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Greenhouse Environmental Design Considerations - Florida Greenhouse Vegetable Production Handbook, Vol 2[1]

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The initial purpose of greenhouses was simply to keep plants alive that could not survive outside winter weather conditions. Early growers in northern latitudes recognized that warm temperatures were necessary for the production of fruits and vegetables at times of the year or in places that the crops were not normally grown. So, early greenhouses were designed to provide plants with two essential ingredients, sunlight and warmth. Later, growers began to recognize the importance of cooling in the production of certain crops during warm times of the year and vents were added to allow warm greenhouse air to be exchanged for cooler outside air.

Currently, horticulturists recognize that each plant variety (even within the same species) has its own particular temperature response characteristics. For the grower, this means that it is not enough to simply keep plants alive through hot and cold weather; a successful grower must consistently provide temperatures in which the crop can develop and produce normally. So, heating and cooling systems should be designed not only to prevent temperatures from reaching extreme damaging levels, but to operate smoothly in the temperature range characteristic of normal plant growth and development for the crop being grown.

Energy Exchange

At any given time, greenhouse temperature depends on the heat balance or the net flow of energy between the greenhouse system and the outside environment. There are three basic energy exchange processes; conduction, convection, and radiation.

Heat conduction is the transfer of energy through a solid material or materials that are in direct physical contact. The rate of heat conduction through a material depends on the physical properties of the material (density and conductivity), the thickness of the material, and the temperature difference across the material. Heat transfer by conduction can be minimized by using materials that are poor

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conductors. For instance styrofoam is a poor thermal conductor while copper has a very high thermal conductivity. Double-layered glazing systems take advantage of the poor thermal conductivity of air to reduce heat loss by forming an insulating blanket of air.

Convection heat transfer is the physical movement of gases or liquids between regions at different temperatures. For example, inside a greenhouse in the winter, convection heat exchange occurs as warm air rises and transfers its heat to the cold surfaces of the glazing material (which transfers the energy to the outside air by conduction). After the greenhouse air is cooled by contact with the glazing surfaces in the top of the greenhouse it flows back to the floor. Another form of convection heat exchange is infiltration which is the exchange of outside for inside air. The rate of infiltration depends on the size and number of cracks and other openings in the greenhouse shell. It also depends on outside wind velocities. The rate of energy exchange due to infiltration is simply a function of the difference in temperature of the air coming into the greenhouse compared to the air leaving. Finally, wind directly increases the convective heat transfer rate from the outside surface of the greenhouse by reducing the thickness of the still air film at the glazing surface.

Radiative heat transfer occurs between objects without any physical contact or transporting medium. All objects radiate energy in all directions, however they vary in their capacity to absorb and emit radiation. All energy delivered from the sun to the earth is a result of radiative energy transport. Of course, humans are directly aware of sunlight because our eyes can see it, but there is also radiative energy from the sun that cannot be seen. When radiative energy strikes an object it is either transmitted, reflected, or absorbed depending on the wavelength of the radiation and the spectral characteristics of the particular object. For example, clear greenhouse glazing materials transmit most of the light that people can see (and that plants use for photosynthesis), reflect about 10%, and absorb very little. However, glazing materials can have very different characteristics in other wavelength bands such as infrared. When radiation is absorbed, it is converted into heat energy and warms the material that absorbs it Generally, highly reflective materials reduce radiative exchange while dark, dull materials are effective absorbers and re-radiators.

Heat Loss Calculations

To correctly size a greenhouse heating system, it is necessary to estimate heat loss for the coldest wintertime conditions expected. In calculating greenhouse heat losses, there are two primary factors; losses through glazing, and losses due to infiltration.

Equation 1 can be used to estimate energy losses through the glazing material from the high temperatures inside the house to the colder temperatures outside.

$$Q_c = U\ A\ (T_i - T_o) \qquad (1)$$

where

Q_c = the total 'conduction' heat loss in Btu/hr,

U = the overall heat transfer coefficient in Btu/(ft^2 ^{o}F hr),

A = the total exposed roof and wall area in ft^2,

T_i = the inside greenhouse temperature in ^{o}F,

and

T_o = the outside air temperature in ^{o}F.

Although energy is transferred through the glazing material by conduction, the actual heat transfer from the outer surface of the greenhouse to the outside environment involves a complex mix of conduction, convection, and radiative exchange processes. Equation (1) simplifies the estimation procedure by using representative overall heat transfer coefficients (U) developed for different glazing systems that integrate the energy exchange processes. Table 1 gives values for some of the more common glazing construction assemblies.

Equation (2) can be used to estimate heat that is lost due to infiltration air exchange.

$$Q_i = .02\ V\ C\ (T_i - T_o) \qquad (2)$$

where

Q_i = the total conduction heat loss in Btu/hr,

V = the greenhouse volume in ft^3,

A = the total exposed roof and wall area in ft^2,

T_i = the inside greenhouse temperature in ^oF and

T_o = the outside air temperature in ^oF .

The value .02 in equation (2) is a conversion factor in units of Btu/(ft^3 ^oF) that accounts for the energy holding capacity of a unit volume of air. The key to this equation is the value for C, the number of air exchanges per hour due to leaks in the greenhouse. Table 2 gives some approximate values for several common greenhouse coverings.

Both equations (1) and (2) involve terms that depend on the physical size of the greenhouse. Since conduction heat losses are through the walls and roof, it follows that total heat loss increases with increasing surface area. Likewise, normal leaks associated with particular styles of construction are directly related to surface area (and volume).

Table 1. Overall heat transfer coefficients.

Glazing materials	**Overall heat transfer coefficient U, Btu/(ft^2 ^oF hr)**
Glass:	
single layer	1.1
double layer, 1/2" space	0.7
Polyethylene film:	
single layer	1.1
double layer, separated	0.7
Fiberglass panels	1.0
Double acrylic	0.6

In both situations, it is clear that there are advantages to minimizing the surface area of the greenhouse relative to the floor area where the product can be grown. This is the reason that gutter-connected greenhouses are typically more energy efficient than free-standing greenhouses.

The heat losses calculated in both equations also depend directly on the difference between greenhouse and outside air temperatures. Values must be chosen for T_i and T_o, in order to use the equations for estimating potential energy requirements. The inside greenhouse temperature (T_i) is the lowest temperature that the crop can safely tolerate. The value for the outside temperature (T_o) should be the lowest wintertime temperature to be expected for the area where the greenhouse is located.

Table 2. Greenhouse leakage air exchange.

Type of construction	Air exchanges per hour
New construction:	
Glass or fiberglass	0.75 - 1.5
Polyethylene:	
Double layer	1.5 - 1.0
Old construction:	
Glass:	
Good condition	1.0 - 2.0
Poor condition	2.0 - 4.0

For estimation purposes, Table 3 gives a listing of Florida towns with their associated winter design temperatures. For each locale, there are two temperatures, the 99% and 97.5% design temperatures, respectively. The 99% designation means that during the months of December, January, and February, 99% of the hourly temperatures recorded were above the design value.

For example, assume that a greenhouse is being constructed near Tallahassee to grow hydroponic tomatoes. It is a single-bay structure glazed with clear double poly, 120 ft long, 36 ft wide, 16 ft tall at the highest point of the arched roof, and with 8-ft high sidewalls. A schematic is given in Figure 1.

For tomatoes, it is recommended that the house temperature should not drop below 50°F in order to prevent damage to the crop. However, for optimum

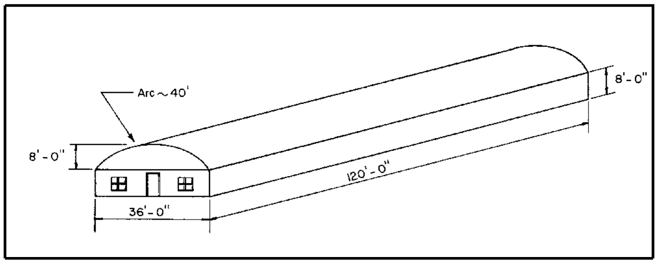

Figure 1. A schematic of a single-bay, double-poly greenhouse typical of vegetable production systems.

fruit set and fruit quality, it is recommended that temperatures not drop below 62°F.

Table 3. Design temperatures for selected Florida towns.

Town	Winter, °F		Summer, °F	
	99%	97.50%	1%	2.50%
Bell Glade	41	44	92	91
Daytona Beach	32	35	92	90
Ft. Lauderdale	42	46	92	91
Ft. Myers	41	44	93	92
Ft. Pierce	38	42	91	90
Gainesville	28	31	95	93
Jacksonville	29	32	96	94
Lakeland	39	41	93	91
Ocala	31	34	95	93
Orlando	35	38	94	93
Panama City	29	33	92	90
Pensacola	25	29	94	93
Sanford	35	38	94	93
Tallahassee	27	30	94	92
Tampa	36	40	94	92
West Palm Bch	41	45	92	91

To calculate approximate conduction heat losses (Q_c): compute the greenhouse surface area (A), pick the appropriate heat transfer coefficient (U) from Table 1, and choose the winter design temperature (T_o) from Table 3. To calculate the total greenhouse surface area, sum up the parts: the sidewalls (A_s = 2 x 120 ft x 8 ft = 1920 ft^2), the endwalls (A_e = 2 x 36 ft x 12 ft = 864 ft^2), and the roof (A_r = 120 ft x 40 ft = 4800 ft^2. From the example, assume that the minimum acceptable greenhouse air temperature (T_i) is 50°F. The values obtained are:

$A = A_s + A_e + A_r = 7584 \text{ ft}^2$,

$U = .7 \text{ Btu/(ft}^2\ {}^oF \text{ hr)}$,

$T_i = 50^oF$, and

$T_o = 27^oF$

$Q_c = .7 \text{ Btu/(ft}^2\ {}^oF \text{ hr) x } 11{,}300 \text{ ft}^2 \text{ x } (50 - 27)^oF$

$= 122{,}102 \text{ Btu/hr}$

To calculate approximate infiltration heat losses (Q_i): compute the greenhouse volume (V) and choose the appropriate air exchange value (C) from Table 2. The same values for temperature apply as were used in the conduction heat loss calculation. The values obtained are:

$V = 51{,}100 \text{ ft}^3$

C = 1 air exchange per hr

$Q_i = .02 \text{ Btu/ft}^3\ {}^oF \text{ x } 51{,}100 \text{ ft}^3 \text{ x 1 air exchange per hr x } (50^oF$

$= 23{,}506 \text{ Btu/hr}$

The total heat loss rate (Q_t) is found by summing the losses due to conduction with the losses due to infiltration:

$Q_t = Q_c + Q_i = 145{,}608 \text{ Btu/hr}$

For the greenhouse in this example, the heating system should be able to provide 160,000 Btu/hr (with a 10% margin of safety) in order to offset the energy losses that can be expected on the coldest winter day in Tallahassee, Florida.

Heating Systems

Once the heating requirement has been calculated, a heating system can be chosen that has the necessary capacity. There are many ways that this can be accomplished from the standpoint of equipment used, type of fuel used, and management practices followed. The system should be consistent with the type of greenhouse construction and the specific crop (or crops) to be grown.

Unit Space Heaters

Unit space heaters are normally fueled with natural gas or fuel oil and use fans for heat distribution. They are often suspended from the greenhouse superstructure, but are sometimes floor mounted. This type of system is relatively easy to install and requires a relatively moderate capital investment Although space heaters that burn propane or natural gas produce $C0_2$ which can be beneficial to plants, they can also produce combustion by-products (such as carbon monoxide and ethylene) that can be harmful to both people and plants. To avoid this potential problem, unit space heaters should be vented. Vent stacks should be adequately sized (follow the manufacturers' recommendation) and should extend at least four feet above the highest point of the greenhouse. Finally, a fresh air intake for each space heater sized to accommodate the unit's burner (usually 6-8 inches) is a necessity in tight greenhouses.

Hot Water Systems

Hot water systems utilize piping to provide perimeter or row heating that relies on natural convection to distribute warmed air. Hot water can also be used in overhead fan forced heating systems. Hot water systems require a boiler, valves, and a pressure/temperature regulated control system. Steam systems are more complex to install and require more maintenance than hot water systems. Although the pipes in hot water systems are slower to heat and to cool than in a steam system, temperatures are usually more uniform.

Steam Heating Systems

Steam heating systems require a boiler, valves, traps, and a control system that varies in complexity depending on the type and size of boiler used. Steam provides rapid heating and cooling of the steam lines and requires less pipe than a hot water system. Lines can be smooth or finned and can be used with fans to provide more even distribution if required. Often with steam systems, about 1/3 of the piping is overhead and 2/3 of the piping is along the perimeter or sidewalls. Steam can be useful in soil production systems for sterilization of the soil. Steam systems require a high initial investment, but have a long life expectancy.

Poly-tube Systems

Poly-tube systems are frequently used in combination with any of the heating units already mentioned to provide more uniform heat distribution, air movement, and ventilation. When poly-tubes are used in a heating system, they are equipped with a heat kit which is a baffled inlet to the fan that inflates the poly-tube. Usually, there are two horizontal discharge heating units located a fixed distance away on either side of the baffle. When the controls (thermostat) call for heating, the unit heaters turn on and blow heated air into the open sides of the baffle. Once the air temperature is raised to the set point level the heaters stop, but the polyfan continues circulating air. These systems are also useful for dehumidification and ventilation with outside air.

In most large (single or gutterhouses), it is best to provide heat via a polyethylene convection tube running the length of the house. The tube is inflated by a jet fan which receives heated air from the heat source and blows the heated air into the house through the convection tubing. Placement of the heat distribution tubing should be carefully considered. Traditionally, the tubing consists of one large, 30-inch-tube running the length of the greenhouse from the jet fan to the opposite end of the house. This tube is generally about 8 feet above the ground. As a result, heat is discharged above the plant canopy and much heat is used raising air temperatures high in the greenhouse. A better approach would be to discharge the heated air into small 8-inch poly tubes placed on or near the floor under the plants. Heat then rises into the plant canopy. This system in Florida has also proven to be effective at reducing foliar diseases in tomato and improving fruit quality. Adding a thermal curtain above the trellis in the system can help reduce energy costs.

Heating can be from liquid propane, natural gas, steam, etc. In a single stand-alone house, it is a good idea to use two small heaters, one on each side of the jet fan instead of one large heater. In this system, freezing of the plants is less likely in case a heater fails. In the double heater system, one heater is controlled so it will turn on when the temperature in the tomato plant canopy drops to 65°F. The other heater is set at 62 or 63°F. If the heaters are sized correctly, the greenhouse temperature should not fall below 62°F.

Ventilation

As a practical matter, the only economical methods for cooling greenhouses involve ventilation which means exchanging greenhouse air for outside air. Ventilation can be either naturally driven by wind and/or temperature gradients (hot air rises) or mechanically created by using fans. Although there are several reasons for warm weather ventilation, the most obvious purpose is for the control of high temperatures. A properly sized ventilation system can prevent the air temperature inside the greenhouse from rising too high above the outside air temperature. The reason for the high temperatures is the influx of solar radiation through the greenhouse glazing material. The ventilation system must effectively move air directly through the crop and over the floor to prevent excessive temperature buildup around the plants. A generally accepted rule of thumb for Florida greenhouses is that at minimum, a ventilation system must be able to provide one air exchange per minute.

Figure 2 shows the relationship on a clear summer day between ventilation rate and temperature increase across the 120-ft long double poly greenhouse shown in Figure 1. The graph shows that as the air exchange rate increases, temperature rise is reduced and the difference between inside and outside air temperature decreases. It would be easy to conclude that the more ventilation available the better, but the disadvantage of providing increased ventilation capacity is the increased cost for fans and accessories, as well as increased operating expenses. It should also be noted that regardless of how high the ventilation rate goes, the inside air temperature will always exceed the outside air temperature. To obtain greenhouse temperatures lower than outside values requires the use of evaporative cooling or some other supplemental means of conditioning the air.

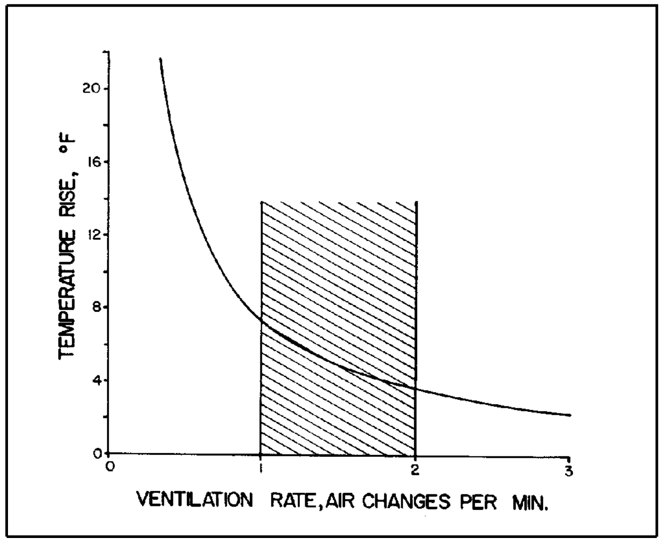

Figure 2. A comparison of ventilation rates and greenhouse temperature rise.

If ventilation is to be used effectively in Florida to moderate high temperatures then fans must be used; natural ventilation is not dependable enough in most situations. To select the correct size and number of fans, the total volumetric flow rate of air to be moved must be calculated. The volume of air to be moved is calculated from the air changes per minute (or hour). One air change is equivalent to the volume of the greenhouse. For example the structure in Figure 1 has a volume of about 51,100 ft^3, therefore one air exchange per minute would correspond to 51,100 cfm (ft^3/min). The volume of a particular house is calculated by multiplying the cross sectional area of one end wall by the length of the greenhouse.

In selecting fans, use only those rated in accordance with AMCA (Air Moving and Conditioning Association) standards. This rating specifies the volume capacity of a fan versus a static pressure of .125 inches H_2O. Fans are tested under these standard conditions so that all fans are rated on an equal basis. This allows the buyer to compare performance data without having to adjust for different test conditions. A fan is an air pump, a machine that creates a pressure difference and causes air to flow. There are two common types of fans that differ in the direction of air flow: axial flow and centrifugal flow. Axial flow propeller fans are the type most commonly used for general ventilation applications and other low static pressure situations.

When choosing a ventilation fan, the following information is necessary. First, as already indicated, the volume of air to be moved per unit time must be calculated. Second, the static pressure (the system resistance to air flow) must be estimated. In most cases greenhouse static pressure resistance is between .07 and .10 inches. For houses with evaporative cooling pads, static pressure due to the pads must be added to the greenhouse static pressure. Estimates should be available from the pad manufacturer. Third, for efficiency, select the fan that delivers the required volumetric flow rate (cfm) at the estimated static pressure with the lowest horsepower requirement. Finally, there are economic considerations. If the most efficient fan costs much more than the nearest competitor then the trade-off between fixed investment costs and variable operating costs will have to be evaluated.

Some other important considerations in sizing and installing fans are as follows:

- If it is necessary to face the fans into the prevailing summer winds, increase fan cfm capacity by 10% with a corresponding increase in fan motor horsepower.
- All fans should be equipped with automatic shutters for weather protection and to prevent backdrafts when the fans are not in use.
- When fans from two adjacent houses are close to each other and exhaust into the same area between the houses, they should be offset from one another to avoid blowing directly against each other.
- Fans should be properly screened and guarded to safeguard personnel from coming in contact with any moving parts (fan blades, pulleys, and belts).
- Exhaust fans should not be spaced more than 30 ft apart.

Evaporative Cooling

With ventilation alone, greenhouse temperatures can only be lowered to near outside levels, but with the addition of an evaporative cooling system, greenhouse air can often be kept below ambient temperatures. Evaporative cooling works on the principle that at a given temperature the air can hold a certain amount of water vapor. Relative humidity is the percentage of the total water vapor that the air can hold that is actually in the air. When the air is holding all of the water vapor that it can, it is saturated and its relative humidity is 100%. If air with a relative humidity of less than 100% comes in contact with water then some of the water will evaporate into the air. The phase change from water to vapor (evaporation) requires energy (the latent heat of vaporization), this energy is provided by the air causing its temperature to go down. An evaporative cooling system is comprised of fans for moving the air through the greenhouse and some means of facilitating the evaporation of water into the airstream. Two systems are commercially used, wetted pad and high-pressure fog systems.

Wetted Pad Systems

Wetted pad systems are composed of porous material from 2 to 6 inches thick installed along the greenhouse wall opposite the exhaust fans. Air entering the greenhouse is pulled horizontally through the porous pad material. An upper gutter evenly distributes water to the tops of the pads. Ideally, as the water moves down through the porous pads it spreads over all of the pads' surfaces. As outside air is pulled through the porous material, it comes into close contact with the pads' considerable wetted surface area which greatly facilitates evaporation. If "perfect contact" between the air and the wetted surfaces were possible, then the system would be 100% efficient and the air leaving the pad would be saturated. In practice, the most efficient systems provide about 85% of potential cooling.

The exact amount of cooling depends primarily on the temperature and relative humidity of the outside air. The relationship is not completely straightforward because as temperature goes up, so does the air's water vapor holding capacity. Table 4 shows some comparisons of temperature, relative humidity, and cooling potential. The values in the table show that in terms of cooling, the higher the relative humidity, the lower the potential and for a given relative humidity, the higher the temperature, the greater the potential. The table also gives values for the cooling that can be expected from an efficient wetted pad system. For example, at 95°F and 70% relative humidity, the potential temperature drop is 8.9°F (to 86.1°F), for an 85% efficient evaporative cooling system the actual drop is 7.6°F. So, the temperature of the air leaving the pads and entering the greenhouse would be about 87.4°F.

Table 4. Cooling potential for different temperatures and humidities.

Temp °F	Relative Humidity %	Temperature Drop °F 100%		Temperature Drop °F 85%	
95	90	2.8	(92.2)	2.4	(92.6)
	70	8.9	(86.1)	7.6	(87.4)
	50	15.9	(79.1)	13.5	(81.5)
90	90	2.6	(87.4)	2.2	(87.8)
	70	8.4	(81.6)	7.1	(82.9)
	50	15.0	(75.0)	12.7	(77.2)
85	90	2.5	(82.5)	2.1	(82.9)
	70	8.0	(77.0)	6.8	(83.2)
	50	14.1	(70.9)	12.0	(73.0)

There are many types of pads ranging from low-cost random aspen chip pads to expensive, high efficiency (85%) cellulose pads. Using the greenhouse shown in Figure 1, the following example demonstrates the general procedure for calculating the crossarea of pad material required to provide a specified level of cooling. Since the length of the pad wall is limited to 36 ft, the actual design problem is to decide on the height of the pads to be installed. To calculate the height, the performance characteristics of each material are needed. Specifically, each type of pad has an associated design velocity; values are given in Table 5 for three different types of materials; a 4-inch cellulose product, a 6-inch cellulose product, and aspen chip pads. Required pad height is computed as follows:

Pad Height = Air Flow Rate / (Pad Length x Design Velocity) (3)

where pad height and length are in ft, air flow rate is in ft 3/min (cfm), and the design velocity is in ft/min (fpm). For this example, assume that the air flow rate is one air exchange per minute; for the greenhouse in Figure 1 shows that is 51,100 ft^3/min. Given the pad length of 36 ft and the three design velocities, the heights for the different materials range from 8.5 ft for the aspen pads to 3.7 ft for the 6- inch cellulose pad.

The degrees cooling can be calculated by multiplying the degrees of potential cooling by the pad efficiency. For example, given outside air entering the pads at 90°F and 50% relative humidity, the potential cooling from Table 4 is 15°F. Therefore, using the efficiencies in Table 5, 10.3°F cooling could be provided by the 4-inch cellulose, 11.0° by the 6-inch cellulose, and 11.6°F by the aspen pads. In choosing among these materials the initial cost, required wall space, and life expectancy must be factored into the business plan for each individual greenhouse.

Other considerations in designing and installing a pad system are as follows:

- When possible, locate the pads on the prevailing summer wind side and the fans on the downwind sides of the greenhouse.
- The exhaust fans should not discharge toward the pads of another house unless they are at least 50 ft apart.

- The maximum practical distance from pad to fan should not exceed 200 ft with distances below 150 ft being more effective.
- The pads must be arranged in a continuous section along the entire wall opposite the exhaust fans, a gap such as a doorway can cause a "hot spot" up to eight times the width of the gap.
- Provide shutters for closing the pad section during times when heating is required instead of cooling.
- Construct a tight house and keep it tight, do not leave doors or vents open when the pad system is operating because air moves along the easiest flow path.
- Provide screens on the pads to keep out insects.

Table 5. Performance characteristics for three evaporative pad materials.

	4" Cellulose	6" Cellulose	Aspen
Design Velocity (ft/min)	250.000	380.000	165.000
Static Pressure (in H_2O) Pad	0.026	0.067	0.065
Pad and Greenhouse	0.126	0.137	0.135
Efficiency	68.5%	73.5%	77.0%
Life Expectancy (yrs)	5 - 10	5 - 10	.5 - 2
Example Calculation Height (ft)	5.6	3.7	8.5
Cooling Degrees (^oF)	10.3	11.0	11.6

Fog Systems

Fog systems operate under high pressure to generate a large percentage of tiny water droplets that remain suspended in the air rather than falling as mist droplets do. To obtain fog requires specially designed nozzles and pressures between 500 and 1000 psi. Ideally, the fog droplets remain suspended in the air until they evaporate. For this reason a fog system has the potential to provide a very efficient means for evaporatively cooling a greenhouse. Lines of nozzles can be distributed across the length of the greenhouse and operated in stages to achieve very even humidity distribution. As with the evaporative pads, high pressure fog systems must be operated in conjunction with ventilation fans.

High pressure fog systems are much more sophisticated than evaporative pad systems and require considerably more maintenance. Reliability of components can vary often as a function of price. The factor that accounts for most failures is water quality. Purity of water varies considerably among locations and each water source should be tested and handled according to recommended test results. With very few exceptions, water must be treated. A combination of filtration and chemical treatment is usually required to keep fog systems operational. Failure to properly evaluate water quality and treatment requirements before installation would be unwise.

High-pressure fog systems are relatively new, although more than 100 systems have been installed in the state in the last several years. Properly designed, installed, and operated, fog systems can be the most efficient method for evaporatively cooling greenhouses. Initial investment and maintenance requirements are high and essential.

Shade Systems

Fan and evaporative cooling systems are acceptable systems for greenhouse ventilation for some of the growing season. However, for the early fall planting season and for the late spring harvest period, additional measures are needed to control excess heat buildup in the greenhouses. Excess heat (above 85°F) can contribute to several growth and fruit ripening problems, as discussed in Volume 3.

During these periods, when the radiation load on the greenhouse is in excess of what the evaporative cooling system can handle, shading of the plants is needed. There are basically two approaches: shade paint and shade cloths. The white shading compound is applied to the outside of the poly greenhouse cover. The shade cloths can be applied over the house or applied within the house on a trellis system.

It is apparent that Florida growers will require a combination of both over-house and inside shading systems. Neither one alone seems to effectively control heat buildup. The problem with the sole use of a shade cloth inside the house at plant level is that excess heat above the cloth is drawn down into the growing area by the exhaust fans. The problem with using the shade compound paint or single cover over the house is that heat buildup still can be a problem because heavy shading is needed and the light level can drop below optimal levels. Another problem with the shading paint compound is that it is an "all or nothing" approach and cannot be "off and on" during low and high sunshine conditions as with the shade cloths.

A workable system to provide needed shade would include shade cloths on cables that could easily be deployed or removed depending on the light level (weather conditions and season). One idea would be to deploy a shade curtain that follows the contour of the house ceiling that could be drawn up on sunny days or dropped on cloudy days. This cover would obviate the need to paint the outside of the house. This inside curtain might also be better than placing a cover over the outside of the house which would be subject to wind damage.

The inside ceiling contour curtain would be supplemented by an above-plant curtain or cloth placed on a trellis system just above the plants. The ceiling curtain would knock down the heat buildup above the plant curtain. The plant curtain would provide additional shading and help provide for increased fan efficiency in drawing cooled air from the pad through the house. The ceiling curtain could be supplemented by "attic" fans and perhaps a fog system to remove hot air from the ceiling area of the house.

Producing vegetables in greenhouses in Florida in fall and spring is an extreme challenge. Dealing with heat buildup requires that fairly drastic measures be taken to remove heat. If heat cannot be effectively controlled, then growers should consider ceasing production during the June-through-September period.

Horizontal Air Flow Fans

When the large ventilation fans are not operating, smaller horizontal air circulation fans can provide more uniform humidity, temperature, and CO_2 in the greenhouse to ensure more consistent performance by plants throughout the house (Fig. 3). Air circulation can also minimize the formation of free water on plants to prevent the development of disease organisms and can prevent condensation on the inner glazing surface.

There are two main systems typically used to provide horizontal air circulation in greenhouses. These are the fan tube system and the high volume, low velocity fan system. The fan tube system takes air from one end of the greenhouse and distributes it through the crop down a perforated poly tube. Fresh, outside ventilation air can be supplied to the tube for small adjustments in greenhouse air temperature and humidity. This system as described above can be used in conjunction with heaters for even distribution of warm air. The tubes can become dirty and can reduce light transmission. In general, the tubes must be replaced annually.

The low speed, high volume fan system distributes air by setting up a general air circulation pattern in the greenhouse. The system consists of one or more fans moving air the length of the greenhouse. When more than one bay is involved, the fans are oriented in alternating directions to promote air flow throughout the house. The fans cast very little shadow and require little maintenance.

CO_2 Injection

The benefits of adding CO_2 to the greenhouse environment are well known. In particular several

Figure 3. Horizontal air-flow fans circulate air inside the greenhouse creating more uniform environmental conditions.

vegetable crops including cucumbers, lettuce, and tomatoes respond consistently well to carbon dioxide enrichment. CO_2 is required for photosynthesis (also called carbon assimilation) during which green plants use energy from sunlight to convert CO_2 and water into sugars. These sugars are then used by the plant for growth and maintenance. In supporting these processes, some of the fixed carbon dioxide is released back into the air as the sugars are "burned up" to release energy in the process of respiration. The difference between photosynthesis and respiration is the basis for dry matter accumulation in the plant. This is important to the grower because in general terms; the more dry matter that accumulates, the greater the growth and the greater the yield.

Through the process of diffusion, CO_2 enters the plants through small holes in the leaves (called stomata). The rate at which carbon dioxide is photosynthetically fixed in the leaves depends on the concentration of CO_2 inside the leaves, which in turn depends on the concentration of CO_2 in the air. Therefore, increasing the CO_2 levels in the air around the outside of the leaves will increase the rate of CO_2 uptake and growth.

Outside air normally contains about 340 parts per million (ppm) of CO_2 by volume (.034%). In general, plants grow well at this level of CO_2, but will respond by producing more sugars if levels are higher. In a closed greenhouse during the day the plants use carbon dioxide, causing levels to fall below 340 ppm and reducing photosynthesis. In new tightly constructed, double-glazed greenhouses which have very low leakage rates, the drop in CO_2 concentration can be especially significant and have a very negative effect on production. Although ventilation can bring levels close to 340 ppm, only supplemental injection of CO_2 can actually raise levels inside the greenhouse to levels higher than the outside air. As a rule of thumb CO_2 concentrations above 1300 ppm are of diminishing value for most crops. A lower level (800ppm) is recommended for raising seedlings (tomatoes, cucumbers, and peppers), as well as for lettuce production.

Burning gas to obtain carbon dioxide produces heat as a by-product which can be an advantage in northern greenhouses, but may prove to be a problem in Florida. For warm weather CO_2 injection, compressed liquid CO_2 can be used without generating unwanted heat. Liquid carbon dioxide also has several other advantages over fossil fuel systems. It is relatively pure, it contains no sulfur and avoids the problem of incomplete combustion. Also, its use neither produces water vapor nor causes "hot spots" near burners. Furthermore, maintenance of a liquid CO_2 injection system is low compared to a burner system. The disadvantage is that the price of liquid CO_2 is typically higher than propane or natural gas.

If elevated CO_2 levels are to be maintained in a greenhouse there are two factors to consider in calculating the amount of CO_2 required to maintain desired levels. Natural air exchange (1eaks) and photosynthesis in the greenhouse reduce elevated CO_2 levels. Leaks exchange the enriched greenhouse air for ambient (outside) air at 340 ppm. Of course, with fan ventilation the exchange losses can become very large. Photosynthetic rates depend mainly on the crop and light level. As a rule, offer a well developed crop under high light about .5 lb/hr/1000 ft^2 of greenhouse floor area is a reasonable estimate of the maximum plant CO_2 uptake rate.

Since CO_2 is taken into the plant by the leaves, it is important to place CO_2 sensors in the plant canopy (best placement would be about 2/3 up from bottom of plant). CO_2 should be injected into the area around the plant canopy also, not into the airspace above the plant. Therefore, it is important not to locate the sensor near an emitter on the CO_2 line. One sensor per house is generally adequate to monitor CO_2.

CO_2 should be added only during the day since plants must have light in order to make use of it. It should also be clear that CO_2 injection is most efficient when the greenhouse is closed. It does not make sense to try to maintain high levels of CO_2 when the ventilation fans are flushing the house out too quickly. The ideal time to use CO_2 is when it is cold and clear. In Florida, winter temperatures are so mild that vegetable production greenhouses are often ventilated during the day. For this reason CO_2 injection is generally not critical for Florida. Therefore, Florida growers, especially those in peninsular Florida should carefully consider whether CO_2 injection will be of benefit.

More Information

For more information on greenhouse crop production, please visit our website at http://nfrec-sv.ifas.ufl.edu.

For the other chapters in the Greenhouse Vegetable Production Handbook, see the documents listed below:

Florida Greenhouse Vegetable Production Handbook, Vol 1

Introduction, HS 766

Financial Considerations, HS767

Pre-Construction Considerations, HS768

Crop Production, HS769

Considerations for Managing Greenhouse Pests, HS770

Harvest and Handling Considerations, HS771

Marketing Considerations, HS772

Summary, HS773

Florida Greenhouse Vegetable Production Handbook, Vol 2

General Considerations, HS774

Site Selection, HS775

Physical Greenhouse Design Considerations, HS776

Production Systems, HS777

Greenhouse Environmental Design Considerations, HS778

Environmental Controls, HS779

Materials Handling, HS780

Other Design Information Resources, HS781

Florida Greenhouse Vegetable Production Handbook, Vol 3

Preface, HS783

General Aspects of Plant Growth, HS784

Production Systems, HS785

Irrigation of Greenhouse Vegetables, HS786

Fertilizer Management for Greenhouse Vegetables, HS787

Production of Greenhouse Tomatoes, HS788

Generalized Sequence of Operations for Tomato Culture, HS789

Greenhouse Cucumber Production, HS790

Alternative Greenhouse Crops, HS791

Operational Considerations for Harvest, HS792

Enterprise Budget and Cash Flow for Greenhouse Tomato Production, HS793

Vegetable Disease Recognition and Control, HS797

Vegetable Insect Identification and Control, HS798