Requirements and Constraints in Designing Mediterranean Greenhouses

A. Baille
Polytechnic University of Cartagena
Paseo Alfonso XIII, 48, 30203 Cartagena, Spain. alain.baille@upct.es

Abstract

This paper deals with some topics linked to Mediterranean greenhouses design, giving a special emphasis on the estimation of greenhouse cooling needs in order to avoid heat and crop water stress during the warm season. The following issues will be discussed: (i) the estimation of greenhouse cooling requirements, taking into account the outside climate and the rate of crop evapotranspiration (ii) the formulas and procedures for designing the cooling equipment, giving a particular attention to natural ventilation and evaporative cooling systems, (iii) the relevance of using canopy temperature as a design criterion and (iv) the usefulness of greenhouse climate models as a tool for optimizing greenhouse design. In the conclusion, some general recommendations and criteria are highlighted in order to improve the design methodology, with a better integration of agronomic criteria (crop requirements) and grower’s objectives into the classical approach currently used in greenhouse engineering.

Key words: ventilation, cooling systems, shading, model, evapotranspiration

INTRODUCTION

The main objectives of greenhouses are to maintain adequate environmental conditions for plant growth and development. Like human beings and animals, plants have their own requirements for air temperature and humidity. Moreover, two environmental factors play an important role on plant productivity: air CO₂ concentration and solar radiation (and especially PAR, Photosynthetic Active Radiation). The control of the latter, which are the two main driving factors of the photosynthetic process, is also required in greenhouse environments. This gives much more complexity in the search and design for a bio-climatic greenhouse and its associated climate control system, which can satisfy all year-round the physiological requirements of a given species. Researchers and growers are now aware that greenhouse structures and equipment must be specifically designed, taking into account local climatic conditions and plant requirements (Baille, 1989, Hanan, 1990).

In Mediterranean countries, the great challenge concerns climate control during the warm season (Baille, 2001). Cooling the greenhouse air is an important issue for greenhouse operators in warm climates, because they potentially limit yield and quality and constraining benefits. This challenge consists in adapting and improving the greenhouse structure and equipment, and in managing skillfully the different components of the production system (climate, crop, irrigation...) in order to achieve the following objectives:

- expand the growing season and the period of the greenhouse use;
- reach satisfactory levels of marketable yield and quality;
- increase the net income of the farming system.
The present context of Mediterranean protected cultivation is characterized by a low level of energy input (Stanhill, 1980) similar to that used in open-field systems. The main reason is that growers only utilize a small amount of energy for controlling the greenhouse environment. Most of the greenhouses are equipped with hand-operated systems of ventilation and are currently not heated (or, in the best case, have some rudimentary heating system). Consequently, insufficient ventilation (during summer) and lack of heating (during winter) lead to inappropriate conditions of air temperature and humidity. Furthermore, the structure and the shape of these greenhouses (e.g. the classical parral-type), with small height and volume, flat roof and low vents surface, have not obviously been designed for the climatic conditions of these regions (Castilla and Lopez Galvez, 1994), thus increasing instead of alleviating the cooling requirements. The consequence of this situation is that the resulting microclimate is far from being satisfactory for crop growth during large periods of the year. Several works have described the summer microclimatic conditions prevailing in these low-cost greenhouses (Montero et al., 1985, Lagier, 1990), underlining that it is not possible for the grower to take full advantage of the prevailing high solar radiation in late spring and summer, due to inappropriate conditions of air temperature and vapor pressure deficit (VPD).

As stated by Castilla (1994), there is a tendency in the northern countries to optimize the greenhouse environment, in order to attain the potential crop production. In contrast, in the Mediterranean area, the prevailing trend until now was rather to adapt the crop to a "non-optimal" environment. However, this strategy of crop adaptation has its own limits, and it should be judicious to look for technological solutions and adequately designed greenhouses that can alleviate the extreme conditions prevailing in Mediterranean greenhouses, mainly during summer periods.

This paper deals with some important topics linked to the choice and design of greenhouse cooling equipment in Mediterranean countries. Special emphasis will given to the greenhouse cooling processes, as it is well known that an efficient cooling system may allow all-year round cropping under Mediterranean conditions. In the following, four main issues will be discussed: (i) the estimation of cooling requirements, taking into account the outside climate and the crop evapotranspiration rate (ii) the formulas and procedures for designing the cooling equipment, with special attention to natural ventilation and evaporative cooling systems, (iii) the relevance of using canopy temperature as a design criterion and (iv) the usefulness of greenhouse climate models as a tool for optimizing greenhouse design. In the conclusion, some general recommendations and criteria are highlighted in order to propose a design methodology, which may allow integration of agronomic criteria (crop requirements) and grower’s objectives into the classical approach currently used in greenhouse engineering.

**COOLING DEVICES USED IN GREENHOUSES**

**Natural and forced ventilation**

In the majority of the Mediterranean Countries, greenhouse cooling is usually accomplished by natural ventilation through the combined action of wind and buoyancy. These systems, generally very rudimental and working with a poor efficiency, are recognized as clearly being unsatisfactory. Recent works indicated that
significant improvements of natural ventilation could be reached through a better design and distribution of the vents. In this way, the use of numerical fluid dynamics numerical codes (CFD) appears to be a promising tool for improving vents design, as it allows the simulation of the air flow distribution around the vents and inside the greenhouse (Kacira et al., 1997; Mistriotis et al., 1997). However, all these efforts may be cancelled out by the necessity of installing insect-proof nets, in order to prevent proliferation of viral diseases. This practice generally induces a high pressure loss, thereby reducing significantly the ventilation efficiency, by about 50% (Montero et al., 1997; Miguel et al., 1997; Bailey et al., 2003.). This is the reason why forced ventilation, via exhaust fans, has recently gained acceptance in the Mediterranean countries.

Evaporative cooling

Cooling pads. Forced ventilation along with the implementation of wet pads may allow a better control of air temperature and humidity (Albright, 1990; Giacomelli et al., 1985), although wet pads tend to induce a longitudinal gradient of these two variables along the air path (Bailey, 1990; Willits, 2003).

Fog (Mist) systems. When using natural ventilation, the evaporative cooling is realized through the injection of very thin droplets of water (ranging from 1 µm to 20 µm or with a higher diameter) provided by fogging or misting systems, respectively. These systems are efficient in reducing air temperature, but are expensive and require good water quality (Arbel et al., 1999).

Shading.

It can be distinguished two main shading techniques:

Whitening. A white paint is deposited on the roof and walls that decreases the transmission coefficient for solar radiation and consequently induces a reduction of the greenhouse heat gain. This is presently a very popular and usual way of alleviating greenhouse summer conditions in Mediterranean countries (Baille et al., 2001).

Shading nets. This technique can also be an efficient way of reducing the greenhouse radiation load when the nets are located outside. When located inside the greenhouse, the material of the net should be reflective (aluminized) in order to get an acceptable cooling efficiency.

PHYSIOLOGICAL CONSIDERATIONS

The design criteria and parameters for human comfort were derived from the knowledge and experiments realized in human buildings (ASHRAE Handbook of Fundamentals, 2001). Similar design criteria and parameters should be available for plant comfort. However, until now, the only criterion is based on the air temperature, and sometimes on the relative air humidity that has to be maintained in the greenhouse. This is clearly insufficient, as these variables are poorly linked to the physiological status of the plants. Other variables, such as canopy temperature or physiological fluxes (transpiration, photosynthesis) should be involved in the definition of plant stress indicators. With
such criteria, the climatization equipment could be designed, considering the harshest
outside conditions, with regards to an acceptable level of stress (mild stress), or a
probability of severe stress occurrence. Several stress indicators are presently available
for determining the physiological status of the crop, mostly based on the prediction of
canopy temperature. However they are not used in the actual process of greenhouse
design.

GREENHOUSE COOLING REQUIREMENTS

As for other buildings, the method used for determining the cooling requirements of the
greenhouse and the subsequent sizing of the cooling devices is based on the energy
balance (sensible and latent heat) and on the mass (H₂O) balance of the air volume. The
first step is to determine the critical values of the heat gain and cooling load, thus
allowing the heat extraction rate to be determined.

Definitions and orders of magnitude

Greenhouse heat gain.
Heat gain is the rate at which energy is transferred to or generated within a space. It has
two components (i) sensible heat and (ii) latent heat, which must be computed and
analyzed separately. Heat gain may be generally classified into:
- Solar radiation passing through the cover material, the amount of which is an
  order of magnitude higher than that entering in human or animal buildings.
- Heat conduction from boundaries, with convection and radiation exchanges from the inner surfaces (ground, walls) into the space.
- Sensible heat through convection and radiation from internal bodies (e.g. canopy)
- Air exchanges through ventilation and infiltration.
- Latent heat gain, or loss, generated within the space. The canopy transpiration rate being one of the main processes generating humidity and lowering air
temperature within a cultivated greenhouse. For a well-developed crop, the
intensity of latent heat transfer is also one order of magnitude higher than in
other buildings.

The radiation load in greenhouse is an important component of the greenhouse heat
gain. It depends on the global transmission coefficient of the structure for solar
radiation, and may be modified through whitening practices and use of shading nets.

Greenhouse cooling load.
The cooling load is the rate at which energy must be removed from a space to maintain
required design values of air temperature and humidity, or other control variable. The
cooling load will generally differ from the heat gain because the radiation from the
inside surfaces, as well as the solar radiation coming directly into the space, does not
heat the internal air directly. The heat storage and heat transfer characteristics of the
structure and internal bodies determine the thermal lag, and therefore the relationship
between heat gain and cooling load. In light structures like greenhouses, the radiant
energy is mostly absorbed by the soil, walls and canopy. Only the soil ground can store
a significant amount of heat and therefore present some thermal lag. In the general case
of a well developed crop covering most of the ground area, the stored amount may be
neglected with regards to the radiation gain when calculating the peak cooling load. Therefore, for greenhouse, it is not necessary to perform a transient analysis of the heat transfer processes.

*Heat extraction rate*

It is the rate at which energy *is removed from the greenhouse* volume by the cooling equipment. This rate is constant and equal to the cooling load when conditions inside the space are constant and the equipment is operating. In greenhouse, this is rarely true due to a certain number of factors, including:

- some fluctuations in temperature or humidity are necessary for the system to operate
- the cooling equipment has a variable extraction rate. This is the case for greenhouses equipped with natural ventilation, whose extraction rate depends on external conditions (wind speed and direction)
- the cooling load is, most of the time, below the peak of the design value, implying intermittent or variable operation of the cooling equipment.

**DESIGN PROCEDURE**

**Design climate information**

The problem of selecting design outdoor conditions for cooling is similar to that for heating. It is not desirable to design for the worst conditions on record, because a great excess of capacity will result. The ASHRAE Handbook, Fundamentals (2001) gives extensive outdoor design data. Tabulation of dry bulb and mean coincident wet bulb temperature, that equaled or exceeded 0.4, 1 and 2 % of the hours during a year are given. For greenhouse design, the local wind speed for summer conditions has to be carefully selected with respect to local topography and nearby obstacles (e.g. windbreak). By default, a value of $3.4 \text{ m s}^{-1}$ is usually taken. Peak dry bulb and mean coincident wet bulb temperatures are appropriate for calculating cooling loads.

**Indoor design conditions**

As stated previously, the indoor design conditions are governed by thresholds of air temperature and relative humidity, which depend on the species requirements. Some species (or within the species, cultivars) may tolerate higher temperatures or higher vapor deficit than others. These values are generally roughly estimated, from the available knowledge on the behavior of the species to extreme conditions. There is possibility to use other indoor design conditions, such as the threshold level of air CO$_2$ concentration, as this variable may be affected by too low ventilation rates.

Rather than establish *a priori* the threshold values for temperature and humidity, it appears desirable to define indoor design conditions with respect to their impact on the physiological status of the crop, for instance, through the calculation of the resulting canopy temperature, or the evaluation of a *crop stress index*. This issue will be treated more in details in the following sections.
**The design equations**

In greenhouse environments, the current method used in the design of cooling devices is the one proposed by the ASAE (1999), which is based on a simplified form of the energy balance of the greenhouse. The simplified form lies on equating the radiation heat load with the sensible and latent heat ventilation fluxes which extract this load.

**ASAE formula**

The design equation for temperature is:

\[
(1-\varepsilon) \tau G_0 = U (T_g - T_0) + \rho C_p Q (T_e - T_i)
\]

where
- \(\varepsilon\) = “evaporation” coefficient
- \(\tau\) = greenhouse transmission coefficient for solar radiation
- \(G_0\) = outside global radiation (W m\(^{-2}\) ground)
- \(U\) = heat transfer coefficient through the cover (W m\(^{-2}\) ground K\(^{-1}\))
- \(T_g, T_0, T_e\) and \(T_i\) are respectively the greenhouse air, outside air, exhaust air and inlet air temperatures (ºC)
- \(Q\) is the ventilation flux (m\(^3\) m\(^{-2}\) ground s\(^{-1}\))
- \(\rho\) (kg m\(^{-3}\)) and \(C_p\) (J kg\(^{-1}\) K\(^{-1}\)) are air density and air specific heat at constant pressure

In the case of natural ventilation and fogging, the inlet temperature \(T_i\) is equal to the outside air temperature, i.e. \(T_i = T_0\). In the case of a wet pad, the inlet temperature will be equal to the wet-bulb temperature at the exit of the wet pad, i.e. \(T_i = T_w\). The exhaust temperature, \(T_e\), is given by:

\[
T_e = \varphi T_g + (1-\varphi) T_i
\]

where \(\varphi = 1\) for natural ventilation and fogging/misting, i.e. \(T_e = T_g\), and \(\varphi = 2\) for forced ventilation and wet pad, i.e. \(T_e = 2 T_g - T\) (Seginer, 2002). Eqn. 1 deals only with air temperature. It can be seen that no solution is available for \(T_g = T_0\), and that the total amount of latent heat dissipated in the greenhouse is assumed to be \(\lambda E = \varepsilon \tau G_0\), where \(E\) (kg\(_{water}\) m\(^{-2}\) ground s\(^{-1}\)) is the total evaporation flux (canopy, soil, evaporative cooling), and \(\lambda\) is the latent heat of evaporation (J kg\(^{-1}\) air).

**Water balance**

In order to include a design criterion based on air humidity, a simplified form of the water balance of the greenhouse volume may be used. Assuming as for Eqn.1 steady state conditions, the water balance may be expressed as:

\[
\lambda E = \varepsilon \tau G_0 = \rho \lambda Q (q_e - q_i)
\]

where \(q_e\) and \(q_i\) are respectively the exhaust and inlet mixing ratio (kg\(_{water}\) kg\(^{-1}\) air).
Design parameters

In Eqn. 1, $T_g$ is the design temperature criterion, i.e. the maximum admissible greenhouse air temperature. $Q$, $U$, $\varepsilon$ and $\tau$ are the design parameters that should be chosen in order to satisfy the design criterion. Usually, the objective of the design is to find the value of $Q$, which satisfies the criterion value, $T_g$, when $U$, $\varepsilon$ and $\tau$ are known. The latter depends on the type of greenhouse (shape, orientation) and covering material. It should be noted that:

- the value of $\tau$ could be modified by shading or whitening the cover.
- the coefficient $\varepsilon$ is an important design parameter, as it represents the fraction of radiation gain dissipated by latent heat. Its value depends on the type of crop, and on the water addition rate from the evaporative cooling systems (wet pad cooling, fogging, misting....). It is convenient to consider $\varepsilon$ as the sum of the contribution of the soil evaporation, $\varepsilon_s$, the canopy transpiration, $\varepsilon_c$ and the cooling system, i.e. $\varepsilon_f$ (fog) or $\varepsilon_w$ (wet pad).

The evaporation coefficient of the ASAE standard may therefore be expressed as:

$$\varepsilon = \varepsilon_s + \varepsilon_c + \varepsilon_f (or \varepsilon_w) \tag{5}$$

For a determined value of $T_g$, and chosen values of $Q$, $U$, $\varepsilon$ and $\tau$, the value of greenhouse humidity, $q_g$, is derived from Eqn. 3. This value should be checked against the admissible range of humidity that would be convenient to maintain in the greenhouse. The range of values is generally given in terms of relative air humidity (RH %), as it is expressed for human comfort criteria. However, it would be better to express this criterion in terms of vapor pressure deficit (D, kPa), as this variable is much more pertinent when dealing with canopy transpiration and plant stress (Baille et al., 1995).

**IMPROVEMENT OF THE ASAE METHOD**

**The transpiration coefficient, $\varepsilon_c$**

The ASAE does not give much information about the values of the transpiration coefficient, $\varepsilon_c$. The designer has to choose, rather arbitrarily, a plausible value in function of the type and status of the crop. Values of about 0.6 to 1 may be chosen for well developed canopies, and lower values, about 0.1 to 0.2, when the crop is young, with a low leaf area index (LAI, m$^2$ leaves m$^{-2}$ ground), or when a given species has a low transpiration rate. As proposed by Seginer (2002), one way of obtaining a better estimation of $\varepsilon_c$ is to introduce a simplified formulation of the canopy transpiration rate, $E_c$, based on a simplified form of the Penman-Monteith formula (Boulard and Baille, 1993; Baille et al., 1994a):

$$\lambda E_c = A G_g + B D_g \tag{5}$$

where $G_g$ ($= \tau G_0$) is the incident radiation in the greenhouse, and $D_g$ is the vapor pressure deficit of the greenhouse air ($= q_{g*} - q_g$, with $q_{g*}$ = mixing ratio at saturation). $A$ (dimensionless) and $B$ (W kg$^{-1}$ air m$^{-2}$ ground kg$^{-1}$ vapor) are two coefficients that express the respective contribution of the “radiative“and the “aerodynamic” terms of Eqn, 5, and
depend mainly on LAI. Baille et al. (1994a) proposed the following relationship that expresses this dependence:

\[ A = A_0 \left(1 - \exp(-k \text{LAI})\right) \quad (6a) \]
\[ B = B_0 \text{ LAI} \quad (6b) \]

It can be shown that A and B are substitutes for the bulk (canopy) aerodynamic resistance, \( r_a \) (s m\(^{-1}\)) and bulk stomatal resistance, \( r_s \) (Baille et al., 1994a, Seginer, 2002). Fixing a couple of values for A and B is equivalent to fix constant values for \( r_a \) and \( r_s \). The transpiration coefficient, \( \varepsilon_c \), can be estimated by the relationship:

\[ \varepsilon_c = A + B \frac{q_g^* - q_i}{\tau G_0} \quad (7) \]

Combining equation (5) with Eqn. (1) and (3), it is possible to solve for \( T_g, q_g \) and \( \varepsilon_c \), for given values of the design parameters (\( Q, \varepsilon_f, \varepsilon_w, t, U \)) and for the design outdoor conditions (\( G_0, T_0 \) and \( q_0 \)). Boulard and Baille (1993) solved numerically the set of equations and applied the analysis to the influence of natural ventilation and fogging on the greenhouse climate. Seginer (2002) proposed analytical solutions for fogging and wet pad cooling, which could be considered as new design equations for cooling design.

This new design procedure presents three relevant advantages:

(i) It allows integration of a second design criterion, \( q_g^* \), i.e. the VPD design value, \( D_g = q_g^* - q_g \)

(ii) It gives an estimate of the canopy transpiration

(iii) It takes into account the influence of a given evaporative cooling system or shading device on the evaporation coefficient.

The major shortcoming of choosing, for a given crop and a given cooling system, constant values of A and B is that they may not realistically represent the variations of the bulk aerodynamic resistance, which is linked to the ventilation rate, Q (Kittas et al., 2001). The bulk stomatal resistance is known to depend on the specific response of the species to VPD (Baille et al., 1994b).

**Typical values of the A and B coefficients**

Values of A and B are available for several greenhouse crops. For instance, Baille et al. (1994a) derived the values of \( A_0 \) and \( B_0 \) for 9 ornamental species. Figure 1 gives a graphical representation of their data, in terms of \( A_0 \) vs \( B_0 \). It can be seen that \( A_0 \) varies from 0.15 to 0.65, and \( B_0 \) from 1.5 to 4 W kg\(^{-1}\) air m\(^{-2}\) ground \( g^{-1}\) vapor. Seginer (2002) carried out the compilation and analysis of values of A and B reported in several works dealing with measurement and modelling of the transpiration of greenhouse crops (tomato, cucumber, rose, lettuce, etc.). However, a reliable catalogue of \( A_0 \) (or A) and \( B_0 \) (or B) values for the main greenhouse species is not still available. A tentative classification of crops with respect to with respect to A and B may be the following:

- Type 1: High A and medium or high B. This would be the case of healthy and well developed (LAI > 3) crops of species that respond mainly to solar radiation
- Type 2. Low or medium A and high B. This would be the case of shade plants, or species that respond mainly to humidity (e.g., Begonia, Baille et al., 1994 b)
- Type 3. Low A and low B, which corresponds to crops with a low LAI (sparse or young crops), or well developed crops that experience stress conditions.

![Graph showing values of \(A_0\) and \(B_0\)](image)

**OTHER DESIGN CRITERIA**

As stated above, air temperature and relative humidity are not pertinent design criteria for evaluating the plant comfort. The use of air VPD is more adequate, as this variable is more or less directly linked to the transpiration flux. Other criteria, directly related to the water or thermal status of the plants could be used in the future.

**Criteria based on the canopy temperature**

Estimates of canopy temperature would be valuable information for the designer. This would be of value for cooling systems design, which are known to reduce efficiently the air temperature. However, they generally have an adverse effect on the canopy temperature, as they increase air humidity that, in turn, reduces the transpiration rate. Using the set of equations previously described, we get:

\[
\lambda E_c = \frac{B}{(1-A)} (q^* - q_g)
\]

where \(q^*_c\) is the saturation humidity ratio at the canopy surface at temperature \(T_c\). Eqn. 8 could be solved for \(T_c\), either by iteration, or using a linear approximation of the humidity gradient by means of the slope of the humidity saturation curve.

**Criteria based on stress indicators**

The relationship between the canopy-to-air difference \((T_c - T_a)\) and \(D_g\) can be used as an index of crop water status. The so called Crop Water Stress Index (or CWSI), currently used for irrigation scheduling, is based on this relationship (Jackson, 1981, Idso *et al.*, 1990). This index is calculated, for given values of VPD and solar radiation, when \(T_c\) is known and two threshold values of \(T_c\) are provided: (i) an upper limit, \(T_M\), which is the temperature of the canopy at its minimum conductance, \(g_m\) and (ii) a lower limit, \(T_m\), assumed to be achieved when the canopy presents its maximum conductance, \(g_M\). CWSI is defined as:
CWSI = \frac{T_c - T_m}{T_M - T_m} \tag{9}

It can be shown that CWSI is equal to 1 − \frac{E_c}{E_{c,M}}$, where $E_{c,M}$ is the maximum evapotranspiration rate reached by the crop (i.e. at maximum stomatal conductance). However, the use of this index requires previous knowledge of the crop physiological characteristics, such as $g_m$ and $g_M$.

Other criteria could be derived from photosynthesis models which predict the photosynthesis rate as a function of solar radiation and canopy temperature. This implies to know the response of photosynthesis and stomatal conductance to both temperature and VPD.

CASE STUDIES

In the following, some characteristic results obtained with the new design procedure are presented and briefly commented.

Effect of outside climatic conditions on evaporative cooling efficiency

The calculations have been realized with the following input data:

\textit{Design parameters:} U = 10 \text{ W m}^{-2} \text{ K}^{-1}, \tau = 0.50

\textit{Design climatic conditions:} Warm and dry Mediterranean climate: $T_0 = 35 \degree C$, RH = 20\%, $G_0 = 1000 \text{ W m}^{-2}$.

\textit{Type of crop:}
- crop with high transpiration rate (HT), corresponding to a healthy and well developed (LAI > 3) crop: $A = 0.66$, $B = 10$
- crop with low transpiration rate (LT), corresponding either to a young and sparse crop with low LAI, ($\approx 0.2$ to 0.5), or to a crop which is strongly stressed: $A = 0.2$, $B = 3$

\textit{Design criteria:} $T_g = 35 \degree C$, $T_c = 35 \degree C$, $D_g = 4 \text{ kPa}$

Figures 2a-d present the trend of air and canopy temperature, air VPD and transpiration rate for the HT crop, as a function of the ventilation rate, Q. The latter is expressed in volumes of air exchanged by hour (h$^{-1}$). The following devices are compared: (1) only natural ventilation, (2) whitening inducing a 40\% reduction of $\tau\%$, (3) fogging with $\varepsilon_f = 0.3$ and (4) wet pad with $\varepsilon_p = 0.3$.

For such a crop, the transpiration rate is the highest in the greenhouse with only ventilation (Fig. 2d), reaching values near 600 \text{ W m}^{-2} at high Q. This allows the greenhouse to maintain inside air temperature near the outside one provided the renewal rate be near or higher than 10 h$^{-1}$. The air temperature is slightly lower than the design value (about -2 to -3\degree C) for fogging and shading, and about 10 \degree C lower for the wet pad. However, looking at the canopy temperature (Figure 2b), it can be seen that the fog system and the wet pad do not supply any significant improvement with respect to ventilation only. This may be ascribed to the significant decrease of the transpiration rate with the evaporative cooling equipment (Figure 2d), which offsets completely the decrease in greenhouse air temperature. Shading appears to improve canopy temperature with respect to the other cases, as it leads to a decrease of $T_c$ of about 3 to 4\degree C, but at the cost of a reduction of 40\% of radiation. The greenhouse VPD is
significantly higher in the non evaporative cooled greenhouses as could be expected (Figure 4 c). It could be maintained below the criterion value of 4 kPa provided the ventilation rate does not exceed 30 to 40 h\(^{-1}\). It can be concluded that ventilation is probably self sufficient for cooling such a highly transpiring crop, and that supplementary cooling device is not absolutely required, if not for giving some margin of security. These results are confirmed by the experimental results obtained by Katsoulas \textit{et al.} (2002) with a highly transpiring rose crop (LAI = 4).

Figures 3a-d presents the evolution of the air and canopy temperature, VPD and transpiration rate for a LT crop as a function of the ventilation rate. The same devices previously presented in Fig. 2a are compared, except that the fogging rate was raised to 0.8. The latent heat of transpiration varies from 200 W m\(^{-2}\) (natural ventilation) to near 100 W m\(^{-2}\) (wet pad). It can be seen that the greenhouse air criterion is achieved with the two evaporative devices, largely in the case of the wet pad (Fig. 3a). The canopy temperature criterion cannot be fulfilled in any case (Fig. 3b), the worst results being given when only natural ventilation is used (T\(_c\) > 45°C for all Q) and the best were obtained with wet pad and shading (T\(_c\) near 40°C). The VPD criterion is satisfied by the two evaporative cooling devices. Therefore, for low transpiring crops submitted to harsh outdoor design conditions, it appears rather difficult to comply the criterion chosen for
\( T_c \), (i.e. \( T_c = T_g \)), while the criteria related to \( T_g \) and \( D_g \) can be fulfilled provided the fogging system or wetting pad being correctly sized.

![Greenhouse temperature vs. Q. LT crop](image1)

![Canopy temperature vs Q. LT crop](image2)

![Greenhouse VPD (Dg) vs Q. LT crop](image3)

![Canopy transpiration (\( \lambda E_c \)) vs Q. LT crop](image4)

On the whole, these case studies confirm that evaporative cooling devices are rather efficient in cooling the air, but much less in decreasing canopy temperature. This is due to the decrease in transpiration rate induced by lower values of VPD, which affects the aerodynamic term (Eqn. 5). This will consequently increase the canopy temperature far above the air temperature, offsetting the advantage of a cooler air temperature, as observed in both case studies.

**USE OF BIO-ECONOMIC SIMULATORS FOR GREENHOUSE DESIGN**

The overall problem in greenhouse engineering is to find a compromise between the cost of maintaining a given indoor environment and the benefits expected from the control. Before deciding on the type of greenhouse and equipments (strategic decision), or before establishing the planning of the cultivation (tactical decision), we have to evaluate the costs and benefits derived from each type of decision. This is a difficult task, even though the pertinent knowledge and information are available. The number of
complex interactions between variables and processes, the various constraints and objectives to take into account is too high to allow a simple or intuitive solution. A systemic approach, based on the modeling and simulation of the greenhouse system, seems to be better adapted to this problem of decision making. This approach is now possible because of the emergence of greenhouse climate simulators that can predict the outputs necessary to the agronomic and economical assessment, design and control of the production system (Deltour et al., 1985; Challa et al., 1988; Jolliet, 1994; Trigui et al., 2001; González Real and Baille, 2002).

These simulators would be very useful in providing information and recommendations about the most suitable configuration of the greenhouse cropping system. They represent a promising way to achieve the optimization of the production system under given environmental and economical constraints. This systemic approach was used for the design of greenhouse cooling facilities by Fang (1995), who raised the following questions:

(i) what is the affordable cooling facility (economical constraint due to the available budget)?
(ii) what are the limits of the cooling facility when working in a given climate, and its efficiency (technical constraint)?
(iii) what crops can be grown in such a controlled environment (biological constraints)?
(iv) what is the potential benefit that the cooling facility will return (performance criteria)?

The last question is probably the most difficult to answer, as the response of the crop to a given environment (with more or less prolonged stress periods) is not straightforward to predict.

**CONCLUSION**

We can conclude this paper with some general comments about the issues related to greenhouse climate control and cooling design:

1 - We have to keep in mind that canopy transpiration is the main source for cooling the greenhouse, except in some special cases (young crop, stressed crop) and that fog and wet pad are generally secondary sources of cooling. Therefore, estimates of the transpiration coefficient is a prerequisite for designing correctly a greenhouse cooling system.

2 - The case studies outlined in this paper demonstrate that the design could be very different in function of the criterion chosen by the designer. Air and canopy temperature may differ by 10°C or more when using evaporative cooling devices. This is due to the decrease in VPD and transpiration rate, which has as a consequence to increase the canopy temperature. The importance of estimating the coefficient B₀ (or B) is therefore evident, as it represents the multiplicative factor of VPD in the aerodynamic component of the transpiration.

3 - Shading appears to be a rather efficient way for lowering the canopy temperature, but at the cost of a reduction in incoming solar radiation. It would be useful to include
in the design procedure a photosynthesis module which could give information about the reduction in CO$_2$ assimilation, in order to evaluate the benefits of shading techniques with regards to evaporative cooling.

4 - As an overall conclusion, it should be stressed that greenhouse engineers dedicated to the design of climate control equipment have to be familiar with the basics of the coupling processes between the crop and its environment, so as to understand the underlying processes that govern the physiological exchanges of the plants. This knowledge will allow them to adopt more pertinent design or control criteria than air temperature and relative humidity. The design procedure outlined here represents only a first step towards this objective. It appears to bring valuable information about the canopy temperature and transpiration rate, and to estimate at what extent they may be affected by the values of the design parameters and the type of cooling device. The next step would be to include a CO$_2$ balance of the greenhouse volume into the set of equations describing the greenhouse energy and mass balance, in order to derive some valuable information related to crop growth and productivity.

REFERENCES


