Greenhouse Temperature Management

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Introduction

One of the benefits of growing crops in a greenhouse is the ability to control all aspects of the production environment. One of the major factors influencing crop growth is temperature. Different crop species have different optimum growing temperatures and these optimum temperatures can be different for the root and the shoot environment, and for the different growth stages during the life of the crop. Since we are usually interested in rapid crop growth and development, we need to provide these optimum temperatures throughout the entire cropping cycle. If a greenhouse were like a residential or commercial building, controlling the temperature would be much easier since these buildings are insulated so that the impact of outside conditions is significantly reduced. However, greenhouses are designed to allow as much light as possible to enter the growing area. As a result, the insulating properties of the structure are significantly diminished and the growing environment experiences a significant influence from the constantly fluctuating weather conditions. Solar radiation (light and heat) exerts by far the largest impact on the growing environment, resulting in the challenge maintaining the optimum growing temperatures. Fortunately, several techniques can be used to reduce the impact of solar radiation on the temperature inside a greenhouse. These techniques are further discussed in this article.

Ventilation

Greenhouses can be mechanically or naturally ventilated. Mechanical ventilation requires (louvered) inlet openings, exhaust fans, and electricity to operate the fans. When designed properly, mechanical ventilation is able to provide adequate cooling under a wide variety of weather conditions throughout many locations in the United States.

Natural ventilation (**Figure 18**) works based on two physical phenomena: thermal buoyancy (warm air is less dense and rises) and the so-called “wind effect” (wind blowing outside the greenhouse creates small pressure differences between the windward and leeward side of the greenhouse causing air to move towards the leeward side). All that is needed are (strategically located) inlet and outlet openings, vent window motors, and electricity to operate the motors. In some cases, the vent window positions are changed manually, eliminating the need for motors and electricity, but increasing the amount of labor since frequent adjustments are necessary. Compared to mechanical ventilation systems, electrically operated natural

Figure 18. Natural ventilation in a glass-glazed greenhouse. Photo courtesy of A.J. Both, Rutgers University.

ventilation systems use a lot less electricity and produce (some) noise only when the vent window position is changed. When using a natural ventilation system, additional cooling can be provided by a fog system. Unfortunately, natural ventilation does not work very well on warm days when the outside wind velocity is low (less than 200 feet per minute). Keep in mind that whether using either system with no other cooling capabilities, the indoor temperature cannot be lowered below the outdoor temperature.

Due to the long and narrow design of most freestanding greenhouses, mechanical ventilation systems usually move the air along the length of the greenhouse (the exhaust fans and inlet openings are installed in opposite end walls), while natural ventilation systems provide crosswise ventilation (using side wall and roof vents).

In gutter-connected greenhouses, mechanical ventilation systems inlets and outlets can be installed in the side- or end walls, while natural ventilation systems usually consist of only roof vents. Extreme natural ventilation systems include the open-roof greenhouse design, where the very large maximum ventilation opening allows for the indoor temperature to almost never exceed the outdoor temperature. This is often not attainable with mechanically ventilated greenhouses due to the very large amounts of air that such systems would have to move through the greenhouse to accomplish the same results.

When insect screens are installed in ventilation openings, the additional resistance to airflow created by the screen material has to be taken into account to ensure proper ventilation rates. Often, the screen area is larger compared to the inlet area to allow sufficient amounts of air to enter the greenhouse.

Whichever ventilation system is used, uniform air distribution inside the greenhouse is important because uniform crop production is only possible when every plant experiences the same environmental conditions. Therefore, horizontal airflow fans are frequently installed to ensure proper air mixing. The recommended fan capacity is approximately 3 cfm per ft^2 of growing area.

Humidity Control

Healthy plants can transpire a lot of water, resulting in an increase in the humidity of the greenhouse air. A high relative humidity (above 80-85%) should be avoided because it can increase the incidence of disease and reduce plant transpiration. Sufficient venting, or successively heating and venting can prevent condensation on crop surfaces and the greenhouse structure. The use of cooling systems (e.g., pad-and-fan or fog) during the warmer summer months increases the greenhouse air humidity. During periods with warm and humid outdoor conditions, humidity control inside the greenhouse can be a challenge. Greenhouses located in dry, dessert environments benefit greatly from evaporative cooling systems because large amounts of water can be evaporated into the incoming air, resulting in significant temperature drops.

Since the relative humidity alone does not tell us anything about the absolute water holding capacity of air (we also need to know the temperature to determine the amount of water the air can hold), a different measurement is sometime used to describe the absolute moisture status of the air: the vapor pressure deficit (VPD). The VPD is a measure of the difference between the amount of moisture the air contains at a given moment and the amount of moisture it can hold at that temperature when the air would be saturated (i.e., when condensation would start; also known as the dew point temperature). A VPD measurement can tell us how easy it is for plants to transpire: higher values stimulate transpiration (but too high can cause wilting), and lower values reduce transpiration and can lead to condensation on leaf and greenhouse surfaces. Typical VPD measurements in greenhouses range between 0 and 1 psi (0 to 7 kPa).

Shading

Investing in movable shade curtains is a very smart idea, particularly with the high energy prices we are experiencing today (**Figure 19**). Shade curtains help reduce the energy load on your greenhouse crop during warm and sunny conditions and they help reduce heat radiation losses at night. Energy savings of up to 30% have been reported, ensuring a quick payback period based on today's fuel prices. Movable curtains can be operated automatically with a motorized roll-up system that is controlled by a light sensor. Even low-cost greenhouses can benefit from the installation of a shade system. The curtain materials are available in many different configurations from low to high shading percentages depending on the crop requirements and the local solar radiation conditions. Movable shade curtains can be installed inside or outside (on top or above the glazing) the greenhouse. Make sure that you specify the use when you order a curtain material from a manufacturer. When shade systems are located in close proximity to heat sources (e.g., unit heaters or CO_2 burners), it is a good idea to install a curtain material with a low flammability. These low flammable curtain materials can stop fires from rapidly spreading throughout an entire greenhouse when all the curtains are closed.

Figure 19. Example of an internal shade system in a greenhouse. Photo courtesy of A.J. Both, Rutgers University.

Evaporative Cooling

When the regular ventilation system and shading (e.g., exterior white wash or movable curtains) are not able to keep the greenhouse temperature at the desired set point, additional cooling is needed. In homes and office buildings, mechanical refrigeration (air conditioning) is often used, but in greenhouses where the quantity of heat to be removed can be very large, air conditioning is often not economical. Fortunately, we can use evaporative cooling as a simple and relatively inexpensive alternative. The process of evaporation requires heat (recall how cold your skin can feel shortly after you get out of the shower or the swimming pool but before you have a change to dry yourself off). This heat (energy) is provided by the surrounding air, causing the air temperature to drop. At the same time, the humidity of the air increases as the evaporated water transitions into water vapor and becomes part of the surrounding air mass. The maximum amount of cooling possible with evaporative cooling systems depends on the humidity of the air you started with (the drier the initial air, the more water can be evaporated into it, the more the final air temperature will drop), as well as the initial temperature of the air (warmer air is able to contain more water vapor compared to colder air). This section will investigate in more detail how evaporative cooling can be used to help maintain target set point temperatures during warm outside conditions when the ventilation system alone is not sufficient to maintain the set point.

Pad-and-Fan System

Two evaporative cooling systems are commonly used in greenhouses: the pad-and-fan and the fog system. Pad-and-fan systems are part of a greenhouse's mechanical ventilation system (**Figure 20**). Note that swamp coolers can be considered stand-alone evaporative cooling systems, but otherwise operate similarly as pad-and-fan systems. For

Figure 20. Evaporative cooling pad installed along the inside of the ventilation inlet opening. Photo courtesy of A.J. Both, Rutgers University.

pad-and-fan systems, an evaporative cooling pad is installed in the ventilation opening, ensuring that all incoming ventilation air travels trough the pad before it can enter the greenhouse environment. The pads are typically made of a corrugated material (impregnated paper or plastic) that is glued together in such a way as to allow air to pass through it while ensuring a maximum contact surface between the air and the wet pad material. Water is pumped to the top of the pad and released through small openings along the entire length of the supply pipe. These openings are typically pointed upward to prevent clogging by any debris that might be pumped through the system (installing a filter system is recommended). A cover is used to channel the water downwards onto the top of the pads after it is released from the openings. The opening spacing is designed so that the entire pad area wets evenly without allowing patches to remain dry. At the bottom of the pad, excess water is collected and returned to a sump tank so it can be reused. The sump tank is outfitted with a float valve allowing for make-up water to be added. Since a portion of the recirculating water is lost through evaporation, the salt concentration in the remaining water increases over time. To prevent an excessive salt concentration from creating salt build-up (crystals) on the pad material (reducing pad efficiency), it is a common practice to bleed approximately 10% of the returning water to a designated drain. In addition, during summer operation, it is common to 'run the pads dry' during the nighttime hours to prevent algae build-up that can also reduce pad efficiency. As the cooled (and humidified) air exits the pad and moves through the greenhouse towards the exhaust fans, it picks up heat from the greenhouse environment. Therefore, pad-an-fan systems experience a temperature gradient between the inlet (pad) and the outlet (fan) side of the greenhouse. In properly designed systems, this temperature gradient is minimal, providing all plants with similar conditions. However, temperature gradients of 7-10 °F are not uncommon.

The required evaporative pad area depends on the pad thickness. For the typical, vertically mounted four-inch thick pads, the required area (in ft^2) can be calculated by dividing the total greenhouse ventilation fan capacity (in cfm) by the number 250 (the recommended air velocity through the pad). For six-inch thick pads, the fan capacity should be divided by the number 350. The recommended minimum pump capacity is 0.5 and 0.8 gpm per linear foot of pad for the four and six-inch thick pads, respectively. The recommended minimum sump tank capacity is 0.8 and 1 gallon per ft^2 of pad area for the four and six-inch pads, respectively. For evaporative cooling pads, the estimated maximum water usage can be as high as 10-12 gpd per ft^2 of pad area.

Fog System

The other evaporative cooling system used in greenhouses is the fog system (**Figure 21**). This system is often used in greenhouses with natural ventilation systems (i.e., ventilations systems that rely only on opening and closing strategically placed windows and do not use mechanical fans to move air through the greenhouse structure). Natural ventilation systems generally are not able to overcome the additional airflow resistance created by placing

Figure 21. Top-down view of a fog nozzle delivering a small-droplet mist for evaporative cooling. Photo courtesy of A.J. Both, Rutgers University.

an evaporative cooling pad directly in the ventilation inlets. The nozzles of a fog system can be installed throughout the greenhouse, resulting in a more uniform cooling pattern compared to the pad-and-fan system. The recommended spacing is approximately one nozzle for every 50-100 ft^2 of growing area. The water pressure used in greenhouse fog systems is very high (500 psi and higher) in order to produce very fine droplets that evaporate before the droplets can reach plant surfaces. The water usage per nozzle is small: approximately 1-1.2 gph. In addition, the water needs to be free of any impurities to prevent clogging of the small nozzle openings. As a result, water treatment (filtration and purification) and a high-pressure pump are needed to operate a fog system. The usually small diameter supply lines should be able to withstand the high water pressure. Therefore, fog systems can be more expensive to install compared to pad-and-fan systems. Fog systems, in combination with natural ventilation, produce little noise compared to mechanical ventilations systems outfitted with evaporative cooling pads. This can be an important benefit for workers and visitors staying inside these greenhouses for extended periods of time.

Psychrometric Chart

In order to use a handy tool (the psychrometric chart, **Figure 22**) to help determine the maximum temperature drop resulting from the operation of an evaporative cooling system, it is important to review a few key physical properties of air:

- Dry bulb temperature (Tdb, °F): Air temperature measured with a regular (mercury) thermometer
- Wet bulb temperature (Twb, °F): Air temperature measured when the sensing tip is kept moist (e.g., with a wick connected to a water reservoir) while the (mercury) thermometer is moved through the air rapidly
- Dew point temperature (Td, °F): Air temperature at which condensation occurs when moist air is cooled
- Relative humidity (RH, %): Indicates the degree of saturation (with water vapor)
- Humidity ratio (lb/lb): Represents the mass of water vapor evaporated into a unit mass of dry air
- Enthalpy (Btu/lb): Indicates the energy content of a unit mass of air.
- Specific volume (ft^3/lb): Indicates the volume of a unit mass of dry air (equivalent to the inverse of the air density).

As mentioned before, the maximum amount of cooling provided by evaporative cooling systems depends on the initial temperature and humidity (moisture content) of the air. We can measure these parameters relatively easily with a standard thermometer (measuring the dry-bulb temperature) and a relative humidity sensor. With these measurements, we can use the psychrometric chart (simplified for following example and shown in **Figure 23**) to determine the corresponding wet bulb temperature at the maximum possible relative humidity (100%). Once we know the corresponding wet bulb temperature, we can calculate the difference (also called the wet bulb depression) that indicates the theoretical temperature drop provided by the evaporative cooling system.

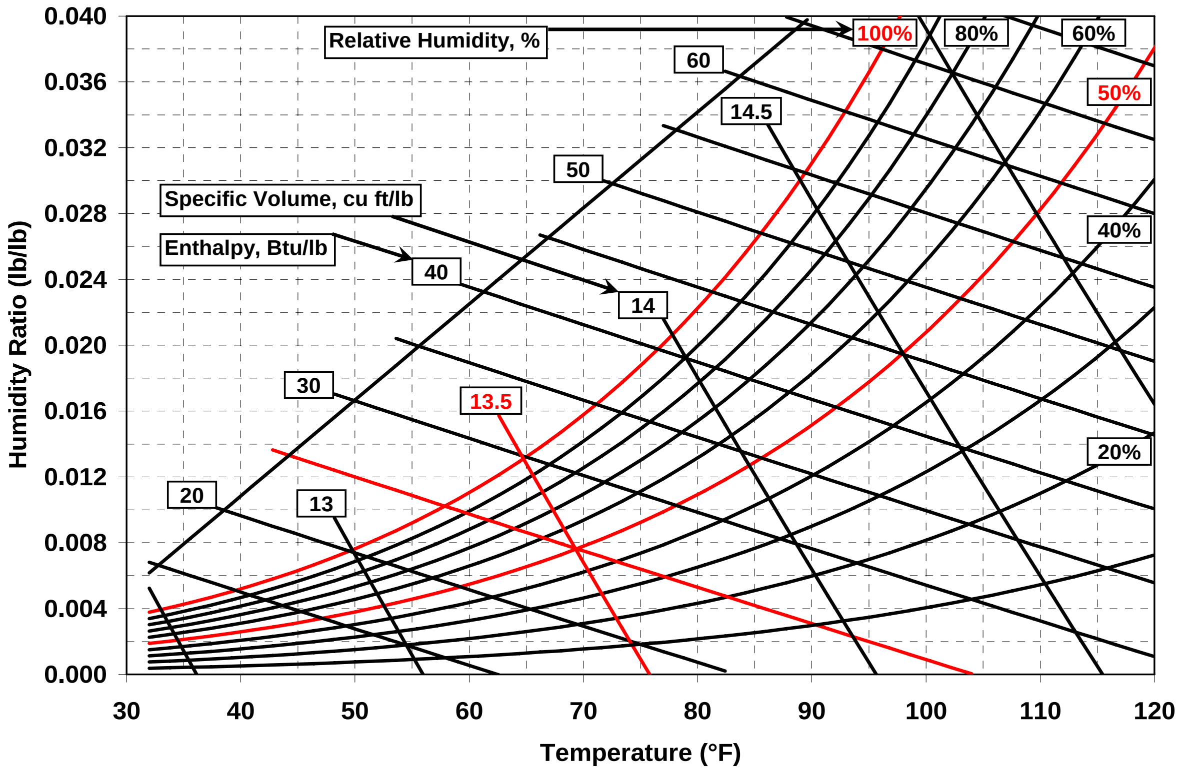

Figure 22. Psychrometric chart used to determine the physical properties air. Note that with values for only two parameters (e.g., dry bulb temperature and relative humidity, or dry and wet bulb temperatures), all others can be found in the chart (some interpolation may be necessary).

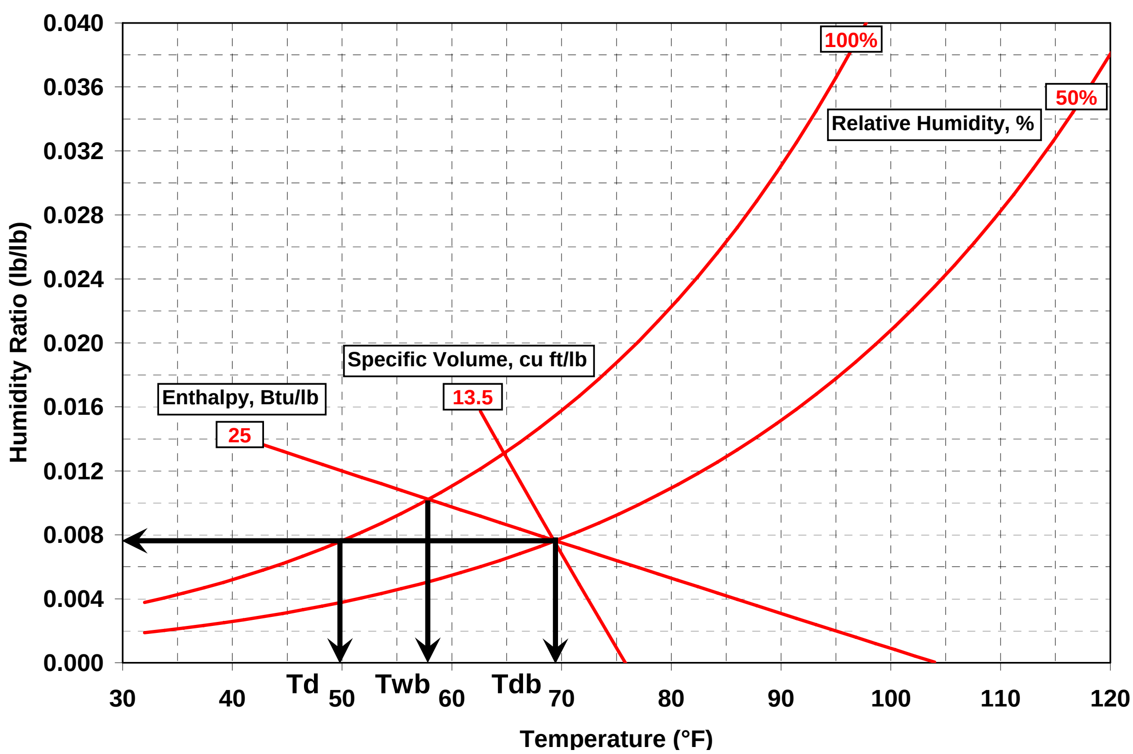

Figure 23. A simplified psychrometric chart used to visualize the evaporative cooling example described in the text.

Since few engineered systems are 100% efficient, the actual temperature drop realized by the evaporative cooling system is more likely in the order of 80% of the theoretical wet bulb depression.

In understanding **Figure 23**, it was assumed that the initial conditions of the outside air were: a dry bulb temperature of 69 °F and a relative humidity of 50% (look for the intersection of the curved 50% RH line with the vertical line for a temperature of 69 °F). From this starting point, we can determine all other environmental parameters from the list shown above: the wet bulb temperature equals 58 °F (from the starting point, follow the constant enthalpy line [25 Btu/lb in this case] until it intersects with the 100% relative humidity curve), the dew point temperature is just shy of 50 °F, the humidity ratio equals 0.0075 lb/lb, the enthalpy equals 25 Btu/lb, and the specific volume equals 13.5 ft^3/lb. Hence, the wet bulb depression for this example equals 69 – 58 = 11 °F. Using an overall evaporative cooling system efficiency of 80% results in a practical temperature drop of almost 9 °F. Of course, this temperature drop occurs as the air passes through the evaporative cooling pad. As the air continues to travel through the greenhouse on its way to the exhaust fans, the exiting air may well be warmed to its original temperature (but is no longer saturated).

In Conclusion

When evaporative cooling pad systems appear to perform below expectation, it is tempting to assume that an increase in the ventilation rate would improve performance. However, increased ventilation rates result in increased air speeds through the cooling pads, reducing the time allowed for evaporation of water. As a result, the overall system efficiency can be reduced while water usage increases. Particularly in areas with water shortages, this can become a concern.

In addition, increased ventilation rates may result in a decrease in temperature and humidity uniformity throughout the growing area. A similar situation can occur with fog systems: installing more fog nozzles may not necessarily result in additional cooling capacity, while system inputs (installation cost and water usage) increase. In general however, fog systems are able to provide more uniform cooling throughout the growing area and this may be an important consideration for some greenhouse designs and crops. It should be clear that, like many other greenhouse systems, the design and control strategy for evaporative cooling systems requires some thought and attention. It is recommended to consult with professionals who have experience with greenhouse cooling in your neighborhood.