HORTICULTURAL ENGINEERING

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Contents

Summary

Horticultural engineering blends (agricultural) engineering, plant science, computer science, and control theory to produce effective and efficient plant growing systems ranging from low-tech row cover systems to high-tech greenhouses. In case of greenhouse production systems, another frequently used term is controlled environment

agriculture (CEA). People trained in this discipline have a strong understanding of and appreciation for the engineering, biological, and environmental aspects of plant production. Horticultural engineers play a vital role in the secure, healthy, and cost-effective production of many edible and ornamental plant species on which we all depend. This chapter discusses various structures, their designs and operation used for CEA crop production. In addition, important environmental parameters and common control strategies are presented.

1. Introduction

Whether for protection, season extension, or year-round production, people have used a variety of techniques and structures to shield plants from unfavorable growing conditions. Because the design and operation of these structures has such a dramatic impact on the growth and development of the plants grown inside, it became clear early on that in addition to plant production knowledge, engineering expertise is critical to designing optimum growing systems. Over the last century, engineers have made significant contributions to structural and equipment designs, as well as to specialized control strategies, and over the last decades have developed a systems approach to designing and operating greenhouse facilities. This approach ensures that the possible impacts of changes made to a single greenhouse component will be considered and evaluated in order to improve the performance of the overall production system. For example, when supplemental lighting is added, plants typically grow faster requiring more water and nutrients (and often carbon dioxide), while releasing more water vapor through transpiration. At the same time, the lighting system will release significant amounts of heat radiation. Thus, the act of adding supplemental lighting has a cascading effect that should be anticipated in order to provide optimum growing conditions, while at the same time maintaining an economically viable business model.

2. Structures

2.1. Low Technology Structures

Very low technology structures such as row covers, rain shelters and screen houses provide minimal but often effective environmental control. Row covers can be porous or solid plastic film which may be manually adjusted during the day for ventilation. Rain shelters and screen houses are covered with solid film or screening respectively and do not require ventilation. Screen houses provide some shading and protection from heavy precipitation and possibly some degree of insect exclusion. Increased environmental control including ventilation is provided by high tunnels, simple hoop houses and Chinese solar greenhouses. Plants are typically irrigated with a simple (and/or manual) irrigation system and little to no supplemental heating is provided to maintain a set point temperature. Some low technology structures incorporate design features that allow for the storage of solar radiation during the day and (slow) release during the night (e.g., Chinese solar greenhouses). Such features can extend the growing season while minimizing the need for supplemental heating. In most of the low technology structures, most crop production practices are performed using manual labor. Typical installation and maintenance costs of low technology structures are much lower compared with the high technology structures. However, designs are not always well thought out and optimized for local conditions, resulting in increased risk for structural failures and/or underperforming crops.

2.2. High Technology Structures

High technology plant growth structures include (year-round) greenhouses and growth rooms. Growth rooms are special types of controlled environment plant production structures that are typically not exposed to outside weather conditions and therefore not further discussed here. The bibliography includes several references that specifically address plant growth rooms and chambers. The ventilation rate in greenhouse structures is typically adjusted automatically by opening/closing strategically placed ventilation windows, and/or by engaging electric fans. Typical covering materials include glass, single or twin wall rigid plastic panels, or single layer or double layer air-inflated plastic film. Plants are irrigated either manually or with one of a range of (automated) irrigation systems. The high technology growing structures are often outfitted with additional equipment including (but not limited to) heating, cooling, humidification, dehumidification, supplemental lighting, shading, benches, carbon dioxide enrichment, material handling systems, and seeding and transplanting equipment. Many crop production practices are typically automated (e.g., irrigation, crop movement), while optimum growing conditions are often maintained by a computerized control system.

2.3. Shapes

A variety of greenhouse shapes have been developed, and are often identified by the shape of a cross section. Common shapes include hoop (bow), A-frame, gable, slant-leg, and gothic, and can be constructed as freestanding or gutter-connected structures. The steeper the roof sections of single span units, the better any snow will shed from the roof but the optimum roof slope should generally be based on light transmission. Gutter-connected greenhouses have less structural surface area per unit of growing area compared to freestanding greenhouses, reducing the cost per unit growing area for maintaining optimum growing conditions. Other greenhouse shapes include lean-to greenhouses that are attached lengthwise to a commercial or residential building, and uneven span greenhouses that have two dissimilar roof sections to optimize transmission of solar radiation at higher latitudes (e.g., a larger south-facing roof section), or to improve ventilation in arid environments (e.g., saw-tooth design). Open roof greenhouses have sections that can move to provide large, natural ventilation openings and include designs with movable horizontal sections.

2.4. Materials

2.4.1. Structure

Greenhouses can be constructed using a variety of materials to support the glazing system, including metal (e.g., galvanized steel, aluminum), wood (including bamboo), and plastic (e.g., PVC piping). While typical greenhouse structures are relatively light, they can (over time) be exposed to a range of external and internal loads that require robust construction (e.g., wind and snow loads, static loads from overhead equipment and plant material). Construction materials need to be able to withstand these loads, as well as high and low temperatures, and long-duration exposure to solar radiation.

Concrete is frequently used in foundations, lower side walls as well as for walkways for material transport and sometimes as a floor for entire growing areas. While more expensive to install, concrete has significant advantages over other flooring materials. These advantages include support and ease of movement for heavier equipment, elimination of runoff from excess irrigation water to the outside environment (if installed properly and as part of a recirculation system), and easy cleanup after completion of the cropping cycle. Because greenhouse environments are humid and sometimes sprayed with chemicals, construction materials should be able to withstand these conditions without premature failure or decomposition. The construction materials can be protected (e.g., by applying paint), but any protective treatments should not result in the release of chemicals harmful to plants. Some growers opt to paint many of the interior surfaces with a white reflective plaint. This helps reflect light from those surfaces that can then be absorbed by the plants.

In higher technology greenhouse operations investment in the structure can be relatively low compared to the total investment and value of the crop so designs should be adequate to withstand all structural loads. It is becoming increasingly common for greenhouse designs to meet zoning code requirements.

2.4.2. Glazing

Greenhouse structures can be covered with glass, rigid plastic panels (polycarbonate or acrylic), or plastic film (e.g., polyethylene (PE), polyvinyl chloride (PVC), ethylene-tetrafluoroethylene (ETFE)). But before discussing glazing issues in more detail, it is important to review some light (radiation) terminology. The radiation spectrum can be divided into several specific wavebands, which are defined by their range of wavelengths or energy content (e.g., radio and TV radiation, microwave radiation, visible light, etc.). The longer the wavelength, the smaller its energy content per photon. Typically, the wavelength of light used by plants is expressed in nanometers (nm; one billionth of a meter). Not all components of sunlight (approximately 280-2,800 nm) are useful for plant growth and development. In general, ultraviolet (UV; less than 380 nm) and excessive infrared (IR; above 770 nm) or heat radiation can be harmful to plants and should be avoided. However, some plant species require a certain amount of UV radiation for proper development. (Note: honey bees use UV radiation for navigation and hence are not ideal pollinators in greenhouses covered with glazing that blocks UV radiation.) Plants primarily use photosynthetically active radiation (PAR; 400-700 nm) as their energy source for the process of photosynthesis. Therefore, greenhouse structures and especially the glazing material should have a high transmittance for PAR radiation. Note that the terms light and radiation are used interchangeably and that visible light is not exactly the same as PAR. Visible light consist of wavelengths that cover a slightly larger part of the radiation spectrum (380-770 nm). Since light is the driving force for photosynthesis, small changes in light intensity have an immediate effect on the rate of photosynthesis. Plants respond to changes in light intensity very rapidly, particularly when the initial intensity was low to moderate. Shade plants or plants adapted to lower light environments require lower light intensities for proper growth and development and may be damaged when placed in high light environments (photoinhibition).

2.4.2.1 Direct and Diffused Radiation

The interaction between incoming light and greenhouse cladding material has a significant impact on crop production. Based on physical properties, surface orientation (angle of incidence), and the number of layers of the glazing material, portions of the incoming light are either transmitted, reflected and/or absorbed.

On a cloudless day, most sunlight travels in a straight path through the Earth's atmosphere. Under these conditions, the incoming light is termed direct radiation. On a cloudy day, the sunlight is diffused by the many water vapor particles in the moisture-laden air. This light is called diffuse radiation. It is important to understand that diffuse radiation reaches the greenhouse surface from many different directions other than the direction of its source (the sun). This phenomenon can actually be an advantage for greenhouse crop production. Diffuse light is capable of reaching deeper into the plant canopy because it can penetrate from many different angles. This results in improved plant growth. However, the light intensity from diffuse light is usually much lower than the intensity from direct light.

In addition to the interaction between incoming light and the greenhouse cladding material, structural elements such as posts, trusses and equipment (e.g., overhead heating pipes, shade curtains and supplemental light fixtures) reduce the amount of light that reaches the top of the plant canopy. It is not unusual for a greenhouse structure to reduce the amount of light that ultimately reaches the plant canopy by an annual average of 30-50% compared to the amount of light available outside the greenhouse. Therefore, the need for maximum light transmission should be one of the main criteria during the design of greenhouses and overhead equipment, and in selecting glazing materials.

2.4.2.2 Types of Glazing Materials

The most common greenhouse glazing materials are glass, rigid plastics and plastic films (Table 1). Glass has the highest light transmission, lasts the longest (30-plus years) and is the most expensive. Tempered or laminated glass is recommended because it is stronger allowing for fewer support bars, and it increases the safety for people working underneath in case of breakage and in some jurisdictions may be required by the local building code. Most glass greenhouses are clad with a single layer resulting in a relatively high heat transfer coefficient (Table 2).

Rigid plastics (e.g., polycarbonate and acrylic) should last 10 to 20 years. For use in temperate regions, they are usually manufactured as twin-walled sheets. The air space between the two walls acts as an insulator. Light transmission through rigid plastics is very good, although it usually decreases over time as the plastics age and can turn yellow as a result of the UV radiation contained in sunlight. The large sheets are much lighter than glass and require fewer support bars to attach them to the greenhouse frame.

Low cost transparent plastic films (e.g., PE and PVC) are the cheapest greenhouse cladding materials, but usually last only three to four years. ETFE can last as long as 10 or more years. Plastic films, normally 0.15 mm (6 mils) thick, are frequently installed in two layers that are inflated by a small fan. This provides some strength to the greenhouse surface and the air space between the layers acts as an insulator, significantly reducing the heat loss from the greenhouse. Air-inflated greenhouse surfaces experience approximately 60% of the heat loss compared to similar surfaces clad with a single layer of glass or plastic. It is important to use outside air to inflate the two layers of film because this will significantly reduce potential condensation between the layers that could reduce light transmission. A common additive to the film material (the so-called infrared or IR films) blocks some of the infrared (heat) radiation from entering or escaping from the greenhouse environment, and thus reduces the amount of heating energy required to maintain optimum growing conditions. Some films are manufactured with a special surface treatment to prevent condensation droplets from falling on the crop (so-called no-drip films). Instead, the condensation water flows along the film and runs off to the lowest point.

Cladding material	**Direct PAR transmittance (%)**	**Infrared (heat) transmittance[1] (%)**	**Ultraviolet transmittance[2] (%)**	**Life expectancy (years)**
Glass	90	0-3	60-70	30+
Acrylic[3]	86	0-3	44	20
Polycarbonate[3]	75	0-3	18	10
Polyethylene[4]	88	50	80	3-4
PE, IR & AC[4,5]	88	30	80	3-4

Table 1. Comparing characteristics of glazing materials.
[1]For wavelengths above 3,000 nm, [2]For wavelengths between 300 and 400 nm, [3]Twin wall, [4]single layer, [5]Polyethylene film with an infrared barrier and an anti-condensate surface treatment.

Cladding material	**U (W/m^2 °C)**	**U (Btu/hr ft^2 °F)**
Single (double) layer glass	6.2 (4.0)	1.1 (0.7)
Single (double) layer polyethylene	6.2 (4.0)	1.1 (0.7)
Double layer + energy curtain	1.7-2.8	0.3-0.5
Twin-wall layer acrylic	3.2	0.6
Twin-wall polycarbonate	3.2	0.6
1.3 cm (0.5 inch) plywood	4.0	0.7
20 cm (8 inch) concrete block	2.8	0.5
5 cm (2 inch) polystyrene board	0.6	0.1

Table 2. Heat transfer coefficients (U-values) for glazing and construction materials.

2.5. Design Loads

Greenhouse design and construction is generally governed by local building codes and standards (e.g., in the USA by the International Building Code (IBC) and ASCE 7: Minimum Design Loads of Buildings and Other Structures; in the Netherlands by NEN 3859 and NEN-EN 13031-1). A term often used by building designers to describe the forces acting on the various structural components is “load.” For example, wind and snow exert forces on a greenhouse structure and these forces are termed wind and snow loads. The common unit of measure used to express loads is kPa (pounds per square foot in British units). When loads exceed design specifications, they can cause irreversible deflection (bending) and/or buckling (twisting) of structural components. There are several other types of loads that also need to be considered. So-called dead loads are forces resulting from the structure itself (e.g. posts, trusses, glazing material, etc.) as well as the equipment attached to the structure (e.g. heating pipes, supplemental lighting system, irrigation booms, etc.). Dead loads can be calculated once the recommended structural materials are known as well as the equipment attached to the structure. Live loads are temporary loads exerted on a structure, for example people walking on the roof during cleaning and maintenance, equipment placed on the roof during repairs, and hanging baskets (provided they are not grown year-round, in which case they should be considered as dead loads). Note that the IBC also requires the calculation of seismic loads that are typically most important in terms of the attachment and mounting of equipment.

Wind loads can exert a positive (as a pressure force on a surface) or negative (as a suction force on a surface) force on the various components of the structure. The challenge with positive (usually on the windward side) and negative (usually on the leeward side) wind loads is that they are present at the same time on different parts of the structure and thus need to be evaluated carefully to determine the overall structural loading. Wind loads are determined by the design and placement of the various greenhouse surfaces, wind speed (determined by location and surrounding structures), direction and gustiness. Design wind loads are usually increased when the greenhouse is accessible to the public, to ensure their safety.

Snow loads are calculated from design ground snow loads published for many locations across the world (for the USA, local building code officials can provide information about the design snow load at the building site). However, designers need to take into account that local snow loads may differ from the published values. Snow loads are determined by the insulation factor (thermal resistance) of the roof material (a single layer glazing has a lower resistance than a double-layer glazing, allowing for easier snowmelt), the design of the roof (flat, angled or curved), local conditions (open exposure or sheltered by neighboring structures or trees) and the presence or absence of a heating system. Design snow loads are typically increased when the greenhouse is publicly accessible. All designs should account for the fact that snow loads can be uneven due to snowdrift and/or sliding, particularly when sliding onto lower roof sections.

The above-described loads can be present singularly or in combination, and for each structural element, including the greenhouse foundation, the worst-case scenario needs to be considered in order to ensure structural integrity under all possible load combinations. Since this can be a tedious process, many greenhouse designers use computer software packages specifically designed to calculate the loads (forces) exerted on the various structural elements. These calculated forces are used to select the appropriate building materials and their dimensions (e.g. pipe size and wall thickness).

In some regions of the world, hail damage is a significant issue. The size and weight of the hailstones and their impact velocity determine the force exerted on the glazing material. Stones larger than 2.5 cm (1 inch) in diameter with an impact velocity exceeding 80 km/h (50 mph) are likely to cause damage. Polycarbonate and modified impact acrylic glazing panels are the best glazing choices for greenhouses located in areas experiencing such conditions. In some cases, tempered glass and double layer polyethylene film have also proven effective against moderate hail storms.

3. Equipment

3.1. Heating

Greenhouses can be heated using a variety of methods and equipment. Typically, a fuel is combusted to heat either air or water that is circulated through the greenhouse environment. In some cases, infrared heating systems are used that radiate heat energy to exposed surfaces of the plant canopy. On rare occasions, electric (resistance) heating is used, but its operating cost is usually prohibitively high. However, as the costs of other fuel sources (particularly fossil fuels) continue to rise more rapidly, electric heating will at some point become competitive even for larger greenhouse operations in more and more locations.

Hot air heating systems include unit heaters and furnaces. The heat generated by the combustion process can be transferred to the greenhouse air through a heat exchanger, or the greenhouse air itself can be used as the oxygen source for the combustion process and then released into the greenhouse. The first approach allows for the combustion air to remain separate from the greenhouse environment (so-called separated combustion), minimizing the risk of releasing small amounts of potentially harmful gasses (e.g., ethylene) into the greenhouse environment. The second approach requires carefully adjusted combustion equipment and complete fuel combustion so that only water vapor and CO_2 are released into the greenhouse environment. An intermediate approach is to use greenhouse air for combustion, but vent the combustion gasses to the outside environment. Fans incorporated in hot air heating systems generate jets of warm air that often require additional distribution strategies to ensure even heating of the growing environment. These strategies include the use of inflatable polyethylene distribution ducts which can be overhead or under the benches or crop rows, (the so-called poly-tube system), or the use of strategically placed horizontal or vertical airflow fans. Hot air heating systems are relatively easy to install at a modest cost, but typically distribute the heat less uniformly compared to hot water heating systems.

Hot water heating systems consist of a boiler and a water circulation system (pumping and piping system). The heat generated by the combustion process inside the boiler is transferred to the circulating water that is pumped to the greenhouse and circulated through a pipe and/or tube distribution system. Boilers can be installed in separate rooms, reducing the risk of contaminating the greenhouse environment with potentially harmful combustion gasses. Insulating the heat delivery pipes between the boiler room and the greenhouse space being heated is important for energy conservation. The heating pipes are typically installed along the posts (in gutter-connected greenhouses), around the perimeter, and overhead (including near gutters where the released heat can increase snowmelt, and additional pipes supported by trusses between widely spaced gutters and spaced to provide uniform heat delivery). Some greenhouses are designed with floor or bench heating and then additional heating tubes are installed in the floor or on/near the benches. These so called root-zone heating systems have the advantage of providing independent control of root zone temperatures and high uniformity heat very close to the plant canopy. However, root-zone heating systems are typically not able to provide sufficient heating capacity during the coldest times of the year, necessitating the use of additional heating capacity in the form of perimeter and overhead heating pipes. Many greenhouses using hot water heating systems are divided into different heating zones, allowing for different temperature control with the help of separately controllable mixing valves.

Infrared heating systems have the advantage of immediate heat delivery once turned on, but only 'exposed' (in terms of line-of-sight) plant canopy surfaces will receive the radiant heat. This can lead to non-uniform heating. In addition, infrared heating systems are typically designed as line-sources and require some distance between the source and the radiated canopy surfaces to accomplish uniform distribution. Finally, like hot air systems, infrared heating systems accumulate little heat storage during operation, so that in case of an emergency shut-down little residual heat is available in the system that could extend the time until the temperature drops below critical levels.

The significant increase in fossil fuel prices experienced during the last decade has put a greater emphasis on energy conservation and alternative energy sources. The energy conservation measures employed include relatively simple measures such as sealing unintended cracks and openings in the greenhouse surface, improved insulation of structural components and heat transportation systems, and timely equipment maintenance, as well as more advanced measures such as movable insulation/shade curtains, new heating equipment with higher efficiencies (e.g., condensing boilers, heat pumps, combined heat and power systems), and novel control strategies (e.g., temperature integration). Some growers have opted to delay crop production to periods with warmer weather, while others have decided to grow crops at lower set point temperatures (often requiring longer production periods and the potential for physiological challenges).

Alternative energy sources (i.e., other than fossil fuels) that are being used and/or evaluated for greenhouse applications include solar electric, solar thermal, wind, hydro power, and biomass. Many alternative energy installations require significant investments that may or may not be offset by a variety of (local or national) financial incentives. It will remain challenging to develop energy conservation and alternative energy strategies for greenhouse operations because of the significant differences in size, scope, and local circumstances. In many cases, individualized approaches will have to be developed that are sustainable both in terms of the economic viability of the greenhouse operation as well as the environment.

3.2. Ventilating and Evaporative Cooling

3.2.1. Ventilating

In order to maintain an optimum growing temperature (and humidity), warm (and humid) greenhouse air needs to be replaced with cooler outside air. To accomplish this, greenhouses use either mechanical or natural ventilation. While air conditioning of greenhouses is certainly technically feasible, the installation and operating costs are typically prohibitively high. Mechanical ventilation requires (sometimes louvered, but mostly not) inlet openings, exhaust fans, and electricity to operate the fans. When designed properly, mechanical ventilation is able to provide adequate cooling under a wide variety of weather conditions throughout many locations in the temperate climate zone. Typical design specifications call for a maximum mechanical ventilation capacity of 0.05 or 0.06 m^3/s per m^2 of floor area (10 or 12 cfm per ft^2 of floor area) for greenhouses with or without a shade curtain, respectively. When an insect screen and/or an evaporative cooling pad are used, the inlet area should be carefully sized to prevent excess pressure drop and reduction of total air volume relative to the fully open inlets. In that case, the ventilation fans should be able to overcome the additional airflow resistance created by the screen and/or evaporative cooling pad (i.e., the fans have to move the same amount of air at a higher static pressure). Multiple and staged fans can provide different ventilation rates based on environmental conditions. Variable speed fan motors allow for more precise ventilation rate control and can reduce overall electricity consumption.

Natural ventilation works based on two physical phenomena: thermal buoyancy (warm air is less dense and rises) and the so-called "wind effect" (wind blowing outside the greenhouse creates small pressure differences between the windward and leeward side of the greenhouse causing air to move towards the leeward side). All that is needed are (strategically placed) inlet and outlet openings, vent window motors, and electricity to operate the motors. In some cases, the vent window positions are changed manually, eliminating the need for motors and electricity, but increasing the amount of labor since frequent adjustments are necessary. Compared to mechanical ventilation systems, electrically operated natural ventilation systems use a lot less electricity and produce (some) noise only when the vent window position is changed. When using a natural ventilation system, additional cooling can be provided by a fog system if the humidity of the air is not too high. Unfortunately, natural ventilation does not work very well on warm days when the outside wind velocity is low (less than 1 m/s or 200 ft/min). Keep in mind that whether using either system with no other cooling capabilities (such as evaporative cooling that is described below), the indoor temperature cannot be lowered below the outdoor temperature.

For most freestanding greenhouses, mechanical ventilation systems usually move the air along the length of the greenhouse (i.e., the exhaust fans and inlet openings are installed in opposite end walls). To avoid excessive air speed within the greenhouse inlet to fan distances are generally limited to 70 to 80 m depending on local climate. Natural ventilation systems generally provide crosswise ventilation (using side wall and roof vents).

In gutter-connected greenhouses, mechanical ventilation systems inlets and outlets can be installed in the side or end walls, while natural ventilation systems usually consist of only roof vents. Sidewall vents have limited influence on ventilation on interior bays in very wide greenhouses. Ultimate natural ventilation systems include the open-roof greenhouse design, where the very large maximum ventilation opening allows for the indoor temperature to almost never exceed the outdoor temperature. This is often not attainable with mechanically ventilated greenhouses due to the very large amounts of air that such systems would have to move through the greenhouse to accomplish the same results.

When insect screens are installed in ventilation openings, the additional resistance to airflow created by the screen material has to be taken into account to ensure adequate ventilation rates. Often, the screen area is made larger compared to the inlet area to allow sufficient amounts of air to enter the greenhouse. The smaller the openings of the screen material (the opening size is typically selected based on the size of the insects to be excluded), the larger the resistance to airflow. The details of the screen design also influence airflow resistance.

Whatever ventilation system is used, uniform air distribution inside the greenhouse is important because uniform crop production is only possible when all plants experience the same environmental conditions. Therefore, horizontal airflow fans are frequently installed to ensure proper air mixing. The recommended fan capacity is approximately 0.015 m^3/s per m^2 of growing area (3 cfm per ft^2 of growing area). The airflow capacity of horizontal airflow fans is very small compared to the capacity of ventilation fans. Therefore, some growers opt to turn their horizontal airflow fans off when the ventilation fans are operating.

3.2.2. Evaporative Cooling

When regular ventilation and shading (e.g., white wash or movable curtains) are not able to keep the greenhouse temperature at the desired set point, additional cooling is needed. In homes and office buildings, mechanical refrigeration (air conditioning) is often used, but in greenhouses where the quantity of heat to be removed can be very large, air conditioning is generally not economical. Fortunately, we can use evaporative cooling as a simple and relatively inexpensive alternative. The process of evaporation requires heat. This heat (energy) is provided by the surrounding air, causing the air temperature to drop. At the same time, the humidity of the air increases as the evaporated water transitions into water vapor and becomes part of the surrounding air mass. The maximum amount of cooling possible with evaporative cooling systems depends on the initial humidity of the air (the drier the initial air, the more water can be evaporated into it, the more the final air temperature will drop), as well as the initial temperature of the air (warmer air is able to contain more water vapor compared to colder air). Two different evaporative cooling systems can be used to help maintain target set point temperatures during warm outside conditions when the ventilation system alone is not sufficient to maintain the set point: the pad-and-fan system and the fog system.

3.2.2.1 Pad-and-fan System

Pad-and-fan systems (Figure 1) are part of a greenhouse's mechanical ventilation system. Note that swamp coolers can be considered stand-alone evaporative cooling systems, but otherwise operate similarly to pad-and-fan systems. For pad-and-fan systems, an evaporative cooling pad is installed in the ventilation opening, ensuring that all incoming ventilation air travels through the pad before it can enter the greenhouse environment. The pads are typically made of a corrugated material (impregnated paper or plastic) that is glued together in such a way as to allow air to pass through it while ensuring a maximum contact surface between the air and the wet pad material. Water is pumped to the top of the pad and released through small openings along the entire length of the supply pipe. These openings are typically pointed upward to prevent clogging by any debris that might be pumped through the system (installing a filter system is recommended). A cover is used to channel the water downwards onto the top of the pads after it is released from the openings. The opening spacing is designed so that the entire pad area wets evenly without allowing patches to remain dry. At the bottom of the pad, excess water is collected and returned to a sump tank so it can be reused. The sump tank is outfitted with a float valve allowing for make-up water to be added. Since a portion of the recirculating water is lost through evaporation, the salt concentration in the remaining water increases over time. To prevent an excessive salt concentration from creating salt build-up (crystals) on the pad material (reducing pad efficiency), it is a common practice to continuously bleed approximately 10% of the returning water to a designated drain. In addition, during summer operation, it is common to 'run the pads dry' during the nighttime hours to prevent algae build-up that can also reduce pad efficiency. As the cooled (and humidified) air exits the pad and moves through the greenhouse towards the exhaust fans, it picks up heat from the greenhouse environment. Therefore, pad-and-fan systems experience a temperature gradient between the inlet (pad) and the outlet (fan) side of the greenhouse. In properly designed systems, this temperature gradient is minimal, providing all plants with similar conditions. However, temperature gradients of up to 4-6ºC (7-10°F) are not uncommon.

The required evaporative pad area depends on the pad thickness. For the typical, vertically mounted 10 cm (4 inch) thick pads, the required area (in m^2 or ft^2) can be calculated by dividing the total greenhouse ventilation fan capacity (in m^3/s or cfm) by the recommended air velocity through the pad (by the number 1.3 when using SI units, or 250 when using British units). For 15 cm (6 inch) thick pads, the fan capacity should be divided by the number 1.8 (SI units) or 350 (British units). The recommended minimum pump capacity is 26 and 42 L/s per linear meter of pad (0.5 and 0.8 gpm per linear foot of pad) for the 10 cm (4 inch) and 15 cm (6 inch) thick pads, respectively. The recommended minimum sump tank capacity is 33 and 41 L per m^2 of pad area (0.8 and 1 gallon per ft^2 of pad area) for the four and six-inch pads, respectively. For evaporative cooling pads, the estimated maximum water usage can be as high as 17-20 L/h per m^2 of pad area (10-12 gpd per ft^2 of pad area).

3.2.2.2 Fog System

The other evaporative cooling system used in greenhouses is the fog system (Figure 2). This system is sometimes used in greenhouses with natural ventilation systems. Natural ventilation systems generally are not able to overcome the additional airflow resistance created by placing an evaporative cooling pad directly in the ventilation inlets. The nozzles of a fog system can be installed throughout the greenhouse, resulting in a more uniform cooling pattern compared to the pad-and-fan system. The recommended spacing is approximately one nozzle for every 5-10 m^2 (50-100 ft^2) of growing area. The water pressure used in greenhouse fog systems is very high (3,447 kPa, or 500 psi, and higher) in order to produce very fine droplets that evaporate before the droplets can reach plant surfaces. The water usage per nozzle is small: approximately 3.8-4.5 L/h (1-

1.2 gph). In addition, the water needs to be free of any impurities to prevent clogging of the small nozzle openings. As a result, water treatment (filtration and purification) and a high-pressure pump are needed to operate a fog system. The supply lines must be able to withstand the high water pressure. Therefore, fog systems can be more expensive to install compared to pad-and-fan systems. Fog systems, in combination with natural ventilation, produce little noise (except for the pump) compared to mechanical ventilation systems outfitted with evaporative cooling pads. This can be an important benefit for workers and visitors staying inside these greenhouses for extended periods of time.

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Biographical Sketch

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