Designing Environmental Control for Greenhouses: Orchid Production as Example

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Abstract

Design of greenhouse environmental control systems are typically specified to meet anticipated extreme weather conditions. The control strategy will typically operate the equipment to maintain specified set points. For a heating system that has adequate maximum capacity and a modulated rate of heat delivery, the set point will be closely tracked. Similarly, a modulated cooling system can closely track set points until ambient temperature and radiation conditions exceed the total capability of the cooling system. A shade system, with no precise modulation of shade level, will cause crop canopy light levels to vary between set points. Multiple layers of shade material that are independently controlled can reduce, but not eliminate variability.

A simple spreadsheet simulation can be a useful tool for design. The database needed is an hourly record of dry bulb temperature, wet bulb temperature and solar radiation. Using the database, the design parameters of the greenhouse, and its environmental control systems, internal conditions can be calculated for each hour. The deviations of achieved conditions from desired set points can be evaluated both in terms of magnitude and frequency. This is of particular interest in selecting a shading system for a crop where control of light level at the crop canopy as well as crop temperature is important. A single shade system will over shade the crop whenever solar radiation is under the maximum design point but over the initial closing set point. This over shading can be significantly reduced by having multiple independent shade systems that will provide finer control.

A number of possible designs for a greenhouse and environmental control system to grow orchids in central New Jersey and Taiwan have been evaluated. The results provide the designer with information on the impact of design options on the predicted performance over the entire growing season or year.

INTRODUCTION

The approach described in this paper was developed in an attempt to address the problems that arose in designing a greenhouse for New Jersey, in which to grow orchids using cultural recommendations developed for the crop in Taiwan. The most critical parameters discussed here are the maximum and minimum temperatures and the maximum light levels that the crop should be subjected to. These parameters are based on long experience in growing the crop in Taiwanese style commercial greenhouses. In developing a design for a New Jersey facility a straightforward approach is to design a greenhouse to cover the needed area and design a heating system to maintain at least the minimum desired crop temperature on the coldest day. In the tropics or subtropics there is little or no need for supplemental heat and simple air heating systems are the common solution unless a delay in flowering is required. The design of the heating system for New Jersey requires more care but is a straightforward design problem.

Cooling is the critical environmental control problem in Taiwan and there is extensive experience leading to specific recommendations for those conditions. Common practices include fan ventilation with evaporative pad cooling and extensive shading, with

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two layers of shade the current state of the art. Based on this experience, the New Jersey and Taiwan designs started with specified maximum target temperatures of 35°C with ventilation starting at 21°C and a minimum night temperature of 15°C. For shading a maximum light level was specified of 390 µmol/(m^2s) in the photosynthetically active radiation (PAR) range, equivalent to 188 W/m^2 solar radiation (assuming 45% of solar radiation falls in the PAR range). Using these values, a fan ventilation system can be designed using fan staging and evaporative pads to accommodate the target maximum airflow. The shade system can be selected so that the inside solar radiation will not exceed the desired light level under the brightest sun conditions expected. The transmissivities of the greenhouse cover and the shade material combined need to meet this requirement. The shade would need to be closed whenever light levels exceed the maximum design light level.

Having followed through with this procedure, a workable design was developed but the level of shading specified was far greater than is common practice for shading other crops in New Jersey. This immediately leads one to question the impact of having a substantial shade in place under relatively moderate solar radiation conditions and cool or cold outside temperatures. These combinations of conditions essentially do not occur in Taiwan where all the crop cultural experience has been gained. Under Taiwanese conditions, whenever solar radiation is significant enough that the radiation at the crop level exceeds 390 µmol/(m^2s) there will need to be ventilation at least. After designing a shade system to provide adequate shade under high PAR conditions, the question arises as to how much of a penalty there will be to PAR levels at the canopy when the shade needs to be pulled but solar radiation remains well below these high intensities.

MATERIALS AND METHODS

Traditionally, greenhouse environmental control systems are designed based upon the characteristics of the structure and the expected extreme weather conditions for the location and the requirements of the crop being grown. For a heating system, the heat loss from the structure (walls, roof and infiltration) can be calculated for the maximum expected temperature difference between outside and desired inside conditions. The capacity of the heating system is then determined based upon this calculation and a reasonable factor of safety. Annual heating energy requirements can be estimated based on reported heating degree data for the region, but the actual requirement in any year will depend on the specific weather conditions that do occur. A well-designed heating system and control strategy with modulated heat delivery should maintain set points acceptably.

Simulations of greenhouse climate have been widely used to study a variety of issues. Manning and Mears (1981) designed a 1.1 ha greenhouse facility utilizing waste heat from an electric power generation station. For their model development, they used historical hourly data on ambient temperature and the temperatures of the station's cooling water (Manning et al., 1983; Mears and Manning, 1996). Ekholt et al. (1983) used a simulation approach to optimize the sizing of a cogeneration system designed to utilize landfill methane to generate electricity for crop lighting and recapture waste heat for climate control using a floor heating system. More recently, Takakura and Fang (2002) discussed a number of simulation examples. They noted that simulation models can be particularly useful as an evaluation or optimization tool in the design of climate control systems utilizing mixed energy sources where the energy costs vary between sources. Finally, Willits (2003) used a modeling approach to investigate the effect of wetting an external shade to cool it and improve greenhouse cooling.

Historical weather data can be useful in comparing the annual contributions to environmental control of various heating, cooling and shading options. However, these results only give estimates that can reasonably be expected as actual contributions depend not only on the actual weather experienced in the future but also can depend significantly on greenhouse management and the control strategies used. Hourly time increments can be too coarse to model detailed dynamic response of the internal climate to changing environmental conditions and to analyze the performance of control systems that influence air temperature.

In developing an environmental control system for orchids in New Jersey based on crop experience in Taiwan, it is recognized that significant differences in climate will no doubt result in different crop responses even if the same environmental set points are used for temperature and maximum light level. One major difference is the amount of heat that will be required to maintain minimum temperatures even though attaining these temperatures should be a straightforward design issue. More difficult to predict is the impact on the crop of the cooling and shading system design. Maximum daily temperatures and maximum intensity of solar radiation are not significantly different. However, the total time at or near highest levels is very different, particularly in the winter when daylength is significantly less in New Jersey.

This is expected to be especially important in considering the design of the shading system and its operating control strategy. In particular, if a single shade is used and it is designed for maximum summer radiation there will be extended periods in the winter when some shade is required but the summer shade is significantly greater than required thus reducing light well below optimum levels for growth. As daylength is relatively short, over shading may well be more of a problem in New Jersey than in Taiwan. However, it is also possible in New Jersey in the winter to maintain cooler air temperatures at higher radiation levels than is the case in Taiwan. Utilizing hourly weather data available for an entire year, a simple spread sheet approach can be used to consider a variety of system design and control strategy options and then evaluate the total amount of time the crop will be subjected to various temperature and light environments either for the entire year or for specific periods.

The weather data needed for this approach is hourly data including columns for month, day, hour, dry bulb temperature, wet bulb temperature and horizontal solar radiation. For the simplified heating calculations, the heat transfer loss rate expressed as energy loss per unit temperature difference inside to outside and the transmission coefficient of the glazing system for solar radiation are needed. For shading for light intensity at the canopy level, the transmissivity of each of the movable shades is needed. For ventilation, the rate of airflow per unit floor area for each stage of ventilation is determined by the proposed ventilation system. To evaluate evaporative cooling and predict inside air temperature, an evaporative pad efficiency based on wet bulb depression is needed. This efficiency is based on the rate of airflow through the pad system so it can be determined for a given product for the ventilation system already specified.

As input data for the simulations, we used data collected over a range of 10-years from the Philadelphia area (New Jersey data), and a complete hourly data set collected in 2002 in Taitung (Taiwan data).

The spreadsheet is set up with several rows at the top for headings and for cells to contain the constants needed for the calculations. The first five columns contain the time and basic weather data, 8760 rows for the year. Additional columns are used to indicate control states. For the light transmission options considered, the four options included presence or not of glazing to allow modeling of an open roof greenhouse and presence or not of one shade, another shade or both. Constants used to calculate light at the canopy level were the transmissivities of the glazing system and each of the two shades. The value of 1 at any given hour in a column indicates that option is in place. For the cases considered in this discussion there is always glazing so the roof-glazing column is all ones. For each level of shading possible, a decision is calculated to place a 1 or 0 based on the predicted canopy level radiation with or without the shading in the appropriate cell. It is convenient to set the spreadsheet up to deal with the options of having two independent shades at different shade densities. The control columns are set up for light intensity levels for: a) glazing only, no shade pulled, b) the lighter shade material pulled, c) the heavier shade material pulled, and d) both shades pulled. To model only a single shade material the value of 1.0 is used for the transmission of the second shade material. The total transmissivity of the greenhouse glazing and structure without shade was assumed to be an annual average of 56%. The manufacturer's data for diffuse transmissivity of three shade materials were used: 65%, 53%, and 34% transmissivity, respectively.

To calculate the heat required for any hour to maintain a given minimum inside temperature, the need for heat can be determined by computing an energy balance based on the desired inside temperature, the outside temperature and the amount of heat being transmitted into or out of the greenhouse. Since most heating is required at night, the shade material can be pulled to reduce heat loss and the coefficient used for this condition was 4.1 W/(m^2 °C). For the calculation of internal greenhouse temperature during daytime, it may be important to consider that the radiation contributing to heating the greenhouse is the radiation received at the crop canopy plus a portion of the radiation intercepted by the shade curtains that may be pulled, so a coefficient for that was needed. For the heating calculations, this is only a factor when it is very cold and overly bright compared to the desired light setting. If the predicted energy input is not adequate to maintain minimum desired temperature, the temperature is set at that level and the amount of energy that needs to be added to maintain this temperature computed.

For cooling, three columns were set up to indicate control at three rates of airflow and a fourth to indicate the use of evaporative cooling. To determine the needed stage of ventilation, the internal temperature was calculated using an energy balance based on the desired internal temperature, the current outside temperature and the radiation received at the plant canopy as well as absorbed by the deployed curtains. After the required stage of ventilation was determined, the canopy temperature was calculated by an energy balance based on the airflow associated with the ventilation rate but without evaporative cooling. Based on this temperature, a decision could be made as to the need to turn on the evaporative cooling, and if that was the case another column was calculated to determine the internal air temperature with evaporative cooling based on the wet bulb depression and the efficiency of the evaporative cooling system.

The three stages of ventilation were set to initiate at 21, 24 and 27°C predicted internal temperatures respectively. The airflow rates were set at 0.31 m^3/min per m^2 of floor area for the first stage and an additional 1.24 and 0.93 m^3/min per m^2 of floor area for the second and third stages, respectively, for a total capacity of 2.48 m^3/min per m^2 of floor area at full ventilation. When under full ventilation, the predicted inside temperature would be above 29°C, evaporative cooling would be turned on and assumed to operate at an efficiency of 80%. A check on radiation levels was used to avoid having evaporative cooling still operating at solar radiation levels at the canopy of under 236 W/m^2. This practice will allow some time to reduce humidity in the greenhouse late in the afternoon, even when temperatures are higher than desired.

RESULTS AND DISCUSSION

After calculating the heat required for all hours of the year that heat is needed to maintain the minimum of 15°C, the data was sorted from maximum to minimum hourly rates. The maximum hourly heat requirement in New Jersey is 114 W/m^2 and the capacity of the heating system including the heat source and the heat exchange system need to be designed to provide at least this level of heating with an adequate factor of safety. In New Jersey heat is required for a total of 3709 hours decreasing from the maximum requirement of 114 to just 2 W/m^2 at a minimum. The cumulative number of hours of heating required at various rates is shown in Figure 1. Totaling all the heat required for all the hours of the year that any heat is required gives a total annual energy requirement of 175 kWh/m^2.

For Taiwan when maintaining the same minimum internal air temperature of 15°C there is virtually no heat required and it is common practice to have no heating system when that is the minimum requirement. The calculations do show heat could be used for a total of just 53 hours totaling only 0.169 kWh/m^2 at a maximum rate of 8 W/m^2. It should be noted that in these calculations quasi steady state conditions are being assumed and no provision is being made for stored heat within the greenhouse, which is a significant factor when temperature differences are small. In Taiwan, when it is important to prevent flowering, significant heat is required, as minimum desired temperature is 20°C. To achieve this a heating system capable of delivering 29 W/m^2 is needed with a total amount of energy of 10.06 kWh/m^2 required for the 1084 hours of heating. Figure 1 indicates that while the requirement to maintain 15°C in Taiwan is insignificant, the requirement to maintain 20°C to prevent flowering does require a significant heating system even though the total energy requirement is still less than 6% of that for New Jersey.

After calculating the requirements for ventilation and evaporative cooling for the entire year, two situations were analyzed. First hourly temperatures predicted without any capability to provide evaporative cooling were calculated, and second the temperatures that could be achieved with evaporative cooling were also computed. Figure 2 shows the cumulative hours at descending temperatures for both situations for New Jersey. Note that on the right side of the figure are all the hours when any heating is required. Without evaporative cooling there were two hours in the year when the predicted inside temperature would reach 42°C and a total of 100 hours above the maximum desired level of 35°C. With evaporative cooling, the maximum reached was 39°C for one hour and there were only 3 hours above 35°C. The figure clearly shows the added benefit of evaporative cooling for the New Jersey site in reducing the time the crop is stressed above the desired limit by 97 hours and providing increased cooling compared to ventilation alone for a total of 2469 hours.

Figure 3 shows similar data for Taiwan for the case when minimum night temperatures are being held at 20°C, which shows up as the 1084 hours requiring heat on the right hand side of the graph. Regardless of minimum temperature requirements, the maximum daytime temperature in the greenhouse without evaporative cooling is 42°C, with three hours above 40°C, and 502 hours above 35°C. While the hottest hours are similar to New Jersey, the time above 35°C without evaporative cooling is much greater. In Taiwan with evaporative cooling, there are only 3 hours above 35°C with the maximum just 36°C indicating the importance of having this capability.

The results of the analysis of the light energy transfer to the plant canopy for New Jersey are presented in Figure 4. The top line shows the total outside solar radiation was significant 4478 hours in this database and for 2810 of these hours the transmissivity of the structure of 56% reduced the canopy radiation to below the 188 W/m^2 solar radiation target so no shading system was required.

With the single 66% shade option only, the shade had to be pulled the remaining 1668 hours as shown by the bottom lines. For the 609 hours of most intense sunlight both the 35% and 47% shade curtains would be pulled under the two-curtain scenario giving essentially the same internal light level as with the single 66% shade curtain. However, for the next most intense 357 hours where the 47% shade curtain alone and the following 702 hours where only the 35% shade curtain is pulled there is somewhat to significantly more light but still under the 188 W/m^2 solar radiation target. The extra light averages about 70 W/m^2 during these 1059 hours of advantaged light.

The results of the analysis of the light energy transfer to the plant canopy for Taiwan are presented in Figure 5. The top line shows the total outside solar radiation was significant 3621 hours in this database and for 1825 of these hours the transmissivity of the structure of 56% reduced the internal radiation to below the 188 W/m^2 solar radiation target so no shading system was required.

With the single 66% shade option only, the shade had to be pulled the remaining 1796 hours as shown by the bottom lines. For the 829 hours of most intense sunlight both the 35% and 47% shade curtains would be pulled under the two-curtain scenario giving essentially the same internal light level as with the single 66% shade curtain. However, for the next most intense 340 hours where the 47% shade curtain alone and the following 627 hours where only the 35% shade curtain is pulled there is somewhat to significantly more light but still under the 188 W/m^2 total radiation target. The extra light averages about 71 W/m^2 during these 967 hours of advantaged light.

The economic question that still needs to be answered is whether or not the extra light during these 1059 hours in New Jersey and 967 hours in Taiwan is worth the expense of a double shade system for an orchid crop. It is important to note that real data will vary over the hour and that the technique of expecting each hour to be a consistent environment for the entire 60 minutes does represent significant approximation and ignores the effects of curtains actually requiring significant time to open or close. Similar analyses for other crops where light for growth is more important than for an orchid crop could also be investigated with the same technique.

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Figures

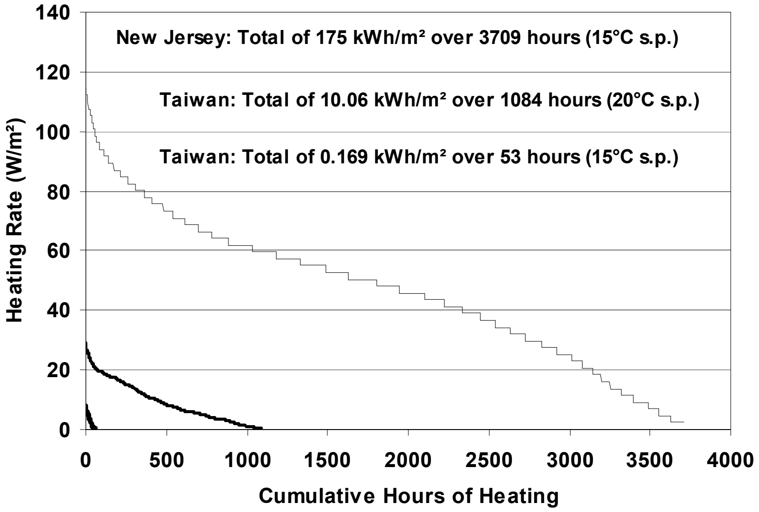

Fig. 1. Heating requirements for New Jersey and Taiwan using different set point (s.p.) temperatures.

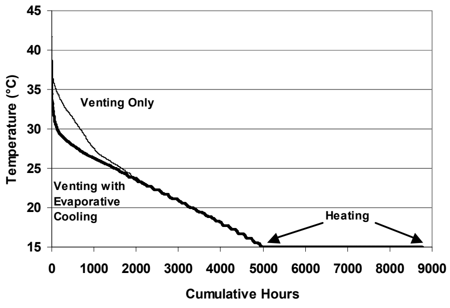

Fig. 2. New Jersey temperatures (15°C heating set point).

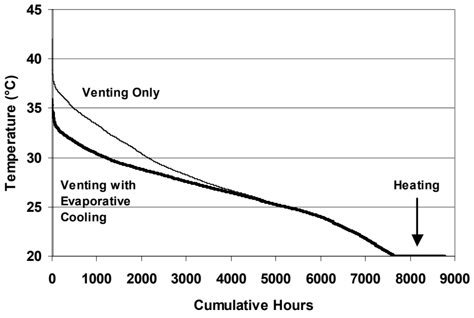

Fig. 3. Taiwan temperatures (20°C heating set point).

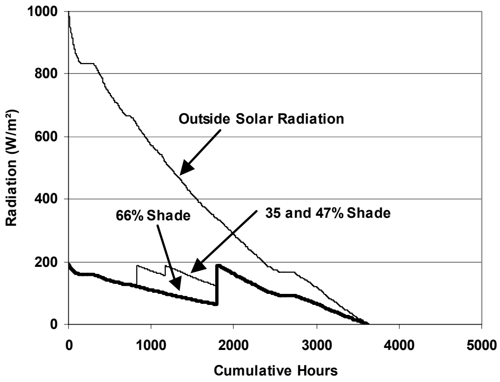

Fig. 4. New Jersey canopy radiation.

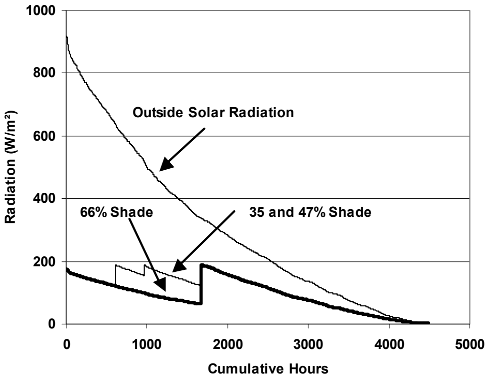

Fig. 5. Taiwan canopy radiation.