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Temperature Control in Greenhouses

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Temperature is the degree of hotness or coldness of a substance. Temperature is commonly measured in Celsius (°C) and Fahrenheit (°F) scales [°C = (°F-32) \times 0.56]. Air temperature is an important determinant of both vegetative growth (Fig. 1) and flowering in greenhouse plants. Therefore, it is important to expose plants to optimal temperature during growth.



Figure 1. Effect of air temperature on butterhead lettuce (variety Rex) growth. Plants were grown at an average temperature of 60 (top) and 70 $^\circ$ F (bottom).

The optimal temperature rate for most of the plant species is between 68 to 78 °F. Some cold-tolerant species can grow normally at lower temperatures of 58 to 63°F. The negative effects of suboptimal air temperature are more prevalent in cold-sensitive species than tolerant species. Cold-sensitive species grow slowly and show delayed flower initiation when greenhouse air temperature is below the optimal range. In many species, plants stop growing (but continue to survive) when the air temperature is below "base temperature," which varies between 36 and 53 °F. On the other hand, air temperature between 78 and 85 °F can result in excess growth. Heat damage (leaf senescence or flower drop) can occur when plants are exposed to higher than 90 °F.

Air temperature in Indiana and surrounding Midwestern states is below or above the optimal range for plants during winter and summer months (Fig. 2). Without temperature control, the air temperature inside a greenhouse is usually higher than outside temperature. The air temperature inside a greenhouse can easily increase above 95 °F during summer months in Indiana. Although air temperature will be slightly warmer inside a greenhouse



Figure 2. Average solar radiation (green bars) and air temperature (orange line) in Indianapolis during different months. Source: National Oceanic and Atmospheric Administration (NOAA). Dashed line shows optimal temperature range for crops. Note that the air temperature is above and below optimal air temperature during summer and winter months, respectively.

compared to the outside in winter months, it will be much lower than the optimal temperature needed for most of the crops. This means that greenhouse growers should control temperature (i.e., cool or heat) during summer and winter months to ensure that crops are exposed to optimal air temperature. This article describes different methods and considerations related to cooling and heating greenhouses.

Greenhouse Cooling Methods

There are different methods available to reduce the temperature inside a greenhouse during summer months. Usually, a combination of two or more methods is used to achieve a desirable temperature range in a greenhouse. Cooling methods are described below, along with some considerations.

1 Plant Transpiration. Solar radiation is the major source of heat energy in a greenhouse (Fig. 2). A greenhouse covered with actively growing plants will be relatively easier to cool than one partially covered with plants. Transpiration is a process by which water is lost from leaf surfaces through tiny pores called stomata. This process is necessary to reduce the temperature of the leaves. Plants absorb a significant amount of energy from solar radiation. It takes about 970 btu of energy for a lb. of water to evaporate. We have seen in our greenhouse studies that actively growing lettuce plants can transpire approximately half to three quarters of a pound of water per square feet every day. This means that a greenhouse covered with actively growing plants can effectively absorb solar energy entering the greenhouse and contribute to a reduction in air temperature.

2 Shade Cloth: A greenhouse can be cooled by reducing the total solar radiation entering the structure. This can be achieved by using a shade cloth. The shading process can be automated based on the outside light intensity. However, shading method should be used only when greenhouse cooling by other methods (see below) is not effective. This is because the shade cloth reduces light intensity needed for normal plant growth. Growers need to pay attention to the intensity of light transmitted through the shade cloth, especially if shading is used for several hours during a day. It is critical to maintain a daily light integral of 10 to 12 moles per square meter in a greenhouse to maintain normal growth and produce good-quality plants. The light requirement can be higher (15 to 18 moles per square meter) for vegetable crops, such as tomatoes and peppers. The daily light integral inside a greenhouse without a shade cloth can be as high as 20 to 25 moles per square meter in Indiana. This

means that Indiana growers should use a shade cloth that can reduces light intensity by 30 to 50 percent to ensure optimal light levels for plants, while reducing radiation load for cooling.

3. Natural Ventilation: This process involves replacing warmer air inside the greenhouse with relatively cooler outside air. Natural ventilation can happen through the openings on the sidewall, end wall, and roof of the greenhouse. Rollup curtains and hinged vents can be used for sidewall ventilation. This method alone can be less effective in wider areenhouses (e.a., autter connected). The height of the side vents can vary between 3 to 6 feet. Side vents are positioned slightly above the plant height to enable outside air to mix with inside air prior to reaching foliage. This placement can also avoid resistance to airflow from plants adjacent to the walls. Roof vents are hinged vents on both sides of the ridge. This design allows for opening of the roof vent located on the leeward side. Research has shown that ridge vent alone is more effective than sidewall vent. However, when roof venting was combined with sidewall vents, a significant improvement in natural ventilation and reduction in greenhouse temperature were observed, especially in warmer regions with wider greenhouses. More recently, open roof designs are becoming popular. Open designs with more than 50% of open roof area can eliminate the need for sidewall vents.

Air pressure gradients and wind cause natural ventilation in a greenhouse. When air becomes hot, it rises and moves closer to the roof. Wind blowing over the roof creates a vacuum on the leeward side (opposite to the direction of wind) of the ridge. This draws hot air out of the greenhouse when the ridge vent is opened (Fig. 3). Horizontal airflow fans should not be operated while using natural ventilation; that's because the fans redistribute the hot air accumulated at the top of the greenhouse. When hot air rises to the roof, a low-



pressure area is formed above the plants. This draws cooler air from the outside through the windows along the sidewalls, even when the wind is absent. However, the efficiency of natural ventilation increases when wind velocities are higher. There are some important considerations for using natural ventilation as a means of cooling greenhouses. The sidewall and roof ventilation should be similar in area, and each should account for 15% to 20% of the greenhouse ground area. For effective ventilation, the ridge vent should make a 60° angle to the roof when fully opened. Vent openings with greater than a 60° angle could create a "sail effect" when outdoor wind speed is severe and lead to vent failure. Lastly, plastic mesh screens used to cover the sidewalls and roof vents to prevent insects from entering the greenhouse can resist wind movement and reduce natural ventilation. In some studies, more than 50% reduction in natural ventilation was observed due to screens.

4. Forced Ventilation: This method uses exhaust fans with louvered vents to remove hot air from the greenhouse. A forced ventilation rate of 8-10 cubic feet of air per min (cfm) for each square feet area of the greenhouse can potentially keep the greenhouse air within 5 °F of outside air temperature. For example, a 3000 square feet greenhouse requires a forced ventilation rate of 24000 cfm (i.e., 3000 square feet × 8 cfm per square feet) to keep the greenhouse air within 5 °F of outside air temperature. This information can be used while purchasing the exhaust fans. In the above example, growers can purchase two exhaust fans each with 12000 cfm capacity (12000 cfm x 2 = 24000 cfm) for temperature control. For effective forced ventilation, exhaust fans should be arranged on the leeward side of the greenhouse. If this is not possible, the fan capacity should be increased by at least 10%. A clear space equivalent to 4 to 5 times the fan diameter has to be maintained in front of the fans for proper forced ventilation to happen. Furthermore, fans should not be spaced more than 25 feet apart.

5. Evaporative Cooling: Forced ventilation may reduce air temperature, but a greenhouse can still be hotter than outside during summer. In this situation, evaporative cooling can be used to cool a greenhouse. This method uses moist cooling pads to reduce the temperature of air entering the greenhouse. Water added continuously at the top of pads runs down through the flutes. The water that runs down the flutes moistens and cleans the pads. The pads are mounted on the windward side of the greenhouse. When exhaust fans pull air into the greenhouse through the cooling pads, the incoming warm and dry air is cooled by exchanging heat with water in the pads. The extent to which the temperature of the incoming air can be lowered will depend on the moisture content or relative humidity of the air (Fig. 4). Moist

Figure 3. Process of natural ventilation occurring in a greenhouse.

incoming air can hold less water vapor and therefore decreases cooling efficiency. The temperature of water has minimal effect on the cooling efficiency. The energy required to evaporate (and to cool air) a pound of water is approximately 540 times more than the energy required to increase the temperature of the water by one degree Fahrenheit. Therefore, differences in water temperature have relatively small effects on cooling efficiency.

Theoretical air temperature that can result inside a greenhouse due to evaporative cooling (or wet bulb temperature) for a given outside air temperature (or dry bulb temperature) and relative humidity can be estimated using a psychrometric chart (Fig. 4). The illustration shown in Fig. 4 indicates that the incoming air temperature can be lowered from 80 to 60 °F when the relative humidity of the air is 40%; whereas temperature can be lowered only to 70 °F when the relative humidity of the air is 60%. However, actual air temperature inside the greenhouse will be slightly higher (5-10%) than theoretical numbers due to efficiency losses of the cooling system. Relative humidity can be an important factor affecting evaporative cooling, especially if the greenhouse is located near a large body of water (e.g., lake). In these areas, a more expensive method of air conditioning is used to cool the greenhouses. Instead of using evaporative cooling, warm air from the greenhouse is forced through the cooling coils using large fans. The warm air exchanges heat with the refrigerant inside the cooling coils, and cool air returns to the greenhouse.

Cooling pads used for evaporative cooling are made using aspen fiber, cellulose, and PVC materials. Among these, cellulose pads are more popular. They consist of alternate layers of corrugated cellulose sheets, with steep



Figure 4. Psychrometric chart showing the relation between wet bulb (greenhouse air) and dry bulb (outside air) temperature at different levels of relative humidity.

(60°) and flat (30°) flute angles that are bonded together to increase evaporation efficiency and mechanical strength, and decrease resistance to airflow. Cellulose pads also resist decomposition and have relatively less algal growth. The porosity of cooling pads is usually high and above 95% to reduce the resistance to airflow.

The required cooling pad area for a given greenhouse is calculated based on air velocity specification of the pad material and the volume of air forced out of the greenhouse by the exhaust fans. The air velocity specification indicates the maximum airflow rate that can pass through the pads. For example, cooling pads made from aspen fiber (4-inch thick) have an air velocity specification of 200 feet per min (fpm), while those made from corrugated cellulose (4-inch thick) can accommodate 250 fpm. The required pad area (square feet) is determined by dividing the forced air volume by the air velocity specification of the material. In the previous example, a forced ventilation rate of 24000 cfm was needed for a greenhouse with a measured area of 3000 square feet in order to maintain the greenhouse air temperature within 5 °F of the outside air temperature. Using this example and air velocity specifications, pad area required is 120 square feet for aspen pads (i.e., 24000 cfm / 200 feet per min) and 96 square feet for corrugated cellulose pads (i.e., 24000 cfm / 250 feet per min).

The pad dimensions (length and height) can depend on the width of the greenhouse. Let's assume the greenhouse in the above example has a dimension of 100 feet in length and 30 feet in width. If the pads are arranged on a short side, then the maximum pad length cannot exceed the side length or 30 feet. In this case, a pad height of 4 feet will result in the required pad area of 120 square feet (i.e., 30 feet x 4 feet =120 square feet) when using aspen material; when using cellulose pads, 3.2 feet in height will result in the required pad area of 96 square feet (i.e., 30 feet x 3.2 feet = 96 square feet).

Cooling pad thickness is an important determinant of system efficiency. Pads are available in thickness of 2 to 8 inches. Thicker pads increase cooling efficiency because surface area increases with thickness. The more contact surface area, the more heat exchange can happen between water and air. However, thicker pads also increase the resistance to air flow. This means exhaust fan capacity must increase (especially if there is a significant pressure drop due to pad thickness) to facilitate sufficient airflow for a given pad area.



Some important considerations for effective cooling when using fan and pads:

- Distance between the fan and pad should not be more than 120 feet;
- Water volume of 50 to 75 gallons per minute should flow across 100 square feet of pad area;
- Pads should be installed on the windward side (on the side prevailing summer winds) and exhaust fans should be installed on the leeward side;
- Fan exhaust should be at least 50 feet from the adjacent pads;
- Pads made of cellulose will likely have less algal growth than those made from aspen; and
- Horizontal baffles should be used to deflect airflow from cooling pads toward plants inside a greenhouse, if air flow from pads is longitudinal (or parallel to gutters).

Fogging is another method of evaporative cooling used to reduce the air temperature inside a greenhouse. This involves atomizing water into small droplets (fog) and spraying them above the plants. The suspended water droplets exchange heat with the air to evaporate. This reduces the air temperature and increases relative humidity. Droplet size is critical for the fogging method. The size of water droplets should not exceed 50 microns for effective cooling. Water droplets greater than 100 microns will not form a fog, but deposit on the plants or ground. Fogging method uses a high-pressure pump to atomize water and form small droplets. The fogger nozzles should be evenly spaced in the greenhouse for uniform distribution of fog above plants. In addition, water quality should be good to prevent nozzles from clogging. Fogging increases relative humidity of the air, so it is a good method for cooling propagation houses. However, the method can be expensive due to the high cost of equipment required for atomizing water, so it is not common in many greenhouses.

Greenhouse Heating Methods

Heating is required to produce crops from November through February in Indiana and surrounding states in the US Midwest because of cold outdoor air temperature in the region during winter months (NOAA-NCDC, link). Before discussing artificial heating methods, it is important to understand how heat is gained/lost from a greenhouse.

A greenhouse can gain or lose heat through radiation, convection, and conduction processes (Fig. 5). Radiation is heat transfer in the form of light. For example, heat energy from the sun reaches Earth in the form of electromagnetic radiation. Sunlight is the major source of heat energy inside a greenhouse during winter, so maximizing sunlight transmission into a greenhouse is important. Sunlight (especially short wave and long wave radiation) transmitted through the greenhouse is absorbed by plants, structural components, and surfaces. The absorption of sunlight increases their temperature. The heat gained by the plants, structural components, and surfaces is transferred to the surrounding air by contact. The warm air transfers heat to cooler areas of the greenhouse by a process called convection - heat transfer through liquids and gases. Infiltration is a form of



Figure 5. Different methods of heat loss from a greenhouse.

convection where hot air inside the greenhouse is lost to the outside through gaps in the structure or areas without insulation. The third method, conduction, involves heat transfer through the solids. For example, heat travels through the glazing (inside to outside during winter) through conduction. However, heat from glazing is lost to the outside air by convection.

Heat gained or lost through conduction, convection and radiation can be calculated using the formula $Q = U \times$ $A \times$ (Ti-To), where Q is heat loss (btu/hr), U is 'Overall' heat transfer coefficient, A is surface area of glazing, Ti is greenhouse temperature and To is outside temperature. (For additional details about calculations, see HO-308-W, available at the Purdue Education Store link). The equation can be used to calculate the heating capacity of a unit heater (btu/hr) used for artificial heating (see below). For calculations, growers should use the coldest outdoor temperatures (To) recorded in their respective regions. Historical minimum temperatures for a location can be obtained from websites such as weather.com or the Indiana State Climate Office. The U-values for different materials and formulae for calculating surface area of glazing material for different greenhouse structures are also described in detail in HO-308-W.

The following are artificial heating methods commonly used in greenhouses:

1. Localized Heating: This method employs the use of unit heaters. The components of a unit heater are fan (to blow air into the unit), fuel manifold/burner unit, heat exchanger, vent (for combustion products), casing (to enclose components), and louvers (to direct airflow) (Fig. 6). Different types of fuels are used in unit heaters, including propane, natural gas, gasoline, #1 or #2 oil, and hot water. Depending on the fuel used, the efficiencies and design of the equipment may vary. The quantity



of heat energy produced also varies among fuels. For example, propane produces 91,000 btu/gal, gasoline produces 124,000 btu/gal, oil (#2) produces 140,000 btu/ gal, and natural gas produces 1000 btu/cubic feet. Fuel is used to fire the burner, which in turn heats the air inside a heat exchanger unit. Air blown into the unit by the fan picks up heat from the heat exchanger and hot air enters the greenhouse. The products of combustion are vented out from the heat exchanger to the atmosphere using a tall exhaust flume.

Some models of unit heaters do not vent air. Venting lowers fuel efficiency because some of the heat generated by combustion is lost through the vented air. Among the vented models, there are both low (80-83% fuelefficient) and high-efficiency (>90% fuel-efficient) units. The low-efficiency venting models are less expensive. In high-efficiency units, a portion of heat lost through the exhaust is retrieved by condensing the fumes and collecting the heat using a secondary heat exchanger. In addition, features like a variable-speed burner and blower, and use of fresh air for combustion, increases energy efficiency in high-efficiency units. These features add to the cost, but the increased cost of high-efficiency units can be recovered over time. Unvented models directly exhaust heat into the greenhouse and thus offer higher fuel efficiency than vented models. However, when unvented models are used, toxic products of combustion can spread inside the greenhouse and affect plants and people.

There are several considerations for using unit heaters:

- Ensuring adequate air supply is important for complete combustion of fuels.
- Temperature control in large greenhouses likely will require several unit heaters. The heaters should be arranged along the periphery of the greenhouse so that the hot air keeps the glazing warm during cold weather. This also increases the uniformity of heating inside the greenhouse. Also, multiple heaters reduce the risk of exposing plants to cold temperature when a unit heater fails to operate.
- A convection tube can be used in conjunction with a unit heater to uniformly distribute the heat inside the greenhouse. The convection tube is connected to a blower, which draws hot air from the greenhouse and redistributes air along the length of the tube through the holes punched on the tube. The tube should be properly inflated during the operation. In order to achieve proper inflation, the tube diameter should be properly sized for airflow, and the holes for air distribution on the tube should be properly spaced along both the length and the circumference.

Figure 6. A unit heater for greenhouses with different components.

- Unit heaters should be checked every year to ensure they are working properly. The best time of the year to render maintenance is before the start of the heating season. Components to inspect include blower, fuel lines, valves, and exhaust vent.
- It is important to note that the condensate collected from high-efficiency heaters should be drained completely and, due to its acidic nature, should not be reused for irrigation purposes. When unit heaters are not used during the cold weather, some condensate can freeze inside the tubes and cause heater failure.

2. Bench Heating: This method uses hot water or warm air to provide optimal temperature to the root zone for germination, propagation, and plant growth. In this method, the greenhouse is usually maintained at lower than optimal temperature (usually 10 °F lower) while the root zone is maintained at the optimal temperature. This method is suitable for smaller plants and seedlings. The overall heating costs are reduced in this method because the greenhouse air is maintained at lower than optimal temperature. Hot air circulated below the benches through pipes or convection tubes can be used to maintain the root zone temperature at an optimal level. Bench heat, using hot water, involves placing containers/ trays on polyethylene tubes of 0.5-inch diameter and circulating water at 95 to 105 °F through the tubing (Fig. 7). The heat from the hot water is transferred to the air surrounding plants by convection and conduction processes. These processes increase the temperature of the air surrounding the root zone. In this method, the water flow rate should be high enough to minimize the temperature difference between the supply and return ends and to avoid sedimentation within the tube. A polystyrene sheet can be placed below the tubing to ensure that the heat is directed toward the plant roots. Usually the tubing is spaced 4 inches apart. Wider spacing can result in non-uniform root zone temperature.



Figure 7. Bench heating using hot water circulated through tubes in a greenhouse at Purdue University. Note that polystyrene sheets are placed below the tubes to redirect heat.

Another method of root-zone heating involves supplying warm water directly to the roots, instead of warm air to the root zone. Hydroponic production offers a unique opportunity to recirculate warm nutrient solution through the production systems housing roots, while maintaining cooler ambient conditions inside the greenhouse. This significantly increases plant growth while decreasing heating costs in a greenhouse. In a study that used different lettuce cultivars, we found that normal lettuce growth can be maintained by supplying heated hydroponic solution at 70°F to the roots while maintaining greenhouse at 55°F (Fig. 8). Plants supplied with hydroponic solution at 60 °F were smaller in size in the same study (Fig. 8).



Figure 8. Effect of root zone heating using warm hydroponic solution on lettuce growth. Plant growth under heated and unheated hydroponic solution treatments is shown.

3. Geothermal Heating. This increasingly popular method can significantly reduce heating costs in greenhouse production. The method extracts naturally available heat in the ground to maintain the greenhouse temperature. The ground temperature at a depth of 6 to 10 feet is nearly constant and close to the average annual temperature of the region. In the US Midwest, the ground temperature at a depth of 6 to 10 feet is between 50 to 55 °F throughout the year. Deeper layers inside the earth can be even warmer. Thus, ground heat can be used as a "source" of heat during winter. Geothermal heat can be captured using two methods: (i) by running a refrigerant through copper pipes placed in the ground and (ii) by running water through high-density polyethylene pipes laid in the ground. Running refrigerant through copper pipes can be more efficient but is guite expensive. When water is used to capture ground heat (i.e., water-source method), long trenches, 6-10 feet deep, are dug near the greenhouse to lay interconnected tubing in the ground. Cold water from the greenhouse is circulated through the tubing. The tubing absorbs heat from the ground and in turn transfers the heat to the cold water. The heated

water returns to the greenhouse. The heat from the warm water that returns to the greenhouse is exchanged with a refrigerant flowing through coils inside a heat pump. Air blowing over the coils picks up the heat, which in turn is distributed throughout the greenhouse.

Installation costs for water-source geothermal heating can be high due to costs associated with digging long trenches. To reduce installation costs, several loops of tubing can be laid in short trenches (100 feet long) dug relatively deeper (15 to 20 feet) in the ground to increase the area of exposure and heat capture. If a large area is not available around the greenhouse, tubing can be laid vertically in the ground by digging a bore (50 to 150 feet deep) to capture heat from deeper layers. It is important to note that the use of heat pump for geothermal heating will require electrical energy for operation. Generally, a pump capacity of 6-8 tons is needed (1 ton can generate 12000 btu/hr) for a greenhouse of 3000 square feet. The overall cost of installation for geothermal heating can be close to \$25,000 for an area of 3000 square feet. However, geothermal pumps have a long life span (about 25 years), and return on investment can be made within 10-12 years of use (assuming \$1000 per month for heating a 3000 square feet greenhouse from November to February, and 50% savings from geothermal heating).

Artificial heating can significantly increase greenhouse operational costs. Some growers use a minimal heating approach to reduce heating costs. However, this approach can delay production time or reduce crop yield. It is important to consider overall profits while using a minimal heating approach in greenhouses. Growing crops with minimal heating may significantly reduce profits under intense cultivation of high-value crops. Instead of minimal heating, growers should consider utilizing alternate methods, such as bench heating, heated hydroponic solution, and geothermal heating to lower heating costs. It is critical to reduce heat losses from the greenhouse. Options to minimize heating losses include using heat curtains, double-layered glazing material (with air insulation), infrared (IR) blockers as additives for the inner layer of a double polyethylene glazing, and foam insulation along crevices and gaps.

For additional information on greenhouse cooling and heating, growers can reach the author of this article by email (knemali@purdue.edu) or phone (765-494-8179).

The article was expert-reviewed by Dr. Elizabeth Maynard (Clinical Associate Professor, Purdue University) and Nathan Deppe (Greenhouse Manager, Purdue University).



Figure 9. An illustration of water-source geothermal heating installation for greenhouse. Cold and hot lines are shown in blue and brown colors, respectively.



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