	1.49	1.65	1.82	1.98	2.15	2.31
79°F	-0.32	-0.15	0.02	0.19	0.36	0.53	0.70	0.86	1.03	1.20	1.37	1.54	1.71	1.88	2.05	2.22	2.39
80°F	-0.33	-0.15	0.02	0.20	0.37	0.55	0.72	0.90	1.07	1.24	1.42	1.59	1.77	1.94	2.12	2.29	2.47
81°F	-0.34	-0.16	0.02	0.20	0.38	0.57	0.75	0.93	1.11	1.29	1.47	1.65	1.83	2.01	2.19	2.37	2.55
82°F	-0.35	-0.16	0.02	0.21	0.40	0.58	0.77	0.96	1.14	1.33	1.52	1.70	1.89	2.08	2.26	2.45	2.64
83°F	-0.36	-0.17	0.03	0.22	0.41	0.61	0.80	0.99	1.18	1.38	1.57	1.76	1.96	2.15	2.34	2.53	2.73
84°F	-0.37	-0.17	0.03	0.23	0.43	0.63	0.83	1.03	1.22	1.42	1.62	1.82	2.02	2.22	2.42	2.62	2.82
85°F	-0.38	-0.17	0.03	0.24	0.44	0.65	0.85	1.06	1.27	1.47	1.68	1.88	2.09	2.29	2.50	2.71	2.91
86°F	-0.39	-0.18	0.03	0.25	0.46	0.67	0.88	1.10	1.31	1.52	1.73	1.95	2.16	2.37	2.58	2.79	3.01
87°F	-0.40	-0.18	0.04	0.26	0.48	0.69	0.91	1.13	1.35	1.57	1.79	2.01	2.23	2.45	2.67	2.89	3.11

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