ENVIRONMENTAL CONTROL OF GREENHOUSES

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Environmental control of greenhouses includes control and modification of day and night temperatures, relative humidity, and carbon dioxide levels for optimum plant growth. Extremes of temperatures and humidity are encountered during winter and summer. A well-designed production facility will normally provide an environment with temperature set points between 55 and 85°F, with humidity levels high enough to reduce water stress and low enough to discourage disease and fungus outbreaks in the crop. When CO_2 enrichment is required, 1000 μmol/mol (ppm) is often considered the desired target level.

HEATING CONSIDERATIONS

The purpose of the heating system is to replace energy lost from the greenhouse when outside temperatures are lower than desired in the greenhouse growing area. Ideally the heating system should have a variable output capable of matching the changing heat load caused by the outside weather conditions.

Heat is transferred by conduction, convection, and radiation. Conduction is the transfer of heat through a solid material, for example a wall, or from one solid to another that are in contact with each other, such as from an electric stove element to a teapot resting upon it. Convection is the movement of heat through a fluid or from a solid surface to the fluid by mixing of one parcel of fluid with another, such as occurs in transferring heat from the metal stovetop to the water in the teapot. The energy is supplied to the teapot by conduction but the transfer that occurs in the teapot to the water is by convection. Convection is also the primary mode of heat transfer to a room from a radiator. Warm water within the radiator heats the surface that in turn heats the air adjacent to the radiator surface. The warmed air rises, and heat transfer begins as convection causes the cold air to replace the warm air and be warmed in the process. Although it is commonly called a radiator, a better name for a room heater would be a 'convector'.

Radiation heat transfer depends on the differences of the fourth power (T^4) of the surface temperatures of the radiating and receiving objects. Therefore, radiation is most important when heat sources are at a high temperature, such as an open flame or a fireplace. During a clear night, the greenhouse can be thought of as a fireplace as it radiates to the very cold clear sky. Plain polyethylene film greenhouse glazing (i.e., not the so-called IR-treated film) is relatively transparent to radiation heat transfer so warm plants inside can actually radiate directly through the plastic to the cold sky. Glass and some other plastics are essentially opaque to infrared (thermal) radiation so the radiative heat loss is from the glazing to the sky and not directly from the plants to the sky. Radiation heat loss can represent 25% or more of the total heat loss for a double-layer polyethylene greenhouse on clear nights (Simpkins et al.)[(10)]. Condensation on either or both of the two layers of film can appreciably reduce the radiation portion of the heat loss since water, like glass, is relatively opaque to infrared radiation.

Infrared inhibitors are successfully being added to greenhouse polyethylene films and giving a significant decrease in the radiation portion of the heat loss. Simpkins et al.[(10)], under tests with similar greenhouses covered with conventional film and IR-treated film, found that an average 1/3 savings could be realized with IR greenhouse glazing. IR polyethylene greenhouse film is a popular choice for growers today. The added price of the film is more than offset by the energy savings possible. For a year-round production facility the additional cost is normally made up in the first growing season.

As with the use of an IR film the use of energy-saving curtains or thermal screens reduce the effect of radiation on plants and result in higher leaf temperatures relative to the air temperature in polyethylene glazed greenhouses, often eliminating condensation on leaves and a reduction in the potential for disease. All thermal screens greatly reduce the overall heat transfer from the greenhouse, and most provide for needed warm weather shading. Their impact in the design-heating load can be an added benefit as the design heat transfer coefficient for the greenhouse can be lowered assuming the curtain will be in place under design weather conditions. Other energy conservation systems can be treated in the same manner. A table of their effectiveness is found in NRAES 3.[9]

The heat loss from a greenhouse depends upon three parameters: (1) the surface area of the greenhouse, (2) the location of the greenhouse and crop to be grown, and (3) the greenhouse heat loss rate which is largely dependant upon the glazing material. Two of these are readily determined, and the third is an approximation depending upon the glazing and its condition and whether or not thermal screens are in place. Heat losses down to the ground are usually negligible relative to losses to the atmosphere. These are usually not included because the temperature difference between the greenhouse and soil is small and the heat transfer coefficient is relatively small.

The design heat loss in Btu/hour is calculated by multiplying the surface area of the greenhouse by the greatest expected temperature difference between inside and outside and the heat transfer coefficients of the glazing materials on the walls and roof. This design heat transfer coefficient includes the effects of infiltration and radiation losses as well as conduction and convection. As heat transfer coefficients vary with weather conditions and the published values are generally average values it is prudent to use a factor of safety in designing the greenhouse heating system capacity.

The surface area of a greenhouse can be readily measured. As mentioned earlier, floor area can be ignored. The design temperature differential (delta T) is determined from Weather Bureau records or experience for a certain location, and the lowest nighttime temperature desired for the crop being grown. Often this is a risk-management decision. For instance, if the site design temperature is 5°F and the temperature falls to 0°F for a few hours a year, the grower decides if the crop can take the few hours of a lower than desired temperature. The heat transfer coefficient, U-value, depends upon many variables but for normal design practice, most heating system designers use the values shown in the table below.

Heat loss equation: $Q = U * A * (T_i – T_o)$
Where:

Q = Size of the heating unit required in Btu/hr
U = Heat transfer coefficient in Btu/hr per ft^2 of surface per °F of temperature difference)
A = Surface area in square feet
$(T_i – T_o)$ = Inside nighttime temperature required for the crop minus the design outside temperature for the greenhouse location

Table 1. Heat transfer coefficients (U-values) for several common glazing materials.

Glazing Material	**Heat transfer coefficient (U-value) (Btu/hour per ft^2 per °F)**
Single (double) layer glass	1.1 (0.7)
Acrylic (twin wall)	0.6
Polycarbonate (twin wall)	0.6
Single (double) layer polyethylene	1.1 (0.7)
Double layer + energy curtain	0.3 - 0.5

Most greenhouses are either single- or double-glazed. Some triple-glazing materials are sold, but the loss in light caused by the third layer of glazing has severely limited their application. Double-glazing consists of either two layers of greenhouse-grade polyethylene film, double glass, or acrylic or polycarbonate structured sheets. Single glazing often consists of single glass, single film plastic, used mostly in warmer climates, or corrugated fiberglass or polycarbonate panels. Laboratory tests of each material indicate differing heat transfer coefficients.

Infiltration losses are often relatively low in plastic-film covered greenhouses, unless the house is very small, but may be very significant in older glass houses, particularly if the joints between glass panes are not sealed. For good environmental control practice, the heat transfer coefficients listed in Table 1 can be used for conservative design. These values include infiltration for well-constructed greenhouses. For older glass houses in poor repair, a larger coefficient would be used. Adding 10 percent to the glasshouse design load is normally adequate. If high humidity and disease appear to be a problem with very tight double-glazed structures, some designers also like to add 10 percent to the design load to provide for winter ventilation.

Thermal screens have variable properties, but reasonable design U-values for double-glazed greenhouses range between 0.3 and 0.5 Btu/hr per ft^2 per °F. For single layer glass houses, a value of 0.8 Btu/hr per ft^2 per °F is used. These coefficients normally apply only to the heat loss through the roof and not the area of the sidewalls, unless a thermal screen is used there as well. Also these coefficients include an allowance for infiltration and radiation loss.

SAMPLE HEAT LOSS DETERMINATIONS:

The heat load on any structure can be determined by calculating the exposed surface area (walls, roof, and ends) in square feet (not the floor area), ascertaining the greenhouse glazing material, and determining the crops to be grown. The type(s) of crop(s) will mandate the greatest expected temperature difference for the location. Thus, in order to calculate the expected heat loss that has to be made up for by the heating system: multiply the surface area in square feet, the expected temperature difference, and the appropriate heat transfer coefficient, and the result will be the greenhouse design heating load in Btu/hr. For example, the greenhouse illustrated in Figure 1 is used to grow roses that require a minimum 58°F nighttime temperature, and is located where the design outside temperature is 2° below zero, resulting in a design temperature difference of 60°F. The total surface area of the house is 4,312 square feet and it is glazed with glass (with a U-value of 1.1 Btu/hr per ft^2 per °F). The total heat load would be calculated as follows:

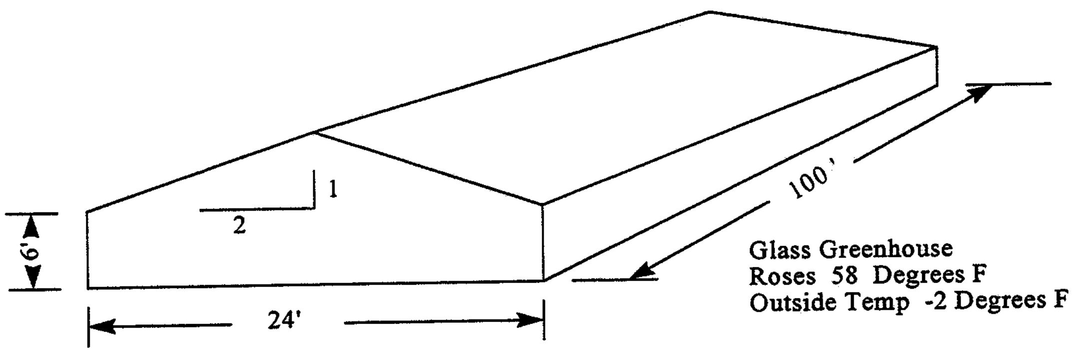

Figure 1. Dimensions of a sample rose greenhouse.

Heat loss equation: $Q = U*(A)*(T_i - T_o)$
L = Length of rafter = $\sqrt{5} * 12/2$, L = 13.4 feet
Area roof = 13.4 * 100 * 2 = 2,680 square feet Area of side walls = 6 * 100 * 2 = 1,200 square feet Area of end walls = (24 * 6) + (24/2 * 6) * 2 = 432 square feet Total area = 4,312 square feet
Delta T = $(T_i - T_o)$ = [58-(-2)] = 60°F
Q = (1.1) * (4,312) * (60) = 284,592 Btu/hr

If the greenhouse in Figure 1 were glazed with polycarbonate panels, the heat loss would be calculated in the same manner, using a U-value of 0.7 Btu/hr per ft^2 per °F. If only part of the greenhouse were glazed with polycarbonate, for example if the walls and the roof were glazed with glass, the appropriate U-value should be multiplied by the appropriate area (roof or wall) to determine the total heat load or loss.

These equations can be used to make an economic study of the value of double glazing. The cost of re-glazing or installing a thermal screen can be ascertained. The projected energy saved and the smaller heating unit can offset the cost of the double glazing over a period of several years. In the case of the thermal screen, the value of its shading ability must also be considered.

HEATING SYSTEMS

HOT WATER SYSTEMS

Traditionally, most glass greenhouses have been heated by steam or hot water, which is circulated through extensive piping systems throughout the greenhouse, normally located under the benches and along the side and end walls. Either finned or plain pipe has been used. In houses more than 30 feet wide, more uniform temperatures are achieved when heating pipes are placed on the exterior side and end walls with a heat delivery capacity equal to the design heat loss from those walls. The rest, with heating capacity equal to the design heat loss from the roof, are placed overhead and spaced uniformly across the width of the greenhouse. In gutter-connected or ridge and furrow greenhouses, heating pipes are placed overhead or under the benches with at least two runs placed near and under each of the gutters to assist in melting snow and ice in the gutter. This helps to keep the gutter free from ice, so that water will drain from the roof and not accumulate (Figure 2).

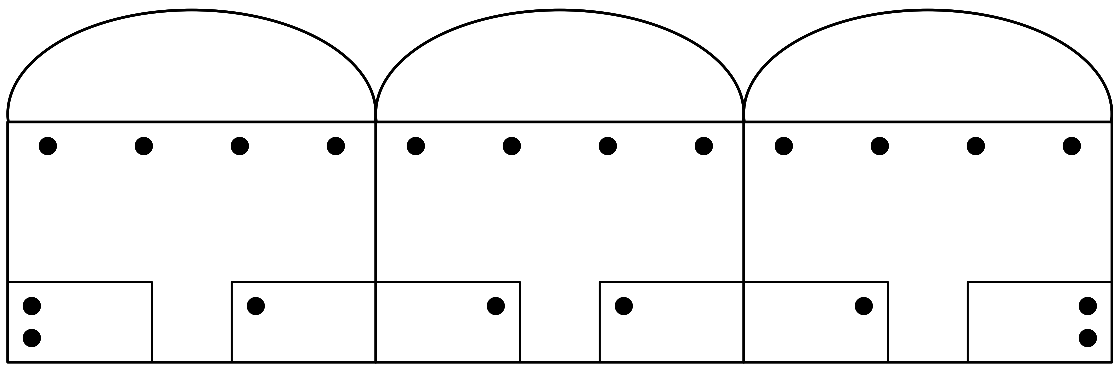

Figure 2. Typical installation locations for 2-inch heating lines.

Hot-water systems are preferred because they are more easily controlled than steam. The temperature of the water circulating in the hot water systems can be controlled to match the heat requirement at any given time. This provides more even heat than steam, which is either on or off. An advantage of steam lies in the fact that large quantities of energy can be carried long distances more efficiently than can be done by hot water. This can be an advantage if heat is needed far from the boiler. In situations like this, one can use steam to hot water heat exchangers in the greenhouse near the point of need, realizing the benefits of both systems, the steam to deliver the energy over the long distance from the boiler to the heat exchanger, and the hot water system to distribute the energy uniformly throughout the greenhouse.

Either three- or four-way mixing valves are used in most hot-water heating systems. These valves have several advantages. They provide water at the temperature needed at any time in any system in the greenhouse. This is most applicable in greenhouses with soil-heating systems and overhead pipe-heating systems. The soil heating system requires warm water, usually in the range of 80-120°F, and the overhead loop much hotter water when maximum heat is required, in the range of 180-200°F. Figures 3 and 4 illustrate the flow characteristics for systems using 3- and 4-way mixing valves. Using mixing valves, the water temperature in the system is controlled to maintain the desired greenhouse temperature. The circulation pumps often run continuously maintaining much more uniform temperatures than is the case with on/off circulating systems.

The heat output for finned pipe with 4-inch fins spaced closely together is approximately 900 Btu/hr per lineal foot, using a 180°F water temperature. Various fin configurations and sizes are available. Heat output data is often provided by the manufacturer. Plain 2-inch pipe is rated at 175 Btu/hr per lineal foot, using a water temperature of 180°F. In the example above, the system that required 285,000 Btu/hr would require approximately 1630 feet of 2-inch plain pipe to deliver the heat to the greenhouse. Since the greenhouse is 100 feet long, this would require 16 runs of pipe for the roof and sidewalls with an additional 100 feet on each end wall. The system would most likely be arranged with eight overhead lines and four lines on each side and end wall or a combination with some of the heating pipes under the bench if appropriate.

Standard 2-inch finned pipe has a high-energy output and should not be used under benches. High concentrations of heat cause the crop on the bench to dry out at different rates and ultimately cause uneven crop growth. Tow-inch finned pipe can best be used along exterior walls or locations of high heat loss. Low-output finned pipe specially designed for such applications can be placed under benches, usually in combination with low water temperatures.

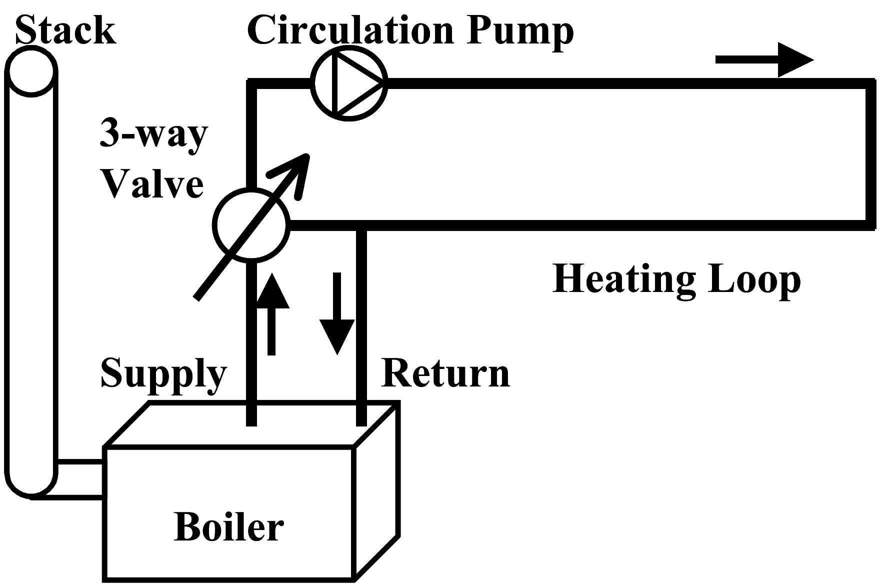

Figure 3. Typical installation of heating system with a three-way mixing valve.

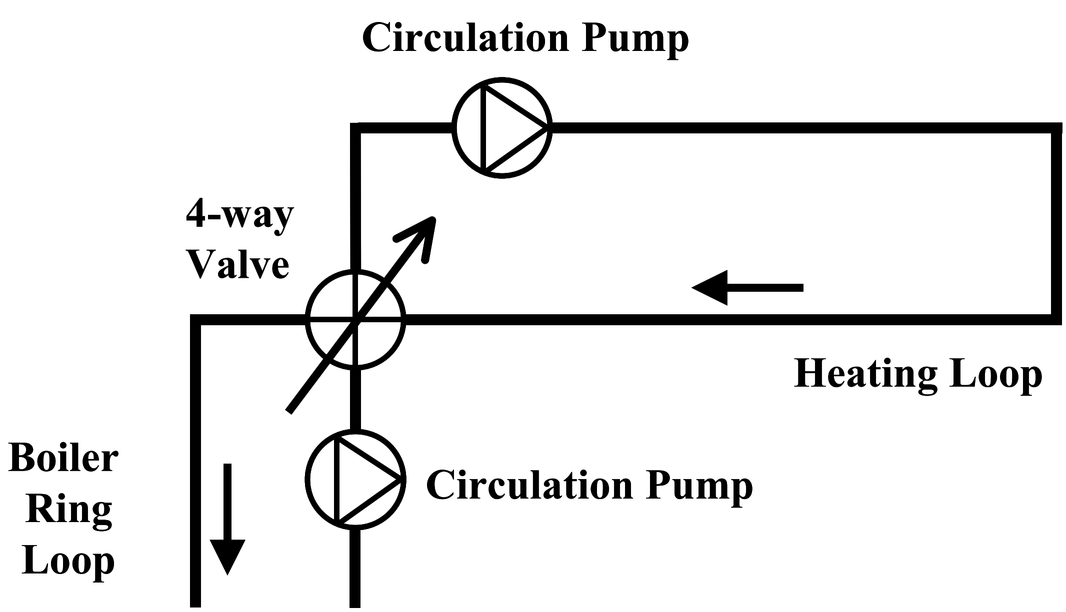

Figure 4. Typical installation of heating system with a four-way mixing valve.

HOT-AIR SYSTEMS

Most free-standing, plastic-covered greenhouses are equipped with warm-air heating systems because of the initial low cost and ease of installation, and because many are used only during portions of the year. These units burn oil, natural gas, or propane. The floor-mounted units often have movable outlets at the hot air output that can be rotated to direct the warm air throughout the greenhouse. Suspended gas fired units may be positioned strategically throughout the greenhouse to give more uniform temperature patterns. It should be noted that forced hot-air systems are inherently less efficient than modulated hot water systems discussed above.

When heaters or furnaces are located within the greenhouse, a small primary delivery air duct should be provided to deliver combustion air directly to the combustion unit. Modern plastic greenhouses are so tight that it is possible to use up the oxygen in the greenhouse and create a dangerous condition for workers. This duct should provide 50 square inches of inlet opening per 100,000 Btu/hour capacity of the heating unit. This ensures good combustion and can reduce operating costs. New hot-air heating units use the concept of separated combustion to ensure that the primary air supply for combustion is always adequate and comes from outside the building. In this type of heater construction, no interior greenhouse air passes through the combustion side of the heat exchanger. There has been some evidence to suggest that pesticide traces and the high humidity of the greenhouse environment have contributed to shortening the life of the heat exchangers used in hanging gas combustion units. Separated combustion has eliminated these potential problems and greatly increased the life of the heat exchangers in the combustion units.

NOTE: ALL COMBUSTION UNITS MUST BE VENTED to the outside with an approved exhaust stack that extends at least 24 inches above the highest point of the greenhouse or the highest adjacent building.

Exhaust gas may contain sulfur and traces of ethylene that are damaging to plant growth. A wind directional draft device should be attached to the top of the exhaust stack to prevent down-drafting during heavy winds. The new separated combustion units, mentioned earlier, also eliminate this problem of back-drafting of exhaust gases into the greenhouse growing space. This can occur in windy conditions or when exhaust fans are being used for humidity control at the same time that the heating units are operating.

Hot-air heating systems and piped hot-water heating systems can be compared to traditional lighting systems. The hot-air system resembles incandescent lighting, and the piped-hot-water system represents a fluorescent lighting system. Incandescent lighting has the energy released in a spot source, and fluorescent lighting has the energy released from a line source. The same is true for the heating systems. Energy is released in a combustion chamber and must be distributed throughout the greenhouse. Energy released in a piped hot-water system is released more slowly over a greater area and is therefore more evenly distributed.

To provide uniform heating, several methods of heat distribution are used. Some systems utilize plastic tubing, used for many years in all types of greenhouses, to convey incoming ventilation air. The clear plastic tubing usually ranges from 24-30 inches in diameter, is attached to the heating unit, and runs the length of the greenhouse. Exiting warmed air from the heater is delivered uniformly throughout the greenhouse through equally spaced holes of 2- to 3-inches in diameter spaced 36 inches apart along the entire length of the tubing. The warm air exits the tube approximately in a perpendicular direction and at a relatively high velocity. The jet action of the high velocity, warmed air causes continuous mixing of the warm air with the ambient greenhouse air. This process tends to reduce natural temperature stratification of the heated air. Often these plastic tubes are placed under the greenhouse benches to provide root-zone heating of the crop placed on the benches. Plastic skirts can be placed on the sides of the benches to encourage the warm air to pass upward through the crop on the bench, warming both the root-zone and the crop canopy.

Note: A plastic heating tube should only be used on hot-air heating units designed for operating at higher static pressures. Normally, these units would be equipped with blower type fans (centrifugal fans), rather than propeller type fans.

The airflow leaving an inflated tube through a smooth circular opening (Figure 3) can be calculated according to the equation: Airflow (cfm) = Constant * Coefficient of Discharge * Area in Square Feet * the square root of the static pressure within the tube in inches of water.

$Q = 4005*(C)*(A)*(P)^{(0.5)}$
Q = Airflow in cfm
C = Coefficient of discharge for circular openings (0.60)
A = Area of opening in square feet (for a circle: $\pi d^2/4$)
P = Static pressure in inches of water; Note: $\sqrt{y} = y^{0.5}$
4005: Constant for air at standard temperature and pressure

For example, assume that a furnace capable of delivering 1800 cfm at ¼-inch static pressure is to be outfitted with a plastic tube. We can calculate the airflow through a 3-inch diameter hole against a 0.25-inch static pressure as:

$Q = 4005 * 0.6 * (3.14 * 0.25^2)/4 * (0.25)^{(0.5)} = 59$ cfm/hole

If the house is 96 feet long, the number of holes should be 1800 divided by 59, or 30 holes. If holes were to be placed in a hanging heating duct at 4 and 8 o'clock, 15 locations would be required. This means that the 3-inch diameter holes would be placed approximately 6 feet on centers along the length of the tube. If more holes are desired, smaller diameter holes should be used.

Temperature uniformity has been reasonable in greenhouses using this heating system. The success of this system has been attributed to the mixing action of the jets of air leaving the plastic tube. The actual size of the jet of air flowing through a smooth opening will be about 60 percent of the total area of the opening. The discharge of the air extends 20 to 30 diameters from the opening. Figure 5 illustrates how greenhouse air is entrained with a jet of warm air, causing thorough mixing. This action will also be described later, when ventilation through inlet openings and the importance of mixing of the outside air with the inside air is discussed. The openings in tubes must be located so as to avoid air directly impinging on the plants.

Horizontal airflow created by circulating fans can also be used to reduce vertical temperature stratification. The system has proven helpful in large-span greenhouses, where the heating system does not provide a uniform distribution of the heat energy. Careful design of the heating system to provide uniform distribution, particularly with floor or under-bench heating may eliminate the need for additional air circulation systems.

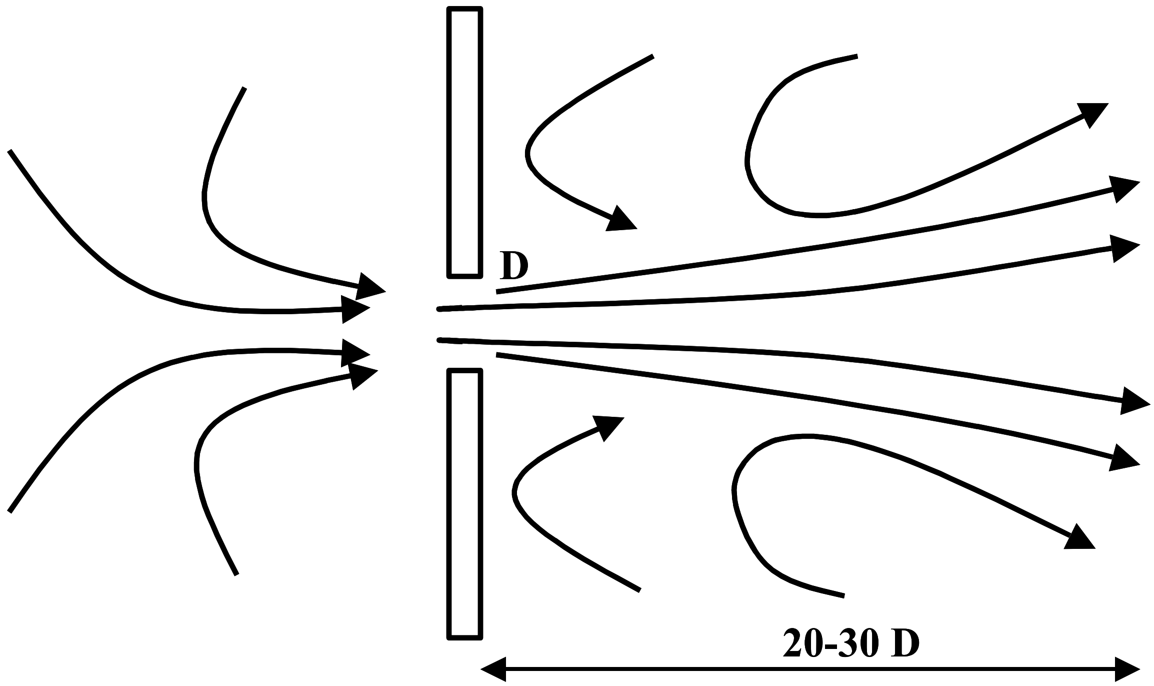

Figure 5. The mixing effect caused by air moving through a small, controlled opening.

The rapidly increasing popularity of root-zone heating (floor and bench heating) has reduced the need for overhead tube systems. The warm floors or benches provide uniform heat throughout the greenhouse, provide modest air movement at the crop levels and through the plant canopy, and eliminate microclimates of high humidity and low temperatures. Warm floors and benches, in combinations with overhead and perimeter heating pipes eliminate the need for the overhead polyethylene tubing system. However, uniform temperature distribution is not always the only environmental parameter affected by internal air circulation. Air movement of approximately 150 feet per minute can also be helpful in delivering CO_2 to the plants and reducing microclimate differences at the leaf surfaces. This idea has also led to the increased use of horizontal airflow fans to create air movement through the plant canopy.

HORIZONTAL AIR FLOW

Horizontal airflow fans (HAF) are often used to circulate air through the greenhouse canopy. Its greatest benefits are creating uniform temperatures within a greenhouse if there is a non-uniform heating system and improving CO_2 uptake and plant transpiration by reducing the (restrictive) boundary layer surrounding the leaf surfaces. Figure 6 indicates the microclimate around a typical potted plant on a greenhouse bench.

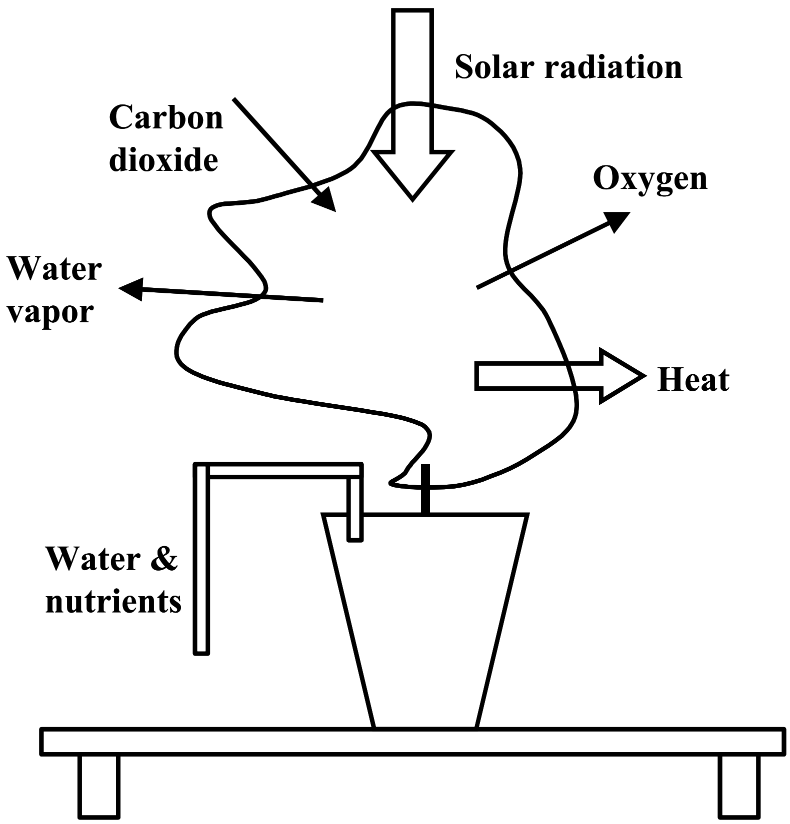

Figure 6. Plant processes affected by air movement.

HAF can improve environmental uniformity throughout the plant production area by mixing the air throughout the growing area. Horizontal air movement is created within the greenhouse by strategic placement of HAF fans. Total installed fan capacity in cfm is approximately 3 cfm per ft^2 of greenhouse floor area. The shielded fans are normally mounted overhead for safety and in race tracks allowing for continuous and relatively unobstructed air movement (NRAES-33 titled "Greenhouse Engineering" by Aldrich and Bartok.[(4)])

HAF systems can be effective in improving plant microclimate and ultimately plant quality. They create air movement within the canopy of those crops growing without the benefit of root-zone heating.

ROOT-ZONE HEATING

Root-zone or soil heating can be accomplished with either floor or bench heating systems. Floor heating systems most often utilize plastic pipe embedded in concrete or sand through which warm water is circulated. In applications using solar energy or waste heat, a flooded gravel layer under the concrete floor has been used to store as well as deliver heat. Bench heating using various types of tubing or plastic pipe filled with circulating low temperature water have also improved the microclimate on benches. Root-zone heating of crops in greenhouses has been a practice used by growers for a long time. In greenhouses using transportable bench systems, steel pipe placed under the bench is used as root-zone and ambient air heating system. Rutgers Cooperative Research and Extension Publication E208, titled "Soil Heating Systems for Greenhouse Production" (revised in April 1996), treats this subject fully.[7]

RADIENT HEATING

Radiant heating provides energy to the plant in a manner similar to the heat energy we receive from the sun. Radiant heating systems use overhead gas-fired units placed as high as possible in the greenhouse. This type of heater provides radiant energy directly to the plant leaves and to any rooting media unobstructed by the plant canopy. There has been some concern that these systems do not provide a uniform microclimate because the pipe temperature varies from burner to burner. A report from researchers in the Netherlands indicated that in some cases this is not a problem, but that it can be a problem for some temperature-sensitive crops.[8] It is also difficult to install overhead radiant heating in an existing greenhouse that uses a thermal screen for energy conservation. In all new installations this problem can be overcome by constructing the greenhouse high enough to permit both installations. A combination of radiant heating and root-zone heating could be an attractive production system for crops with a horizontal canopy, such as potted plants on a bench or bedding plants on the floor.

VENTILATION

Many of the principles discussed above concerning air movement for heating systems also apply to ventilation systems. The National Greenhouse Manufacturing Association has developed excellent standards for ventilating and cooling greenhouses.[2] These include recommendations and designs affecting site elevation, sunlight intensity, orientation and shape of the greenhouse and crops being grown. The following is a discussion of systems and requirements.

Greenhouse ventilation is required to control temperature and moisture levels and provide CO_2 for good crop production. There are two basic ventilation systems used in greenhouse production systems, natural and mechanical ventilation systems. Natural ventilation depends upon normal air movement created by wind pressures or by gradients induced by differences in air temperature between the growing area and the outside environment. Mechanical ventilation is defined as air movement created by fans that bring air into the growing area through controllable openings built into the greenhouse walls and exhaust it through the fan assembly. The ability to change the size of inlets is important for proper design of mechanical ventilation systems. Fan ventilation is normally controlled by thermostats and in some cases by humidity sensing devices when relative humidity is the control parameter (e.g., for disease control).

NATURAL VENTILATION

Natural ventilation is driven by temperature differences (the so-called stack or chimney effect, also know as thermal buoyancy) and/or wind conditions creating small air pressure differences around the greenhouse (the so-called wind effect). We can make use of the stack effect when there is a temperature difference between the inside and the outside of the greenhouse and a vent is opened to allow the warmer air to leave and cooler replacement air to enter. The greatest potential for natural ventilation driven by the stack effect is during the winter, when the temperature difference between inside the greenhouse and outside is the greatest. Unfortunately, this occurs when the need for ventilation is the least. On hot summer days, the outside temperature may be only slightly cooler than the inside temperature. Thus, the ventilation potential driven by the stack effect is practically nonexistent when the need is the greatest. Adequate natural ventilation during warm and hot summer periods can only be realized based on the wind effect that is often site-specific. Locations with naturally occurring breezes provide the best opportunities for warm weather natural ventilation.

Naturally occurring breezes and proper greenhouse orientation can make for excellent natural ventilation at some sites. However, the wind can be unpredictable in some locations, and adequate temperature control may be difficult to achieve. Evaluating meteorological data for a proposed greenhouse site is essential for designing successful natural ventilation systems.

Natural ventilation system designs include roll-up sides, either hand or automatically operated, side vents, roof vents, and/or ridge vents constructed as an integral part of the greenhouse structure. Although difficult to install, ridge vents in polyethylene-glazed structures can provide good options for natural ventilation. In gutter-connected or ridge-and-furrow greenhouses, ridge vents perform better than the vents that open at the gutter. Although the gutter units are easier to re-glaze and construct, they do not perform as well as ridge systems. Time investment required for daily operation and adjustment, and the loss of control, particularly during cold weather, are the most frequently mentioned complaints of natural ventilation systems using roll-up sides. Some glass greenhouses are naturally ventilated using roof and side vents, other use only roof vents that can act as both inlets and outlets. These are usually automated systems, but their successful operation is still limited by the factors listed above.

Greenhouses without glazing

Several newer greenhouse designs for warmer climates feature greenhouse structures with no glazing. These are designed with retractable thermal/shade screens and provide opportunity for excellent environmental control during warmer weather. Site selection is important for heating considerations when growing throughout the year. Many growers use these systems to harden off plant material in the spring.

MECHANICAL VENTILATION

Fan ventilation systems with properly designed inlets can provide excellent temperature control during all seasons. The most desirable feature is the ease of automating the entire system. This is especially true when using computer-based greenhouse control systems. This feature is especially useful to growers with other responsibilities who may be away from the greenhouse during the day and who have difficulty obtaining labor on the weekends. The negative aspects of mechanical ventilation systems are the higher installation and operating costs and the associated noise levels.

Fan ventilation systems are designed to provide a maximum capacity of approximately 8-10 cfm per square foot of floor area. If thermal screens are used for summer shading, 8 cfm/ft^2 is the commonly accepted design parameter. It is generally desirable to provide this ventilation capacity with multiple fans or 2-speed fans, unless the greenhouse is very small and costs for such installation would become too high. The use of multiple and/or multi-speed fans provides an easy opportunity for using more than one ventilation stage, a feature particularly desirable in cooler times of the growing season.

The design for a 30 * 96 ft greenhouse would be as follows:

Design cfm = (length)*(width)*(8) or (10)
A: 30 * 96 * 8 = 23,040 cfm
B: 30 * 96 * 10 = 28,800 cfm

For two fan installation: A = 2 @ 12,000
B = 2 @ 15,000

The fans should be rated at 0.1 inch static pressure and have an electric motor capable of delivering 15,000 to 20,000 cfm per horsepower. If one of the fans selected were a two-speed fan, three levels of ventilation could be provided. If three levels of ventilation were desired and using 10 cfm/ft^2 as the design parameter, the ventilation rates could be (1) 7,500 cfm, (2) 15,000 cfm and (3) 30,000 cfm. This provides the opportunity for better and more uniform temperature control.

In any ventilation system the size and location of the inlets and outlets are the most important design consideration. Air entering the greenhouse is always cooler than the inside temperature during colder weather. It is important to obtain proper mixing of the inlet air with the ambient greenhouse air, so that local cold spots or unequal temperatures are not experienced throughout the growing area. Figure 5 illustrates the action of air moving through a restricted opening and the resultant distribution and mixing pattern. The relatively high velocity air moving through the opening causes significant mixing of the cold incoming air with the ambient greenhouse air. It is similar to using a jet of water coming from a hose to mix a solution in a barrel. Another example is the human nose. We exhale CO_2 from our lungs and inhale O_2. The reason we do not inhale the breath we just exhaled is because of the mixing action of the tiny jets of air created by our lungs when we exhale. The action of these jets mixes the CO_2 with the ambient air so that when we inhale we get a proper mixture of fresh air.

Observations taken in a double glazed polyethylene greenhouse, 72 x 210 feet on a bright January day, revealed that the first fan stage was operating intermittently and ventilation occurred when the inside temperature reached 75°F, while the outside temperature was 0°F. Thorough mixing occurred without any damage to the crop adjacent to the inlet window because the air was coming through the inlet at a high velocity and was directed upward as indicated in Figure 7. The fans were operating in cycles of approximately 2 minutes during these conditions.

As mentioned before, in ventilation systems the location of the inlets and outlets is of paramount importance. It is desirable to keep the length of air travel to less than 200 feet. Fans are usually mounted on one end of the house and air inlets on the other. Fans should be provided with gravity shutters and safety wire screens and have the fan motors protected locally with proper electrical protection and an on-off switch to protect workers when servicing the fans. Inlet shutters or window vents should be motorized. Gravity-type shutters have been used, but are subject to wind forces during windy conditions and are not suitable for winter operation.

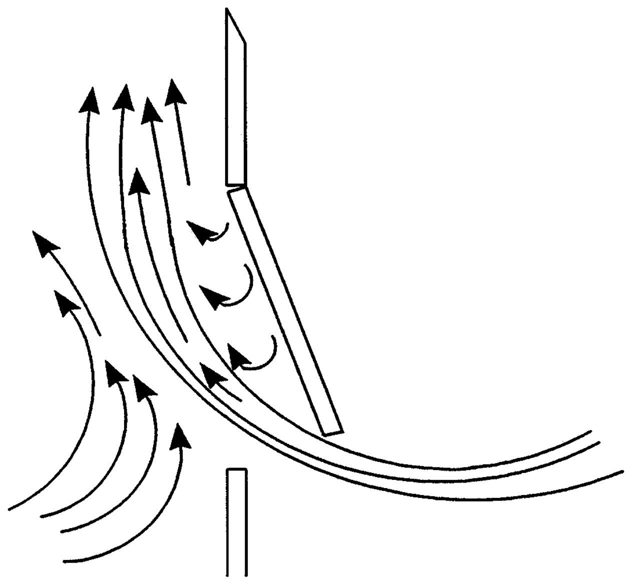

Figure 7. Diagram describing the mixing of cold incoming air with greenhouse ambient air through a controlled window vent opening.

Inlets should be sized to provide an apparent velocity of 700 feet per minute (fpm) or 1.4 square feet of inlet opening per 1,000 cfm of installed fan capacity. The cross-sectional area can be determined by dividing the air capacity of the fan in cfm by the inlet design velocity in fpm, which gives excellent mixing. Following is an example of a suggested procedure for determining the appropriate size of a ventilation inlet:

Using the example cited earlier, a 30*96 foot greenhouse with two 15,000 cfm fans would require the following inlet area:
Area = cfm/velocity
Without shade curtain: Area = 30,000/700 = 43 square feet
With shade curtain: Area = 24,000/700 = 35 square feet
For example, two 48 x 48 inch and one 42 x 42 inch openings with motorized shutters would provide a total of 44 square feet of ventilation opening.

Motorized shutters can be a problem during the colder part of the year. The inlets direct a large volume of air to the crop placed directly in front of the opening and this can cause reduced temperatures at that location. If the velocity of air moving through the shutter is low, then the cold air tends to settle without mixing and moves across the greenhouse to the fan before being exhausted, potentially having had little impact on the control thermostat usually located at 6 ft above the floor. The fan will continue to operate because the thermostat cannot sense the cold temperatures at the floor level. It would be desirable to open the shutters in stages to match the number of fans operating. Because of this, continuous window vents with continuously variable opening stages are very popular and useful. The manufacturer often provides continuous aluminum extrusions that serve as hinges, making the windows essentially maintenance free. They are often glazed with acrylic or polycarbonate panels.

For example, an 84 x 150 feet greenhouse would have an installed fan capacity from 90,000 cfm to 126,000 cfm. If six 20,000 cfm fans were installed in the house, a total window inlet of 168 square feet would be required. This would require 10 motorized shutters each measuring 48 * 48 inch. Another way to provide the inlet area required would be the use of a continuous vent window on the side of the greenhouse opposite the fans. Since 168 square feet is required, and the greenhouse is 84 feet long, a maximum continuous opening of only 24 inches would be required. The window can be opened in stages to match the number of fans operating. Figure 6 illustrates a continuously variable ventilation inlet window.

In the above example, the design calls for six 20,000 cfm fans. A suggested control strategy would be to use three stages. If the fans were aligned along one of the walls, fan number 3 could operate as stage number 1. Fans 1 and 6 could be turned on for the second stage, and fans 2, 4 and 5 could be turned on for the final stage of ventilation. The table shown in the box below indicates the three fan stages, the ventilation volume being delivered and the window opening required to provide a velocity of 700 fpm through the opening resulting in good mixing of the incoming air. Computer-based systems provide excellent control by staging the inlet window opening depending on the number of fans operating, as determined by the desired temperature settings maintained in the control software.

Fan staging scenario:

Stage	Fans in operation	Airflow (cfm)	Area (ft^2)	Opening (inches)
1	Fan 3	20,000	28	4
2	Fans 3,1,6	60,000	84	8
3	Fans 3,1,6,2,4,5	120,000	168	24

Combination Heating and Partial Ventilation System

Some growers have had good success with a system designed to provide both heating and partial ventilation maximizing the use of the system. Figure 8 illustrates a system designed many years ago and used successfully by both flower and vegetable growers who were trying to eliminate the pollution effects caused by heating units located within the greenhouse. Separated combustion units, as discussed earlier, have eliminated many of these problems. A system described in Figure 8 is available from the Modine Manufacturing Company (Note: Reference to commercial products or trade names is made with the understanding that no discrimination or endorsement is intended or implied).

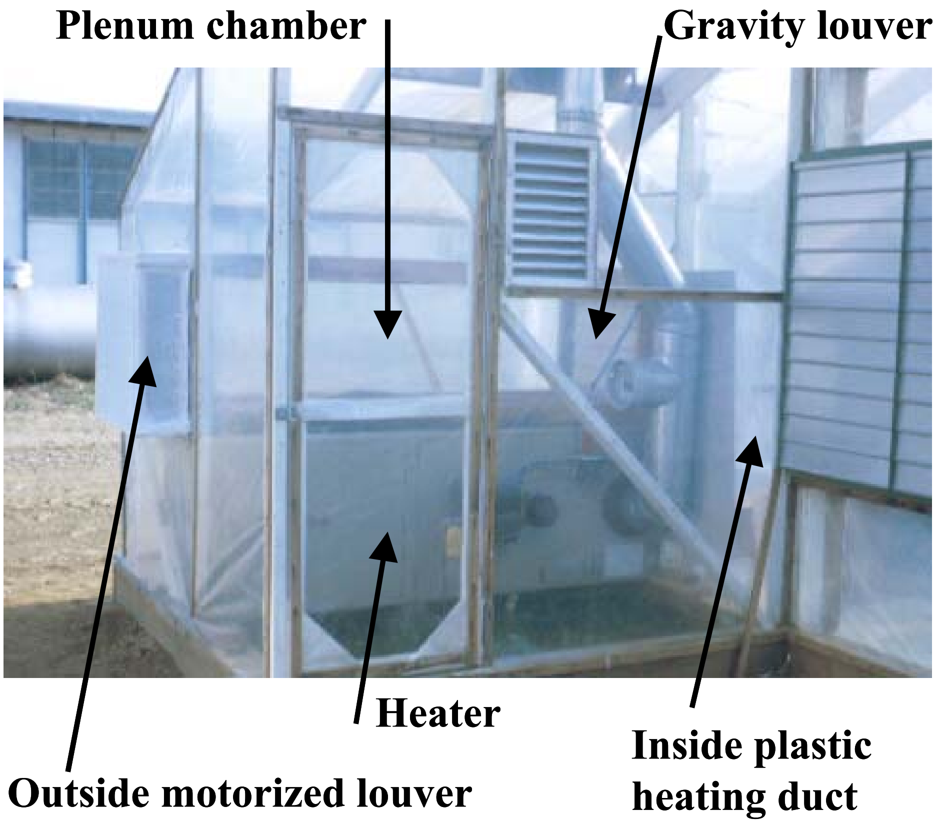

Figure 8. A heating and partial ventilation system attached to a greenhouse.

A horizontally fired unit is used, which is connected directly to a polyethylene heating tube located along the exterior wall of the greenhouse. Directly above the furnace is a plywood chamber, approximately the same size as the furnace. This chamber has one inlet from the greenhouse and one from the outside, each controlled by a motorized shutter.

EVAOPRATIVE COOLING

Evaporation of water requires the energy of conversion from liquid water to water vapor, requiring approximately 1,050 Btu/pound of water. In evaporative cooling systems, this energy is extracted from the air, which is cooled as it evaporates water provided by the system. Evaporative cooling has been used successfully for many years.

The system outlined by Acme[3] uses fans on one side of the greenhouse and wetted pads mounted on the opposite side of the greenhouse at the ventilation inlet. The pads are wetted by water flowing down through them by gravity. Air is drawn through them, evaporating some of the water and causing the air to be cooled nearly to the wet bulb temperature. These systems are particularly successful in areas of low humidity, where a significant temperature drop can be realized. Problems with this system include the amount of maintenance of the system, depending on the quality of water available for cooling. Salt buildup is a significant problem in some areas and it is important to control this by draining a portion of the water away and replacing it with fresh water to maintain a modest salt concentration of the circulating cooling water.

Very high-pressure fog systems are also used successfully for greenhouse cooling. Since the fog nozzles can be placed throughout the greenhouse as well as at the air inlet, this system has the advantage of evaporating water throughout the greenhouse, compared to evaporation that occurs only along one wall, as is the case with the wet pad system. The fog systems can be more expensive because of the large number of nozzles required and the expensive high-pressure pump (500-900 psi) utilized to create extremely fine droplet sizes. Good filtration and water treatment is essential for good performance of fog systems as the nozzles have very small openings in order to produce true fog rather than mist. Biological, and chemical buildup in the nozzles will cause system failure, so good maintenance is important.

ENVIRONMENTAL CONTROLS

Controls are an important part of any heating and ventilating system. Capillary bulb-type thermostats are the most durable for greenhouse use. Residential home-type thermostats are usually more accurate but are also more subject to deterioration and malfunctioning caused by the greenhouse environment. Mercury-type thermostats are often affected by vibration that can occurs as a result of strong winds or equipment operation, and should not be attached to the greenhouse structure. Aspiration, or passing air over thermostats or computer sensors, is very important for proper operation of the environmental control system. Figure 9 shows an example of an aspirated box containing a small blower or fan that draws air over the sensing units of the thermostats. Experimental results obtained by simply blowing air on a traditional capillary bulb thermostat resulted in a significant energy savings since the fluctuations of the measurement temperature were significantly reduced. Sensors for computer control systems usually come mounted in and aspirated housing and frequently have sensors for humidity as well as temperature control.

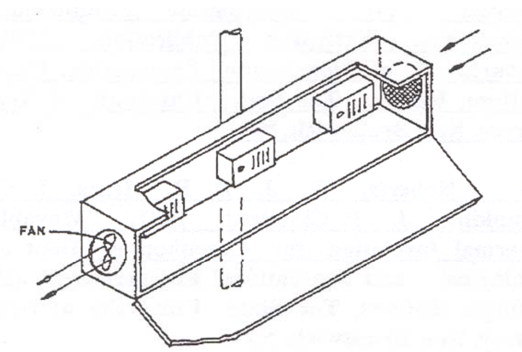

Figure 9

Figure 9. Example of a home-made aspirated box for mounting sensors and thermostats (under normal use, the front door and top of the box will be completely closed).

Thermostats can directly control small motors. However, using electrical relays to start the heating and ventilating equipment can increase the life of the thermostat. Relays are required if there are multiple or large motors that exceed the current rating of the thermostat contacts. The initial costs of a relay system are higher, but the life of the equipment will be extended significantly. Additional thermostats can be wired to provide different day-night settings when also using a 24-hour time clock.

Sophisticated computer based environmental control units now being marketed have the distinct advantage of providing an archive of temperatures recorded throughout the day as well as implement complex pre-programmed temperature scenarios if needed. The data acquisition feature of these computer-based systems is often an attractive aspect for the grower as such records are helpful in determining what the actual growing conditions were for a particular crop. These systems provide various stages of heating and ventilation control for different times of the day, can integrate light sensing equipment into the control, and control the operation of a thermal/shade screen and/or CO_2 enrichment.

Computer-based systems should only be used to control a well-engineered heating and ventilating system. A heating or ventilation system that is poorly designed cannot be improved simply by installing a better control system. The control system provides the best results when it works in conjunction with a properly engineered heating and ventilation system.

ENERGY CONSERVATION

There are many effective ways for growers to reduce the energy needed to heat their greenhouse. The most effective way to do this is through the use of thermal screens or energy-saving blankets. These screens can often be used for effective summer cooling as well if the proper material is chosen. The best energy saving screens can reduce the heating energy required by 30-40% for a double-layer polyethylene greenhouse. A common material used for summer shading, providing approximately 55% shade, may provide an energy saving of only 25-30 percent. However, the benefit of summer shading added to the somewhat reduced energy savings may be a reasonable compromise. Some growers use a double screen system; others pay the difference in energy costs, use the common stripped aluminum shade material, and realize less energy savings during the heating season. Growers who do not use the system for summer shading should select a material that gives the best energy savings. A complete treatment of the materials tested in earlier years is given in the publication[8] "Movable Thermal Insulation for Greenhouses". The manufacturers of newer materials publish their estimates of shade factors and energy savings in their sales literature.

Other conservation methods include the use of transportable or movable bench systems that reduce the heating energy required per unit of product by substantially increasing the space efficiency of the greenhouse. Some growers opt to switch to less expensive or alternative fuel sources. NRAES 3, "Energy Conservation for Commercial Greenhouses"[9] is an excellent publication describing various energy saving techniques for reducing heating costs.

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