Introduction

Ventilated greenhouses frequently become too warm when high levels of solar radiation occur. Under normal conditions, the inside temperature in a greenhouse during a warm summer day will exceed the outside temperature, the magnitude of excess being dependent on the magnitude of solar energy entering the greenhouse, the efficiency of the ventilation system, and the rate of ventilation. Though shading can help limit the temperature rise by reducing the solar energy entering the greenhouse, the remaining energy which enters represents a heat input to the house which results in an increase in the inside temperature. If temperatures near or slightly above the normal summer temperatures are above those considered acceptable, some form of cooling must be provided.

To cool interior greenhouse temperatures, water evaporation systems which not only cool the air but also increase the humidity are preferred to mechanical (refrigeration) cooling systems. The humidity is important due to its effect on the rate of water loss from plants. The lower the humidity, the greater the water loss from the plants, and hence the greater the probability of wilting. A cooling system which reduces the air temperature and which simultaneously increases the relative humidity would therefore work best. An evaporative cooler which cools by utilizing the heat in air to evaporate water operates in this manner.

Mechanical refrigeration (conventional residential air conditioning) has the disadvantages of reducing humidity levels and being extremely expensive due to the large amount of solar energy which enters a greenhouse. A greenhouse with a good clean covering material has a potential heat input of approximately 300 BTU/hr. per square foot of interior floor area. This means that a ton of mechanical refrigeration capacity (12,000 BTU/hr.) would be required for every 40 sq. ft. of floor area. Even when shading compounds are used which reduce the solar energy transmission 50%, a ton of capacity is required for every 80 sq. ft. of floor space.

Theory of Evaporative Cooling Systems

An evaporative cooling system is a system which moves air through a screen or spray of water in such a manner that evaporation of water occurs. Approximately 1000 BTU of heat are required to change one pound of water from liquid to vapor. If the evaporation heat comes from the air, the air is cooled. The maximum cooling which can occur is limited by the ability of air to hold water in vapor form. The measure of the amount of water held by air in comparison to the maximum amount it can hold is called the relative humidity. A relative humidity of 50% means the air is holding one-half of the maximum amount that air can hold at that temperature.

Well-designed evaporative coolers are constructed to operate at an efficiency of 85% or better. In other words, they can cool the air 85% of the difference between its original temperature prior to cooling and the coolest temperature which could be achieved. The cooling which can be achieved with an 85% efficient unit for various outside
temperatures and humidities is shown in Figure 1. As shown in the figure, the lower the outside humidity, the greater the cooling which can be achieved. The curves show that air at 90°F with an initial humidity of 50% can be cooled to 77°F with a well-designed evaporative cooler. When the humidity is 70% the air can only be cooled to 83°F.

![Figure 1. Cooling potential of 85% efficient evaporative cooling systems.](image)

Fortunately, ambient relative humidities tend to be low during the hottest weather periods. Even in areas considered to have high daily humidities, the relative humidity is generally between 50 and 60% and often less during the warmest days. In regions of the United States such as the south-west, even lower humidities are common.

As mentioned, when high humidities do occur in conjunction with high temperature, the amount of cooling which can be achieved is reduced; but, correspondingly, on these days the transpiration potential of the plants is less, due to the high humidities. In other words, an evaporative cooling system provides maximum cooling when temperatures are highest and when the air is lowest in humidity (drying potential the greatest), and it provides the least amount of cooling when it is needed least.

Though an evaporative cooling system may well cool the air entering a greenhouse to a desirable level, it must be realized that solar heat will still be entering the house and therefore a temperature rise within the house will occur. In greenhouses with well-designed ventilation systems which provide one air change per minute, a temperature rise of 10°F can be expected as air passes through the greenhouse. With lower air flow rates, or with houses not fully occupied with plants, higher temperatures can be expected. It is for this reason that air change rates of at least one house volume per minute are generally recommended when evaporative cooling system are used in a greenhouse (1CFM per cubic foot of house volume).

**Fan and Pad Cooling Systems**

The most commonly used cooling system in greenhouses is the fan and pad cooling system. With this type of a system, fans are placed in one wall of a greenhouse and pads are in the opposite wall. To achieve a cooling efficiency of 85%, at least 1 sq. ft. of pad area should be provided for each 150 CFM of air moved by the fans. The pads are normally about 2" thick and are of a coarse shredded wood fiber; however, other materials have been used successfully. The material must be such that, when it is wetted, a complete water film *does not* form, thereby blocking air from entering the house. For this reason, multiple layers of cloth materials have not proven successful.

The pads are generally enclosed in a welded wire mesh and are wetted by running a pipe with closely spaced holes above the top of the pads as shown in Figure 2. The holes in the pipe are usually oriented so the water runs against a sheet metal spreader directly above the center of the pads. Standard rain gutters with holes in the bottom of the gutter have also been used to distribute water along the length of the pad.

A collection gutter is placed below the pads to catch the excess water which is not evaporated. To assure wetting, about 1/3 gallon of water per foot of pad length is normally recirculated. However, a valve is usually placed in the line from the pump so that the flow to the distribution pipe can be adjusted. The water collected by the bottom gutter is returned to a sump from which water is pumped to the upper distribution pipe or gutter. The sump should have about 1 to 1 1/4 gallons of capacity for each linear foot of pad in order to hold the water which drains back to the sump when the system is stopped.

The fans in the wall opposite the pads are normally mounted at any convenient height. When fans are placed in the long sidewall of the greenhouse, the fan spacing is limited to 25 to 30 feet apart. This is to prevent dead warm dry spots in the plant growth area between the fans. The total number of fans required can be determined by dividing the house length by 25 or 30 feet. When placed in the end-wall as shown in Figure 3, any number of fans can be used.

The total fan capacity is determined by computing the house volume. For one air change a minute, this is the total fan capacity in CFM at 1/8 inch static water pressure. If some other air change rate is selected, the house volume is multiplied by the desired air change rate to obtain the fan capacity. The total capacity is divided by the number of fans to be used to obtain the capacity for each fan.

An anti-back-draft shutter is normally installed in front of the fans to prevent air from entering the greenhouse when the fans are not running. The fans should preferably be installed so that prevailing winds do not blow against them. Fans ventilating one house should not discharge air directly towards pads or air inlets for another house. When
Figure 2. Pad arrangement for fan-and-pad cooling system. Sump should be large enough to take all run-off when pump is turned off.

The fans will create a small vacuum in the house, and air will enter the house through any openings, including cracks between glass panes. Since air which enters through openings other than the pads will not be cooled, a greenhouse must be in good repair to be effectively evaporatively cooled with a fan and pad cooling system. Well constructed, tight fitting doors must also be provided.

The pads should be continuous in the opposite wall with no gaps. The top of the pad should preferably correspond to the top of the plants grown in the greenhouse. The pads must not sag and the water distribution system must keep the pads uniformly wet at all times (no dry spots).

A means for preventing air flow through the pads in cold weather must also be provided. Normally this is done by placing the pads inside end or sidewall vents, as shown in Figure 4, and then manually opening the vents when cooling is needed. For large pad areas in the end-walls, hinged panels are sometimes fabricated. These panels would normally be covered with glass or fiberglass.

The pads can also be placed outside the side or end-walls in a false wall. This allows the standard end or side vents to be used. The area between the pad wall and the greenhouse must be tightly enclosed so that any air pulled...
into the greenhouse has to be pulled through the pads. A disadvantage of this arrangement is the inability to keep rainwater off the pads, which in turn can result in overfilling the sump. Since algacides are generally used in the recirculating water to control algae growth on the pads, overfilling of the sump results in a loss of the algacide. Pads are sometimes mounted horizontally adjacent to the house in a suitable framework and wetted by spray nozzles. This permits providing greater surface area, such as for the end of Quonset type buildings. The problem with rainwater also exists with this arrangement.

Other than small, package-type coolers, which are described later, the installation of pads in an enclosure on the suction side of fans discharging air into the house (pressure fans) has not worked well. One problem is heat build-up in the enclosure between the pads and the fan due to the sun shining on the enclosure. Another problem is uniformly distributing the cooled air discharged by the fan. Localized warm spots often occur.

**Mist Cooling Systems**

A cooling method which has been used by a few greenhouse operators is to use some form of water spray nozzle to provide a fine mist of water droplets within the greenhouse space as shown in Figure 5. As the droplets fall towards the ground, evaporation with cooling occurs. Two problems exist with such systems. One is how to economically obtain very fine droplets which will fully evaporate before the drops fall and wet the foliage or ground.

A number of different types of nozzles have been tried, but the most commonly used are high pressure nozzles (150 to 200 psi). To achieve high pressure of this magnitude, a high-pressure pump must be used. The nozzles with such systems have a very fine orifice and, consequent-

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**Figure 4.** Manually operated fiberglass covered panels for closing the pad end-wall during cold weather.

**Figure 5.** High pressure mist nozzle for evaporative cooling within the plant growing space.
Yet in spite of these disadvantages, fine mist cooling systems have been used with fair results both from a viewpoint of the temperatures obtained and the improved plant growth and quality produced. Coarse mist systems have been totally ineffective.

Package Unit Evaporative Coolers

Package unit evaporative coolers are available. These consist of a centrifugal pressure fan which discharges air into the greenhouse as shown in Figure 6. Outside the fan, thin pads are placed in the walls of an enclosure. A pump in the unit distributes water to the pads. Excess water drains into the bottom of the enclosure which serves as a sump. The air handling capacity of the units such as these is 2,200 CFM to 21,000 CFM.

Figure 6. Schematic drawing of a unit-evaporative cooler which can be installed in the sidewall of greenhouses.

The problem with these units is to provide uniform distribution of the cooled air which is discharged into the house. Normally units are installed in one or both sidewalls of the greenhouse. The closer the units are spaced along the sidewall of the greenhouse, the less the problem with uniformity of air distribution. Because of the problems with air distribution, package coolers are most frequently used in small, hobby-type greenhouses.

As cooled air is introduced into a greenhouse, it must displace air already within the house. It is therefore necessary to crack vents or to install motorized back-draft shutters in the side or endwall. One square foot of vent area should be provided for each 1000 CFM of fan capacity.

Evaporative cooler units must receive periodic maintenance for reliable, consistent operation. Rusting is also a problem with such units.

Summary

Cooling in greenhouses should be some form of evaporative cooling since mechanical refrigeration is too expensive and such units reduce relative humidities, thereby increasing water loss from plants. The most common type evaporative cooling system is the fan and pad system. Such systems have high efficiency over a wide range of temperatures and ambient humidities.

With any evaporative cooling system air change rates (ventilation rates) must be kept near one air change per minute. If air change rates are reduced below this level, temperature rises within the house become too large. Shading can be used in conjunction with cooling to reduce the solar energy entering the house and thereby reduce the temperature rises within the house; however, some temperature rise will always occur. Effective temperature control during the summer will therefore depend upon the performance of the cooling system.