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Heating, Ventilating and Cooling Greenhouses

American Society of Agricultural Engineers

STANDARD

ASAE-The Society for engineering in agricultural, food, and biological systems
2950 Niles Rd., St. Joseph, MI 49085-9659, USA ph. 269-429-0300, fax 269-429-3852, hq@asae.org

Heating, Ventilating and Cooling Greenhouses

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1 Purpose and scope

This Engineering Practice presents design information for heating, ventilating and cooling greenhouses. Generally accepted methods of heating, ventilating and cooling are presented and the important design features of typical systems are indicated.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Standards organizations maintain registers of currently valid standards.

ANSI/AMCA 210-99, *Laboratory Methods of Testing Fans for Aerodynamic Rating*
ANSI/ASAE S493 NOV98, *Guarding for Agricultural Equipment*
ASAE D271.2 DEC99, *Psychrometric Data*
ASAE EP460 DEC01, *Commercial Greenhouse Design and Layout*

3 General definitions

3.1 air circulation: The process of moving or mixing air within a greenhouse to control temperature, humidity and carbon dioxide distribution.

3.2 aspirate: To circulate air continuously across or through an object, such as a temperature sensor.

3.3 cooling: Generally, the removal of heat from the interior of the greenhouse; however, the term may also be applied to the conversion from sensible to latent energy, as in evaporative cooling (see 3.4).

3.4 evaporative cooling: The addition of moisture to air (usually ventilation air) to reduce its dry bulb temperature. Sensible energy is converted to latent energy with negligible change in the enthalpy of the air.

3.5 glazing: The transparent or translucent covering of a greenhouse; e.g., glass, plastic film, rigid plastic panels, etc.

3.6 heating: The addition of heat to the interior of the greenhouse from any energy source, including the sun.

3.7 horizontal air circulation: A system utilizing fans to generate a horizontal air circulation pattern above and through the plant canopy.

3.8 infiltration: Uncontrolled air exchange which occurs through small, uncontrolled openings in the greenhouse covering, such as gaps around doorways, utility service entrances and between cover sections. These exchanges are driven by wind pressure and/or temperature differentials inside and outside the greenhouse. Infiltration rate is generally expressed in terms of internal air volume changes per unit of time (e.g., air exchanges per hour).

3.9 fan ventilation: Air exchange through side wall and/or roof openings, which occurs when fans are used to move air into, and exhaust air out of, the greenhouse. Fans may be located either at the inlet end (positive pressure) or the exhaust end (negative pressure); however, the most common location is at the exhaust end.

3.10 natural ventilation: Air exchange which occurs in response to temperature and pressure variations inside and outside the greenhouse. These variations are created and maintained by solar energy, internal heat sources, and/or wind.

3.11 ridge and furrow: A type of greenhouse construction where modular units are connected at the gutters to cover large ground areas; also called gutter-connected greenhouses.

3.12 ventilation: The process of exchanging air inside the greenhouse with outside air to control temperature, humidity and carbon dioxide levels.

3.12.1 ventilation rate: The volume of air exchanged per unit of time per unit floor area. Ventilation rate is often expressed as $m^3/(s{\cdot}m^2)$ (cfm/ft^2) of greenhouse floor area.

4 Principles of heating and heat loss determination

4.1 Most undesirable heat loss from a greenhouse occurs by long-wave radiation, conduction and convection (q_{rc}) and by infiltration (q_i). Heating requirements are determined by calculating the sum of q_{rc} and q_i based upon the guidelines in 4.6 and 4.7.

4.2 The heat loss by radiation, conduction and convection, q_{rc}, (W or Btu/h) can be determined by:

$$q_{rc} = UA_c(t_i - t_o) \tag{1}$$

where:

U is overall heat transfer coefficient (table 1), $W/(m^2 \cdot °C)$ ($BTU/[h{\cdot}ft^2 \cdot °F]$);
A_c is area of the cover, m^2 (ft^2);
t_i is greenhouse air temperature, °C (°F);
t_o is outside air temperature, °C (°F).

4.3 Greenhouse heat loss by infiltration, q_i, (W or Btu/h) can be estimated by considering that the total exchange will be the sum of the sensible and latent energy exchanges:

$$q_i = \rho_i NV[c_{p_i}(t_i - t_o) + h_{fg}(W_i - W_o)] \tag{2}$$

where:

ρ_i is density of the greenhouse air, kg/m^3 (lb/ft^3);
c_{p_i} is specific heat of the inside air, $J/(kg{\cdot}°C)$ ($Btu/[lb{\cdot}°F]$);
N is infiltration rate (table 2), s^{-1} (h^{-1});
V is volume of the greenhouse, m^3(ft^3);
h_{fg} is latent heat of vaporization of water at t_i, J/kg (Btu/lb);
W_i is humidity ratio of the inside air, kg_{water}/kg_{air} (lb_{water}/lb_{air});
W_o is humidity ratio of the outside air, kg_{water}/kg_{air} (lb_{water}/lb_{air}).

Table 1 – Approximate overall heat transfer coefficients (*U*-values) for greenhouse glazing methods and materials

Greenhouse covering	*U*-value	
	W/(m^2·°C)	Btu/(h·ft^2·°F)
Single glass, sealed	6.2	1.1
Single glass, low emissivity	5.4	0.95
Double glass, sealed	3.7	0.65
Single plastic	6.2	1.1
Single polycarbonate, corrugated	6.2–6.8	1.1–1.2
Single fiberglass, corrugated	5.7	1.0
Double polyethylene	4.0	0.70
Double polyethylene, IR inhibited	2.8	0.50
Rigid acrylic, double-wall	3.2	0.56
Rigid polycarbonate, double-wall[1)]	3.2–3.6	0.56–0.63
Rigid acrylic, w/polystyrene pellets[2)]	0.57	0.10
Double polyethylene over glass	2.8	0.50
Single glass and thermal blanket[3)]	4.0	0.70
Double polyethylene and thermal blanket[3)]	2.5	0.44

[1)]Depending upon spacing between walls.
[2)]32 mm rigid acrylic panels filled with polystyrene pellets.
[3)]Only when blanket is closed and well sealed.

4.4 If outside temperatures are near or below −20 °C (−4 °F), and inside relative humidities are 40% or less, latent heat exchange will be limited, and equation 2 can be approximated by

$$q_i = 1800VN(t_i - t_o) \tag{3}$$

where:

q_i is in watts;
t_i is in °C;
t_o is in °C;
N is in s^{-1};
V is in m^3.

4.5 Natural air exchanges (table 2) can be very low if cracks become sealed with frozen condensate. During low wind conditions, even unfrozen condensate can serve to seal cracks. The degree to which either will happen will depend upon the type of cover, size and orientation of the cracks, the inside and outside temperatures, and the amount of transpiration by the canopy.

4.6 Outside design temperatures for heating are tabulated for various locations in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook—Fundamentals. The 99% winter design dry bulb temperature is recommended for sizing greenhouse heating systems that are to be used year round. A warmer temperature may be selected if use is intended only during warmer parts of the year. Local weather data should be consulted where available.

Table 2 – Estimated infiltration rates for greenhouses by type and construction

Type and construction	Infiltration rate (N)[1)]	
	s^{-1}	h^{-1}
New construction:		
double plastic film	2.1×10^{-4}–4.1×10^{-4}	0.75–1.5
glass or fiberglass	1.4×10^{-4}–2.8×10^{-4}	0.50–1.0
Old construction:		
glass, good maintenance	2.8×10^{-4}–5.6×10^{-4}	1.0–2.0
glass, poor maintenance	5.6×10^{-4}–11.1×10^{-4}	2.0–4.0

[1)]Internal air volume exchanges per unit time (s^{-1} or h^{-1}). High winds or direct exposure to wind will increase infiltration rates; conversely, low winds or protection from wind will reduce infiltration rates.

4.7 Maximum design heating load should be based upon the inside temperature required by the plants at night. A temperature of 16 °C (60 °F) generally meets the needs of most plants. While daytime temperature settings are generally 6 to 11 °C (10 to 20 °F) higher than nighttime settings on bright sunny days and 3 to 6 °C (5 to 10 °F) higher on cloudy days, solar radiation will generally provide the necessary additional energy.

4.8 Heat loss through concrete or masonry walls should be calculated by conventional means such as those described in ASHRAE Handbook—Fundamentals.

5 Heating and air circulation systems

5.1 Central heating

5.1.1 Central heating systems generally use hot water or steam distributed to heat exchangers made up of standard black pipe (natural convection), finned-pipe (natural convection), or steam/hot-water unit heaters (forced convection). Hot water may also be circulated through hollow structural members.

5.1.2 Sizing of the heat exchangers is accomplished by standard heat transfer calculations taking into account heating requirements, heating fluid characteristics and exchanger characteristics. Manufacturer's data may be required to get accurate results for finned-pipe and unit heaters. Additional considerations for unit heaters are presented in 5.2. Considerations for standard-pipe and finned-pipe heat exchangers are discussed in clauses 5.1.3 to 5.1.6.

5.1.3 Greenhouses 9 m (30 ft) or less in width may be heated with standard black pipe or finned-pipe placed only along the sidewalls. For single-span houses wider than 9 m (30 ft), distribute the pipes along the sidewalls and below/between the crop (or under the benches) in proportion to the expected heat loss for the walls and roof, respectively.

5.1.4 If steam is used as the heating medium, heating surfaces should be installed at least 0.30 m (12 in.) away from any plant material. For narrow-span ridge and furrow houses, heating pipes should be placed along the exterior walls and below the gutters between sections. Pipes may also be placed below benches, between the rows or adjacent to root media for root zone heating.

5.1.5 When using black-or finned-pipe, naturally induced air circulation does not always provide sufficiently uniform air temperatures at plant height. If increased temperature uniformity is desired, air circulation fans can be installed in accordance with 5.4.

5.1.6 Since maximum heating capacity is rarely needed all of the time, central heating systems should be designed with two or three zones. The primary zone should be floor or under bench heat. In ridge and furrow houses, the heat pipes under the gutters should be capable of being operated manually to melt snow, if necessary.

5.1.7 All boilers and hot water heaters shall have appropriate valves, controls and safety devices and shall be installed in accordance with all applicable codes.

5.1.8 If heating pipes are galvanized or painted with aluminized paint, heat delivery rates will be approximately 15% less than from black pipe.

5.1.9 Stacks/chimneys: Heating stacks should terminate not less than two feet above the tallest point of the greenhouse structure. Stacks should be located so that prevailing winds carry the exhaust gases away from the greenhouse and not over the greenhouse (especially important for greenhouses with roof vents, including open-roof greenhouses).

5.2 Unit heaters

5.2.1 Unit heaters are available in steam/hot-water, direct oil-fired and direct gas-fired versions.

5.2.2 Vertical discharge unit heaters placed overhead are not recommended because they may damage crop with the high temperature discharge air plus they do not maintain sufficiently uniform temperatures in the crop zone.

5.2.3 For low-growing crops on benches or in ground beds, horizontal discharge unit heaters designed specifically for greenhouse heating can be used without additional circulation fans; however, temperature variations within the greenhouse may exceed those in houses with black or finned-pipe heat exchangers. Horizontal air circulation (see 5.4) or perforated-tube air distribution (see 5.3) can reduce these variations significantly.

5.2.4 The fans on the unit heaters may be operated continuously to provide improved air circulation. Two heaters with continuously operating circulating fans can be used in houses 20 m (66 ft) or less in length. Heaters should be located in diagonally opposite corners discharging toward the far walls in a direction parallel to the sidewalls.

5.2.5 For houses longer than 20 m (66 ft), but less than 40 m (130 ft), heater fans alone may not be sufficient to maintain air circulation patterns. In this case, it is recommended that two additional fans be placed at the middle of the greenhouse, one on each side with the air discharge directed toward the end walls, to aid air circulation. Alternatively, additional heaters can be positioned to achieve the same result, with the size of the original heaters reduced in proportion to the capacity of those added.

5.2.6 Direct-fired heaters shall be provided with outside air for combustion. It is recommended that this be supplied through ducts with cross sections of 880 mm^2/kW (1.0 $in.^2$ for every 2500 Btu/h) of heater capacity.

5.2.7 All gas or oil-fired heaters shall be vented in accordance with manufacturer's recommendations using stacks configured as outlined in 0 and equipped with weather caps. The use of unvented heaters (to take advantage of the CO_2 produced) is not recommended because of the potential for generation of toxic gases due to incomplete combustion and/or the burning of contaminated fuels. Incomplete combustion can be detected using carbon monoxide detectors and alarms. Moreover, it is generally true that periods of high heat demand (usually non-daylight hours) do not coincide well with periods when CO_2 enrichment can be employed effectively (i.e., daylight hours). CO_2 enrichment, if desired, should be accomplished as outlined in 5.8.

5.3 Perforated-tube air circulation

5.3.1 Air circulation is essential for minimizing CO_2, temperature, and moisture gradients in closed greenhouses. Overhead perforated plastic tube systems can be used for this purpose, although at reduced efficiency compared to horizontal airflow (see 5.4). The tube is generally connected directly to the outlet of a fan which forces air down the length of the tube and out through appropriately spaced discharge holes. If the system is used to distribute heat, unit heaters are typically installed at the inlet end of the tube system, and the exhaust air of the heaters is directed into the inlet of the fan.

5.3.2 Discharge holes are generally located on opposite sides of the tube, about 30 to 45 degrees below the horizontal, and are typically spaced 0.3 to 1.0 m (12 to 36 in.) apart along the axis of the tube, depending upon tube diameter and length.

5.3.3 The tubes should be sized to handle a flow rate of 1/4 to 1/3 of the greenhouse air volume per minute with an air velocity at the entrance of the tube of 5.1 to 6.1 m/s (1000 to 1200 ft/min). The total area of the discharge holes should not be less than 1.5 nor more than 2.0 times the cross-sectional area of the tube.

5.3.4 The discharge holes and tube height should be arranged so that air is not blown directly onto the plants.

5.3.5 One tube is generally sufficient for greenhouses 9.1 m (30 ft) or less in width. Two or more tubes are necessary for wider greenhouses.

5.3.6 Circulation tubes should not exceed 49 m (160 ft) in length. Best distribution occurs when the length is 23 to 30 m (75 to 100 ft) or less.

5.3.7 The warm air discharge from each unit heater should be directed behind the plastic-tube air circulation fan. The capacity of the circulation fan shall be equal to or greater than the heater fan capacity.

5.3.8 Air circulation fans should be run continuously during the heating season and whenever exhaust fans are not running during the cooling season to minimize moisture and temperature gradients within the greenhouse.

5.4 Horizontal air circulation

5.4.1 Horizontal air circulation consists of air circulated in a horizontal pattern (in 'racetrack' fashion) above and within the plant canopy using large-diameter, low-power propeller fans. Reduced fan pressures, reduced maintenance (no tubes to replace) and lower initial costs make this a more efficient method of air circulation and/or heat distribution compared to perforated tubes.

5.4.2 In ridge and furrow greenhouses, circulation can be directed down one section and back through another. Fans should be located over the crop in each section.

5.4.3 In single-span greenhouses, fans should be installed with their axes parallel to the long dimension of the house at a distance of 1/4 the house width from the sidewalls. The air should be circulated parallel to the side walls, down along one side and back along the other.

5.4.4 Fans should be mounted perpendicular to the ground and at least 0.6 to 0.9 m (2 to 3 ft) above the plants. If the fans are higher than 0.9 m (3 ft), they tend to move the air above the canopy but not within the canopy. Guards should be provided to protect personnel from the propellers.

5.4.5 The fans should be placed along the direction of air movement at spacings of approximately 25 to 30 times the fan diameter and at least 4.5 to 6.0 m (15 to 20 ft) from end walls.

5.4.6 Fans should be selected to provide a total air flow of 0.01 $m^3/(s{\cdot}m^2)$ (2 cfm/ft^2) of floor area. Fan mounts should be designed to allow adjustment of the fans to insure that local velocities in the vicinity of the canopy do not exceed 1.0 m/s (200 ft/min). Fans with shrouds or venturi that produce a longer 'throw' distance are preferred.

5.5 Bench heating

5.5.1 Bench heating can be used to provide optimum temperatures in the root zone for seed germination, propagation and general plant growth. It can also be used to reduce heating costs if air temperatures can be lowered to compensate for higher root zone temperatures.

5.5.2 Hot water at temperatures of 35 to 40°C (95 to 104°F) is generally circulated through 13 mm (0.5 in.) polyethylene, PVC, CPVC, polybutylene pipe, or 6 mm (0.25 in.) EPDM tubing for maximum temperature uniformity. The heating pipes or tubes should be configured with a 'reverse return' header system with supply and return headers at the same end of the bench. In this system, each heating loop has the same length and the water has to travel the same distance through the supply and return system to reach each heating loop. Thus, the total friction losses for water traveling through each of the heating loops are the same. The design flow rate should be sufficiently high so that the temperature difference between the supply and return side in each loop remains small and potential sedimentation is avoided. On the other hand, the flow rate should not be so high as to increase friction losses. The pipe or tube spacing should be approximately 100 mm (4 in.) to allow the higher temperature on the supply side to be balanced by the lower temperature on the return side.

5.5.3 The pipe or tubing loops can be placed directly on the bench or attached underneath. Polystyrene insulation board placed immediately below the pipe or tubing will insure that most of the heat is directed into the root zone.

5.5.4 Temperature uniformity can be improved, if necessary, by decreasing the spacing of the pipes/tubes or by adding a 25 to 50 mm (1 to 2 in.) layer of wet sand over and around the pipes/tubes. If sand is used, provision should be made to retain the moisture by covering the sand with a perforated plastic film.

5.5.5 A remote-bulb thermostat, with the bulb inserted in a representative plant container, can be used to control temperature. Where present, bench heating should be used as the first stage of heating.

5.6 Floor heating

5.6.1 Floor heating is considered good practice where plant containers can be set directly on the floor. It is particularly well suited where a minimum amount of protection is needed, as in over-wintering houses for azalea and other hardy shrubs. It can also be used to some advantage in supplementing conventional heating systems, subject to the considerations outlined below and the understanding that the response time associated with floor heating are generally larger than those for conventional systems. When used, floor heating should be configured as the first stage of heat.

5.6.2 Loose gravel, porous concrete (concrete without sand), solid concrete or sand can be used for the floor material. A floor thickness of 75 to 100 mm (3 to 4 in.) is generally recommended. If solid concrete is used, the floor should be sloped for drainage. Sand floors should be covered with perforated plastic to retain moisture (to promote heat transfer between the pipes and the sand). If ground water is within 1.8 m (6.0 ft) of the floor, 25 to 50 mm (1 to 2 in.) extruded polystyrene insulation board should be installed below the floor.

5.6.3 A typical installation circulates 35 to 40 °C (95 to 104 °F) water at velocities of 0.61 to 0.91 m/s (2.0 to 3.0 ft/s) through 20 mm (0.75 in.) polyethylene, PVC or polybutylene pipe embedded in the floor. The heating pipes should be configured with a 'reverse return' header system with supply and return headers at the same end of the greenhouse. In this system, each heating loop has the same length and the water has to travel the same distance through the supply and return system to reach each heating loop. Thus, the total friction losses for water traveling through each of the heating loops are the same. The design flow rate should be sufficiently high so that the temperature difference between the supply and return side in each loop remains small and potential sedimentation is avoided. On the other hand, the flow rate should not be so high as to increase friction losses. Typical pipe spacing is 305 mm (12 in.) to allow the higher temperature on the supply side to be balanced by the lower temperature on the return side. Each pipe may be configured in a series of loops, but the total length of a heating loop should not exceed 122 m (400 ft).

5.6.4 A typical floor heating system provides 47 to 78 W/m^2 (15 to 25 $Btu/[h\cdot ft^2]$) depending on the crop density on the floor and the desired temperature difference between the root zone and the greenhouse air.

5.6.5 Pipe spacings of 0.30 m (1.0 ft) on centers in a porous concrete floor will provide approximately 47 W/m^2 (15 $Btu/[h\cdot ft^2]$) of floor area to the greenhouse when the floor is completely covered by plants. Hot water may be supplied by a water heater separate from the main heating system or it may be from a zone of a hot water system for heating the greenhouse. If separate, the 47 W/m^2 (15 $Btu/[h\cdot ft^2]$) can be used to size the heater, and the main system capacity can be reduced accordingly. If it is to be part a of a central system, a total system capacity determined by equation 1 and equation 2 will allow sufficient capacity to handle both floor and air heating. A remote bulb thermostat with the bulb inserted into a typical plant container can be used for controlling the flow.

5.7 Heating controls

5.7.1 Heating controls and sensors should be capable of withstanding extreme humidity and dust conditions.

5.7.2 Sensors should be continuously aspirated at a speed of 3.0 to 5.1 m/s (600 to 1000 fpm) to reduce temperature gradients in the vicinity of the sensors. Aspirator fans should have totally enclosed motors and should pull the air across the sensors to avoid temperature measurement errors due to the addition of motor heat to the airstream.

5.7.3 The control sensors should be fully shaded from direct and diffuse solar radiation. The material used to shade the sensors should have a low thermal conductivity and should be painted or coated white on the side(s) facing external radiation to minimize energy absorption.

5.7.4 Sensors should be located near the center of the growing area. The location should be representative of that occupied by the plants and should not be unduly affected by heating and ventilating systems or structural members.

5.8 Carbon dioxide levels

5.8.1 Depletion of carbon dioxide (CO_2) levels below the normal atmospheric concentration ranges of 350 to 400 µmol/mol (350 to 400 ppm) may commonly occur on clear, cold winter days. Since CO_2 levels below atmospheric will retard plant growth and levels in excess of atmospheric may increase growth, addition of CO_2 to the greenhouse atmosphere is a recommended practice in northern latitudes during the winter. Although CO_2 levels up to 2000 µmol/mol (2000 ppm) may be used for extended periods and as much as 5000 µmol/mol (5000 ppm) may be used to good effect for short periods, the normal target for CO_2 enrichment is 1000 µmol/mol (1000 ppm). CO_2 enrichment may also be provided when supplemental lighting is applied. Supplemental lighting without CO_2 enrichment will be less effective.

5.8.2 CO_2 may be obtained from liquid CO_2 in tanks or by the unvented burning of fuel gases (natural gas, liquid propane or liquid butane) in units specifically designed and maintained for the purpose; however, CO_2 generation from unvented, primary heaters is not recommended (see 5.2.7). CO_2 generation using fuels other than those listed above is not recommended because of the high probability of contamination. Sulfur contamination in kerosene, for example, can lead to serious crop damage. CO_2 injection need only be accomplished when the plants are photosynthesizing.

5.8.3 If CO_2 is generated from the unvented burning of fuel gas, care must be taken that the fuel does not include impurities and that adequate air is available for complete combustion. Impurities likely to cause trouble are organic nitrogen compounds, ethylene and propylene. The former two are normally controlled to within acceptable limits in commercial fuel gases; however, propylene can be a major constituent of liquid propane. Since propylene injury mimics that of ethylene, a by-product of incomplete combustion, unburned propylene escaping into the house through loose connections in the feed line may produce symptoms suggestive of combustion problems. Incomplete combustion can be detected using carbon monoxide detectors and alarms.

5.8.4 In addition to fuel impurity concerns, water vapor production in CO_2 generation from burning fuel gases can lead to difficulties. In pure form, natural gas (CH_4) will yield 1 volume of CO_2 and 2 volumes of water vapor for each volume of gas burned, propane (C_3H_8) will yield 3 volumes of CO_2 and 4 of water vapor for each volume of gas burned, and butane (C_4H_{10}) will yield 4 volumes of CO_2 and 5 of water vapor for each volume of gas burned. The actual yield of CO_2 and water vapor obtained in practice will differ from these values somewhat since commercial grades of fuel gases are rarely available in pure form.

5.8.5 The amount of CO_2 required to maintain 350 µmol/mol (350 ppm) in a closed greenhouse is low (only that quantity consumed by the plants need be replaced); however, the amount necessary to elevate CO_2 levels above 350 µmol/mol (350 ppm) will vary depending upon the tightness of the house, outside windspeed and the level of CO_2 desired. For a greenhouse with an infiltration rate of 1 air-exchange per hour under normal wind conditions (see table 2), a CO_2 injection rate of approximately 0.0030 $m^3/(h\cdot m^2)$ (0.010 $ft^3/[h\cdot ft^2]$) of floor area will maintain a level of about 1000 µmol/mol (1000 ppm) in a fully cropped house. An injection rate of 0.0043 $m^3/(h\cdot m^2)$ (0.014 $ft^3/[h\cdot ft^2]$) can be expected to maintain a level of about 1500 µmol/mol (1500 ppm) under the same conditions.

5.8.6 CO_2 alarms should be employed whenever CO_2 is being added to a greenhouse. CO_2 levels greater than 5000 µmol/mol (5000 ppm) exceed safe levels for extended periods of moderate human activity (lifting, bending, walking). Alarms should be available locally from commercial heating and ventilating suppliers or from gas companies.

5.8.7 CO_2 enrichment is not recommended when ventilation rates exceed 0.020 $m^3/(s\cdot m^2)$ (3.9 $ft^3/[min\cdot ft^2]$) of floor area. CO_2 depletion is generally not a problem at ventilation rates that high, and the quantity of CO_2 required to elevate CO_2 levels under those conditions generally makes enrichment uneconomical. The advisability of enrichment at lower rates of ventilation will depend upon level of CO_2 desired and the cost of CO_2.

5.8.8 The limitation on the use of CO_2 during venting generally makes enrichment impractical for greenhouses located in the southeastern U.S. (below about 36 deg N latitude). Although variable from year-to-year, the number of daylight hours when venting is not required is generally insufficient, even during the winter, to cause extended periods of significant CO_2 depletion or to make CO_2 enrichment cost effective.

6 Natural ventilation systems

6.1 Natural ventilation is a direct result of pressure differences created and maintained by wind or temperature gradients, and it depends heavily on evapotranspiration cooling provided by the crop to maintain acceptable temperatures within the greenhouse. Its suitability as a primary means of cooling must be judged based on local environmental conditions, type of crop grown and the design of the greenhouse.

6.2 Natural ventilation may be used to advantage in moderately warm climates or in hot, arid climates, depending upon the availability and dependability of the wind. Crops capable of high rates of transpiration should be chosen to maximize evapotranspiration cooling.

6.3 Naturally ventilated greenhouses are typically provided with vent openings on both sides of the ridge and on both sidewalls. Vent operation should be such that the leeward vents are opened to produce a vacuum at the top of the ridge. Opening of the windward vents produces a positive pressure in the house which is typically less efficient than vacuum operation.

6.4 Pressure gradients are typically small so that large vent openings are necessary to provide adequate ventilation. The combined sidewall vent area should equal the combined ridge vent area, and each should be at least 15 to 20% of the floor area.

6.5 Ridge vents should be top-hinged and should run continuously the full length of the greenhouse. The vents should form a 60 deg angle with the roof when fully open.

6.6 Open roof designs may eliminate the need for side or end wall roof vents when more than 50% of the roof area is open.

6.7 Any natural ventilation system should have the means to open partially or fully in response to inside temperature, with automatic control of such systems highly recommended. Incremental opening and closing should also be possible.

6.8 Automatic vent systems should be equipped with rain and wind sensors to permit closing during periods when crop or ventilator damage might occur.

7 Fan ventilating and cooling systems

7.1 Basic considerations

7.1.1 The emphasis of this section is on the design and specification of summer cooling systems; however, since cooling is needed year round in some locations, considerations relative to winter cooling are also presented (7.5.1 and 7.7.3).

7.1.2 The response of plants to high daytime temperatures is sufficiently varied and complicated that it is difficult to provide clear guidelines for the selection of appropriate design temperatures. Optimum growth generally occurs over a wide range of temperatures. Cool season and shade plants, for example, typically grow best at 10 to 20 °C (50 to 68 °F) and most other non-tropical plants at 20 to 30 °C (68 to 86 °F); however, the detrimental effects of high temperatures generally occur gradually enough that most plants can tolerate short periods above their optimum range. On the other hand, flowering abnormalities may occur at temperatures significantly below the upper end of the optimum growth range. In the end, selection of design temperatures, especially in warm climates, is typically limited by what can be economically achieved, rather than by the optimum limits of the crop, with the realization that some economic loss may be unavoidable.

7.1.3 As a general rule, greenhouse temperatures should be limited to less than 30 to 32 °C (86 to 90 °F) unless tropical, cool season or shade plants are to be grown. For tropical plants, an upper limit of 35 °C (95 °F) should be considered from the standpoint of worker comfort and safety. For cool season and shade plants, strict adherence to the 20 °C (68 °F) upper limit of optimum is likely to be unattainable, except in the northern U.S. and Canada. This may require the selection of an alternative crop or the acceptance of some degradation in quality.

7.1.4 Traditional cooling alternatives for greenhouses depend upon exhaust fans to remove excess energy. As outside air is brought into and then through the house, its energy level rises due to sensible heat gain from the canopy, ground and surrounding structure. The volume of air required to maintain a given temperature rise, $t_{ex} - t_{inlet}$, may be estimated using the following approximate energy balance:

$$(1-E)\tau I A_f = U A_c (t_i - t_o) + \left(\frac{Q_v A_f c_{p_{ex}}}{v_{ex}} \right) (t_{ex} - t_{inlet}) \qquad (4)$$

where:

E	is	evapotranspiration coefficient, dimensionless;
τ	is	solar transmissivity of cover, dimensionless;
I	is	solar radiation, W/m^2 (Btu/[h·ft^2]) of floor area;
A_f	is	floor area, m^2 (ft^2);
v_{ex}	is	specific volume of air leaving greenhouse, m^3/kg$_{air}$ (ft^3/lb$_{air}$);
Q_v	is	ventilation rate, m^3/(s·m^2) (ft^3/[min·ft^2]) of floor area;
$c_{p_{ex}}$	is	specific heat of air leaving greenhouse, J/(kg·°C) (Btu/[lb·°F]);
t_{ex}	is	temperature of exhaust air leaving greenhouse, °C (°F);
t_{inlet}	is	temperature of air entering greenhouse, °C (°F).

7.1.5 The terms U, A_c, t_i, and t_o in equation 4 are the same as in equation 1. The inside air temperature, t_i, can be taken to be the average of the inlet and outlet temperatures, or $(t_{ex} + t_{inlet})/2$. The overall heat transfer coefficient, U, may be obtained from table 1. The specific volume, v_{ex}, and specific heat, $c_{p_{ex}}$, of the air leaving the greenhouse may be determined from the psychrometric relationships presented in ASAE D271.2. If evaporative pads are used, inlet air temperature, t_{inlet}, should be that just inside the pads (see 7.2.1), otherwise it is simply t_o. Outside dry bulb and wet bulb temperatures for a given location can be estimated using the procedures outlined in the ASHRAE Handbook—Fundamentals.

7.1.6 Solar transmissivity, τ, can be estimated from the photosynthetically active radiation (PAR) transmittance values published in ASAE EP460 or, alternatively, 0.88 can be assumed for single layer covers or 0.79 for double layer covers with little error. Direct normal incidence values of τ will approximate summertime conditions over most of the U.S.; values at other times of the year, and for other locations, should be adjusted downward according to the expected solar incidence angles at midday. It should be noted that approximating the net solar radiation entering the greenhouse by τI neglects the energy reflected out of the house by the structure. A more correct analysis would include an appropriate correction factor; however, little information exists to suggest how such a factor should depend upon the various types of structures available. Observations suggest that the net solar gain can be as little as 50% of that incident on a horizontal surface outside for older greenhouses with numerous structural and heating members positioned overhead. However, until better information is developed, designers should be aware that equation 4 will likely over-predict ventilation requirements.

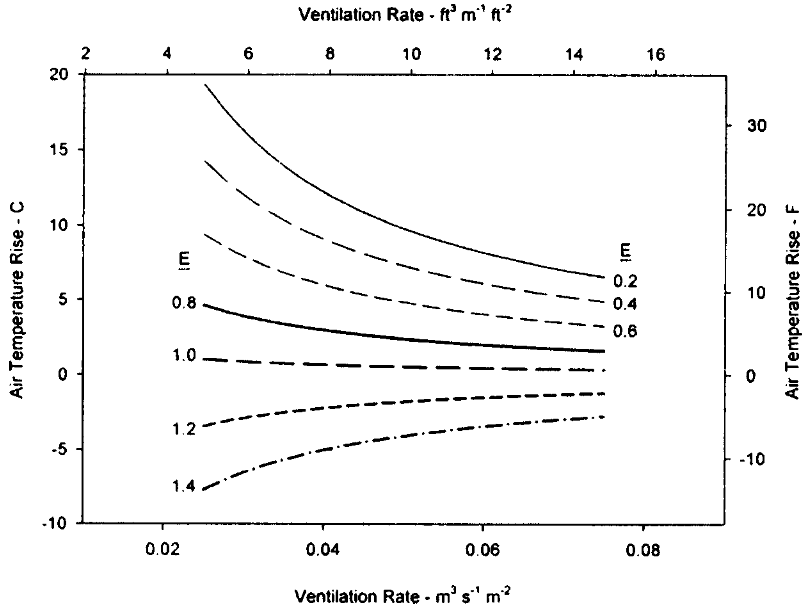

Figure 1 – Air temperature rise, $t_{ex}-t_{inlet}$, as a function of ventilation rate, Q_v, and transpiration coefficient, E (using equation 4). I = 900 W/m^2 (285 Btu/[h·f^2), τ = 0.80, A_c/A_f = 1.2, U = 4.0 W/(m^2. °K) (0.70 BTU/[h·ft^2· °F]), t_o = 33 °C (91.4 °F). For heavy lines, $t_{inlet} = t_o$, intended to represent cooling without evaporative pads; for thin lines, t_{inlet} = 26 °C (78.8 °F), intended to represent cooling with evaporative pads.

7.1.7 Solar radiation, I, can be estimated from tables presented in the ASHRAE Handbook—Fundamentals. For a given latitude, the radiation (identified as solar intensity in ASHRAE) on a horizontal surface at solar noon on July 21, corrected for atmospheric clearness, will provide a reasonable compromise between the generally higher solar levels during June and the generally hotter temperatures during August.

7.1.8 The evapotranspiration coefficient, E, in equation 4 may vary between 0.0 and 1.0, depending upon the type, amount, age, health, and/or stress level of the crop, the humidity ratio of the ventilation air at the inlet, and the amount of moisture available for evaporation from non-plant sources within the house. Very young plants without fully established root systems, stressed plants, very old, or diseased plants, plants that exhibit low daytime transpiration rates (e.g., most succulents), and high inlet humidity ratios will all tend to decrease E. Evaporative pad cooling reduced E by increasing inlet humidity ratio. Water evaporated within the house from wet floors, free standing water, and/or fog cooling must be accounted for by increasing E. Decreasing the humidity ratio of the inlet air will increase E. For a healthy, stress-free mature plant canopy cooled with very low humidity inlet air, E can exceed 1.0, resulting in a decrease in air temperature from inlet to exhaust.

7.1.9 Figure 1 illustrates air temperature rise, $t_{ex} - t_{inlet}$, as a function of ventilation rate, Q_v, and transpiration coefficient, E, as determined by equation 4. Solar energy, I, outside temperature, t_o, and inlet temperature, t_{inlet}, were chosen to be typical of the upper southeastern U.S. The curves plotted with heavy lines are intended to be representative of cooling without evaporative pads for a moderately full greenhouse approximately 3 times as much leaf area as floor area while those with thin lines are typical of cooling with evaporative pads for the same conditions.

7.1.10 Exhaust fans should be sized to deliver the required flow rate at 0.015 kPa (0.060 in. H_2O) static pressure when all guards and louvers are in place, unless specific design criteria require delivery at higher static pressures; e.g., insect screens or evaporative pads (see 7.2.2).

7.1.11 Fans should be spaced no more than 7.6 m (25 ft) apart along the walls or ends of the greenhouse. When possible, fans should be located on the leeward sides or ends. If the fans must be located on the windward sides, ventilation capacity should be increased by at least 10%. Summertime prevailing wind directions can be estimated from climatic data tabulated in the ASHRAE Handbook—Fundamentals.

7.1.12 A distance of 4 to 5 fan diameters should be maintained between the fan discharge and any nearby obstructions. Fans may be mounted in the roof if obstructions interfere with other mountings; however, the following trade-offs should be considered before selecting this option. In cold climates, roof mounted fans increase infiltration rates because of air leakage through the louvers, and the possibility exists that the fans will become inoperable due to sealing of the louvers through frozen condensate and/or precipitation. Roof mounted fans also generally increase the chances of the fans will become inoperable due to sealing of the louvers through frozen condensate and/or precipitation. precipitation leakage and shading.

7.1.13 In order to reduce friction losses, the fan louvers should be installed upstream of the fans (i.e., on the inside of the fan-louver system). The louvers should open freely and completely when the fans are turned on, but should close tightly when the fans are turned off to prevent unwanted air exchange.

7.1.14 Air inlet louvers or shutters should open outward. They should be motorized and wired to open during fan operation. Louver area should be at least 1.25 to 1.50 times the area of the fan, unless additional criteria (see 7.2) require otherwise.

7.1.15 Gaurds shall be used on fans to prevent accidents. Guards shall meet the requirements of ANSI/ASAE S493 and any applicable state and/or local codes.

7.1.16 Fans that have been tested and rated according to Air Movement and Control Association, Inc. (AMCA) 210 and which bear the seal of the AMCA Certified Rating Program are recommended. It should be noted, however, that fans may be tested with or without guards and louvers in place. Be sure that the fans provide the required capacity with guards and louvers installed.

7.2 Evaporative pad cooling

7.2.1 Evaporative pads are commonly used to aid greenhouse cooling in warm climates by lowering the dry bulb temperature of the inlet air. Pads and inlets sized to maintain the face velocities presented in table 3 can be expected to reduce inlet air temperature to within 2.0 °C (3.6 °F) of the outside wet bulb temperature at pressure drops through the pads not exceeding 0.015 kPa (0.060 in. H_2O). Higher face velocities typically result in reduced cooling. Temperature rise in a house cooled with evaporative pads will generally be greater, all other things being equal,

Table 3 – Recommended air velocities through various pad materials

Material type	Face velocity of air through pad[1)] m/s	ft/min
Aspen fiber mounted vertically 50 to 100 mm (2 to 4 in.) thick	0.76	150
Aspen fiber mounted horizontally 50 to 100 mm (2 to 4 in.) thick	1.00	200
Corrugated cellulose 100 mm (4 in.) thick	1.27	250
Corrugated cellulose 150 mm (6 in.) thick	1.78	350

[1)]Velocities may be increased by no more than 25% where spacing is limiting.

than in a house where evaporative pads are not used; however, average inside temperatures will generally be significantly lower (see figure 1).

7.2.2 Exhaust fans used with evaporative pads should be sized to provide the required airflow rate at an overall static pressure drop of 0.030 kPa (0.12 in. H_2O). The preferred pad-to-fan distance is 30 to 45 m (100 to 150 ft), but the limit is generally end-wall area available for pads. For very long houses where end-wall area is limiting, installing fans in the roof (see 7.1.12) or walls at the midpoint and pads at both ends may prove acceptable, although a stagnant hot spot may form at the midpoint of the house in this configuration.

7.2.3 Pads are normally installed in a continuous line along the side or end of the house opposite the exhaust fans. Vertical height should not be more than 2.4 m (8.0 ft) nor less than 0.60 m (2.0 ft) to insure uniform wetting of the pads.

7.2.4 Air inlets should be constructed so that they may be easily covered (during winter) without removing the pads.

7.2.5 When possible, pads should be located on the side of the house from which prevailing summer winds originate (see 7.1.11), unless the greenhouse is sheltered by another building or greenhouse within 7.6 m (25 ft).

7.2.6 Fans should not exhaust directly into pad inlets unless the distance between fan and inlet is more than 15 m (50 ft).

7.2.7 Fans should not exhaust directly into each other. Opposing fans should be offset from each other unless they are more than 4 to 5 fan diameters apart.

Table 4 – Recommended water flow and sump capacities for vertically mounted cooling pads

Pad type and thickness	Minimum water flow rate per unit length of pad L/(min·m)	gal/(min·ft)	Minimum sump capacity per unit pad area L/m^2	gal/ft^2
Aspen fiber 50 to 100 mm (2 to 4 in.)	3.7	0.30	20	0.50
Aspen fiber, desert conditions 50 to 100 mm (2 to 4 in.)	5.0	0.40	20	0.50
Corrugated cellulose 100 mm (4 in.)	6.2	0.50	33	0.80
Corrugated cellulose 150 mm (6 in.)	9.9	0.80	40	1.00

7.2.8 Cooled air tends to sink; therefore, vertical baffles above the plant growing area are not necessary or recommended. Sometimes baffles covering the lower two-thirds of the area under benches are installed for better cooling at bench height.

7.2.9 Recommended minimum water flow rates and sump capacities for vertically mounted pads are listed in table 4. These rates should be sufficient to insure that the pads remain wet from top to bottom, provided that the pads have been sized according to table 3.

7.2.10 Horizontal pads can be irrigated at a rate close to the evaporation requirements. The maximum recommended rate is 0.2 L/(s·m^2) (0.3 gal/[min·ft^2]) of pad area. Lower rates can be achieved by intermittent operation of the pad irrigation system.

7.2.11 The water returned to the pump should be screened to filter out debris and algae. A 50 mesh inclined screen mounted below the return flow is effective. The sump should be covered to protect it from insects, debris and sunlight (which can promote algae growth). Removable caps or valves should be installed on the ends of the water distribution pipes (located over the pads) to allow periodic flushing.

7.2.12 As water evaporates, mineral concentration in the sump increases. Either a continuous bleed-off or a periodic flushing of the sump will be necessary to keep concentrations to an acceptable level. Continuous bleed-off is the preferred option, at a rate of 0.002 L/min per m^3/s (0.005 gal/min per 1000 cfm) of air flow for areas where the make-up water mineral concentration is below 700 ppm (the upper limit for good quality agricultural water) and the maximum evaporation rate is less than or equal to 0.012 L/min per m^3/s (0.03 gal/min per 1000 cfm). For areas with mineral concentrations as high as 1500 ppm (generally accepted as the upper limit for irrigation), a bleed rate of 0.006 L/min per m^3/s (0.015 gal/min per 1000 cfm) should be adequate. Linear interpolation between (and extrapolation outside) these points should be adequate for salinities other than those listed.

7.2.13 It is preferable to protect the pad assembly by installing it inside any air inlet openings. The air inlet opening need not be continuous but should be uniformly distributed across the house.

7.2.14 If the pad assembly is located outside an inlet, the opening should be continuous, have no large obstructions and be centered in relation to the pad. Maximum design velocities through the inlet should be limited to 1.8 m/s (350 ft/min).

7.2.15 When the height of the pad exceeds that of the inlet, set the pad back from the inlet a minimum of half the height difference.

7.3 Fog cooling

7.3.1 Fog has long been used to supplement cooling when the ability of the plants to transpire is expected to be impaired (e.g., in rooting and transplant houses).

7.3.2 Fog is generally produced using a high pressure pump to atomize water by forcing it through fixed nozzles, nozzles attached to the tips of rotating fan blades, or similar arrangement. Atomization may also be accomplished by a rotating disk or acoustic oscillator. The atomized water droplets should be 0.5 to 50 µm (0.00002 - 0.002 in) to insure proper cooling.

7.3.3 Fog may be distributed through: 1) fixed nozzles located appropriately throughout the house, 2) perforated poly-tubes, 3) horizontal air circulation systems, or 4) oscillating fan-nozzle designs.

7.3.4 Good quality water is needed for fogging systems. The water should be free of precipitates and salts, and filtered where necessary.

7.3.5 In naturally ventilated greenhouses, nozzles should be uniformly spaced throughout the house. Pipes and nozzles should be located over aisles to prevent water dripping directly onto plants.

7.3.6 In fan cooled houses, most of the fog should be concentrated near the inlet with a small amount distributed evenly over the rest of the house.

7.4 Shading

7.4.1 The use of shading to aid cooling is not without problems; however, in some circumstances it may provide the only means for continuing production during the hottest part of the year. Most shading is accomplished using porous, woven or knitted materials, usually plastic, placed on top of the greenhouse cover (external) or suspended between the gutters (internal) in ridge and furrow houses or mounted parallel to the roof line. Shade cloths are typically green, black, white, or aluminized.

7.4.2 The ability of shade materials to control temperature is limited by the solar and thermal radiation characteristics of the material. Black and green external shade cloths have been observed to reduce temperature gains by less than 50% of the shade rating (amount of visible radiation blocked). White cloths tend to provide greater temperature reduction but they generally cost 50 to 100% more. Very little information is available on the performance of aluminized materials.

7.4.3 Where shade cloths cannot be easily retracted during periods of cloudy weather, shade ratings of the cloths used should be carefully chosen to avoid limiting growth. Higher values can be used with shade (“low-light”) plants or crops with a shallow canopy depth (e.g., potted plants on benches). Lower values should be used with taller, more dense crops (e.g., mature tomatoes, cucumbers, etc.).

7.4.4 State-of-the-art shading systems generally mount shade cloths in a manner that facilitates automatic extension or retraction as needed (e.g., between the gutters or parallel to the roof line). This allows materials with higher shade ratings to be used without retarding growth significantly. Control should be based on both temperature and light levels to avoid shading during hot, hazy periods when light may be limiting.

7.4.5 Some curtain materials are highly flammable when exposed to a heat source (e.g., unit heaters or CO_2 burners). It is recommended that fire retarding curtain materials are installed to prevent rapid spread in case of fire. At a minimum, every other section (e.g., between successive trusses) of curtain material should be made of fire retarding materials.

7.4.6 Shading compounds, sometimes referred to as “whitewash,” can be applied to the outside of greenhouses with some degree of success. Degree of shading is controlled by the thickness of the coating or by application of the material in alternating strips so that only a portion of the glazing is covered. These materials are expected to wear away as a result of exposure to the weather; however, it is common for physical removal to become necessary as light becomes limiting in late fall. Compounds can be purchased with differing degrees of adhesion (lower adhesion levels are recommended for plastic glazings); however, physical removal will be more difficult with flexible plastics (e.g., polyethylene film) compared to rigid plastics or glass. Care should be used during application and removal to prevent the compounds from dripping onto foliage through cracks in the glazing.

7.5 Winter ventilation considerations

7.5.1 Winter ventilation requirements may vary with location and climate more so than summer ventilation rates. From 10 to 50% of the summertime ventilation requirements, or 0.0050 to 0.020 $m^3/(s \cdot m^2)$ (1.0 to 4.0 cfm/ft^2) of floor area, will generally suffice in cooler climates; however, warmer regions may require more. Local weather records, in conjunction with equation 4, can be used to provide a reasonable estimate.

7.5.2 If exhaust fans are individually controlled (see 7.6.1), there should be no need to provide winter ventilation control separate from that for summer ventilation, even in the colder regions of the US. If individual control is not possible, separate winter ventilation control may have to be provided to prevent the introduction of excessive quantities of cold air into the greenhouse and the resulting possibility of crop damage.

7.5.3 If daytime outside temperatures below 5 °C (40 °F) are expected, incoming air should be introduced so that it mixes and is warmed by the interior air before contacting the plants. A continuous vent window located high on the wall opposite the fans provides one alternative. In such cases, the inlet should be sized to provide an air velocity of 3.6 m/s (700 ft/min) at the required flow rate. Either perforated-tube (see 5.3) or horizontal airflow (see 5.4) systems can be used to distribute the cold air within the house so as to maximize mixing before it contacts the plants.

7.6 Venting controls

7.6.1 It is preferable to control ventilation in multiple stages. Where only a few fans are needed, two-speed motors can provide additional flexibility. Fans should be activated sequentially and in equally spaced groups in response to cooling needs.

7.6.2 If thermostats are used, the first stage of ventilation should be at least 4 to 6 °C (8 to 10 °F) above the heat setting to prevent heating and ventilating from cycling. More accurate or more sophisticated controls (e.g., dedicated controllers or computer control systems) require smaller deadbands.

7.6.3 Solid-state sensors should be used for humidity control, if needed, because of the frequent calibration required of the older types of humidistats. Humidity sensors should be aspirated in a manner similar to that described in 5.7.2.

7.6.4 Control sensors should be located and shielded according to 5.7.3.

7.6.5 Inlet vents should be controlled so that they are activated in proportion to the number of active fans or in response to the pressure drop generated across the inlet. Experience suggests the latter approach provides superior control in windy conditions if the pressure drop is at least 0.01 kPa (0.04 in. H_2O).

7.6.6 If line voltage controls are used, care must be taken to isolate the control systems from accidental human contact. Low voltage controls may be a better choice in some situations based upon safety and wire-cost considerations.

7.6.7 A switch should be provided with each fan to allow manual override in cases of automatic control failure.

7.6.8 Safety disconnects should be installed near each fan and pump. All wiring and electrical equipment installations should be according to applicable codes. Some consideration should be given to installing back-up electrical generation in case of power failure, especially for exhaust fans during hot weather but also for other critical power needs.

7.7 Cooling and ventilating small greenhouses

7.7.1 Small greenhouses (less than 28 m^2 [300 ft^2] floor area) may be naturally ventilated using ridge vents and doors (or side vents) or using mechanical ventilation. If mechanical ventilation is used (including evaporative cooling), the following design criteria should be adhered to:

- summer ventilation rate: 0.06 $m^3/(s \cdot m^2)$ (12 cfm/ft^2) of floor area;
- evaporative cooling capacity: 0.08 $m^3/(s \cdot m^2)$ (15 cfm/ft^2) of floor area.

7.7.2 Evaporative cooling can be accomplished with a packaged evaporative cooler for less cost and greater operating convenience than with a fan-and-pad system. An exhaust opening (such as a door or automatic shutter) is required at the end of the house opposite the cooler.

7.7.3 Maximum winter ventilation rates are about 1/2 the maximum summer ventilation rates and will be greatest for lean-to houses attached to the east, south or west wall of a building. Either two speed fans or natural airflow is generally used for ventilation.

Annex A
(informative)
Bibliography

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