Requirements and Constraints in Designing Mediterranean Greenhouses

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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 CO_2 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 (H_2O) 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 trough 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 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:

$$(1-\varepsilon)\,\tau G_0 = U(T_g - T_0) + \rho Cp\ Q(T_e - T_i) \qquad (1)$$

where

- ε = "evaporation" coefficient
- τ = 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})
- ρ (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:

$$T_e = \varphi T_g + (1-\varphi)\,T_i \qquad (2)$$

where φ = 1 for natural ventilation and fogging/misting, i.e. $T_e = T_g$, and φ = 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 λ 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:

$$\lambda E = \varepsilon\ \tau G_0 = \rho\ \lambda Q\ (q_e - q_i) \qquad (3)$$

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, ε and τ 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, ε and τ are known. The latter depends on the type of greenhouse (shape, orientation) and covering material. It should be noted that:

- the value of τ could be modified by shading or whitening the cover.
- the coefficient ε 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 ε as the sum of the contribution of the soil evaporation, ε_s, the canopy transpiration, ε_c and the cooling system, i.e. ε_f (fog) or ε_w (wet pad).

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

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

For a determined value of T_g, and chosen values of Q, U, ε and τ, 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, ε_c

The ASAE does not give much information about the values of the transpiration coefficient, ε_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, $m^2_{\text{leaves}}\ m^{-2}_{\text{ground}}$), or when a given species has a low transpiration rate. As proposed by Seginer (2002), one way of obtaining a better estimation of ε_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):

$$\lambda E_c = A\, G_g + B\, D_g \qquad (5)$$

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 $kg_{\text{air}}\ m^{-2}_{\text{ground}}\ kg^{-1}_{\text{vapor}}$) 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:

$$A = A_0 (1 - \exp(-k\ LAI) \qquad (6a)$$

$$B = B_0\ LAI \qquad (6b)$$

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, ε_c, can be estimated by the relationship:

$$\varepsilon_c = A + B\frac{q_g^* - q_i}{\tau G_0} \qquad (7)$$

Combining equation (5) with Eqn. (1) and (3), it is possible to solve for T_g, q_g and ε_c, for given values of the design parameters (Q, ε_f, ε_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 $_{air}$ $m^{-2}{}_{ground}$ $g^{-1}{}_{vapor}$. 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.

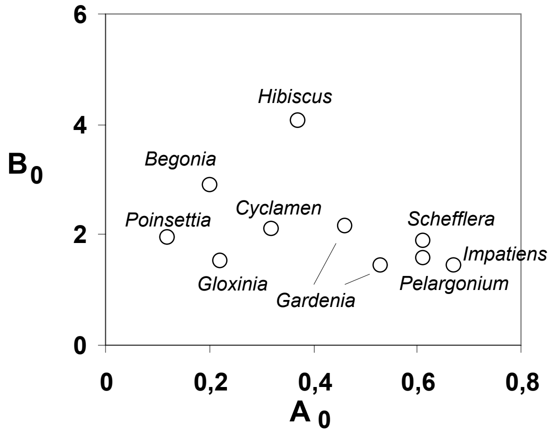

Figure 1. Values of A_0 /dimensionless) and B_0 (W kg_{air} $m^{-2}{}_{ground}$ $g^{-1}{}_{water}$ for various ornamental species (from Baille *et al*., 1994a)

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:

$$\lambda E_c = \frac{B}{(1-A)}(q_c^* - q_g) \qquad (8)$$

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:

$$CWSI = \frac{T_c - T_m}{T_M - T_m} \qquad (9)$$

It can be shown that CWSI is equal to $1 - E_c/E_{c,M}$, 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:
Design parameters: $U = 10$ W m^{-2} K^{-1}, $\tau = 0.50$
Design climatic conditions: Warm and dry Mediterranean climate: $T_0 = 35$ ºC, RH = 20%, G_0 =1000 W m^{-2}.
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, (≈ 0.2 to 0.5), or to a crop which is strongly stressed: A = 0.2, B = 3
Design criteria: $T_g = 35$ºC, $T_c = 35$ºC, $D_g = 4$ 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 τ%, (3) fogging with ε_f = 0.3 and (4) wet pad with ε_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 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 -3ºC) for fogging and shading, and about 10 ºC 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 4ºC, 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 *et al*. (2002) with a highly transpiring rose crop (LAI =4).

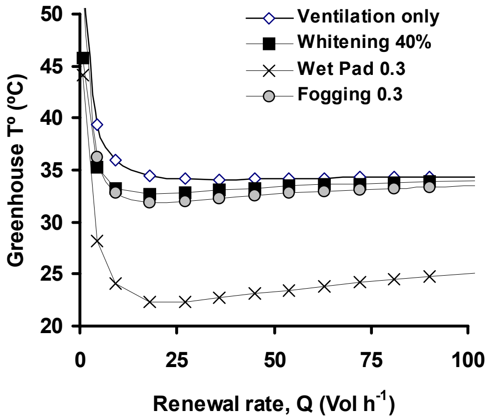

Figure 2a. Greenhouse temperature vs Q. HT crop.

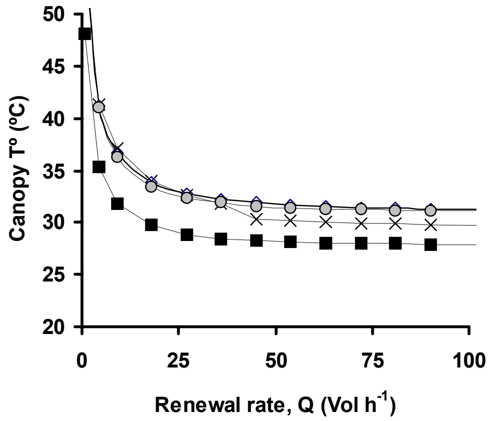

Figure 2 b Canopy temperature vs Q. HT crop

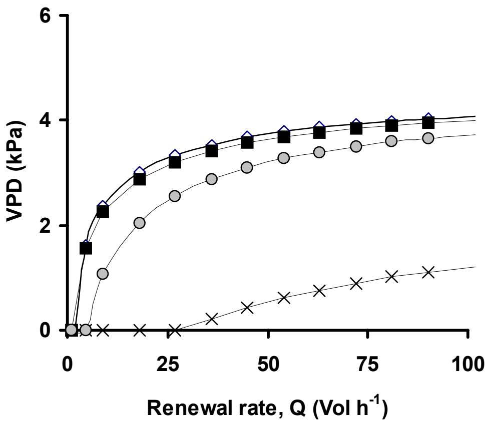

Figure 2 c. Greenhouse VPD (D_g) vs Q. HT crop

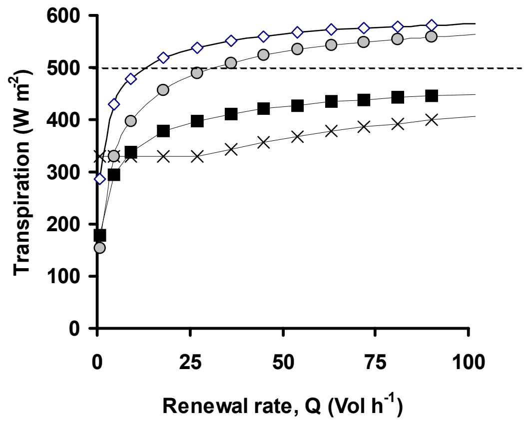

Figure 2d. Canopy transpiration (λE_g) vs Q. HT crop

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^{-} (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 > 45ºC for all Q) and the best were obtained with wet pad and shading (T_c near 40ºC). 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.

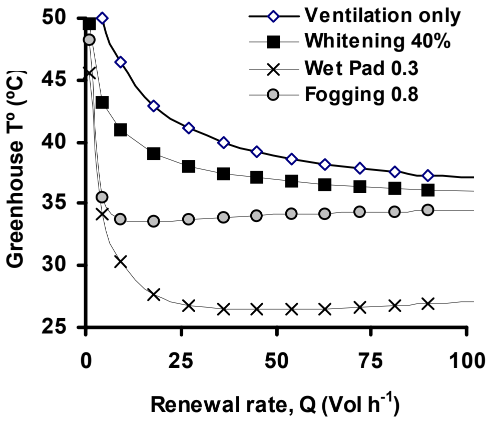

Figure 3a. Greenhouse temperature vs. Q. LT crop

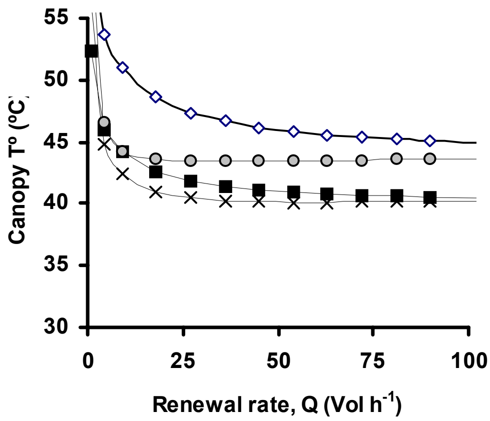

Figure 3 b Canopy temperature vs Q. LT crop

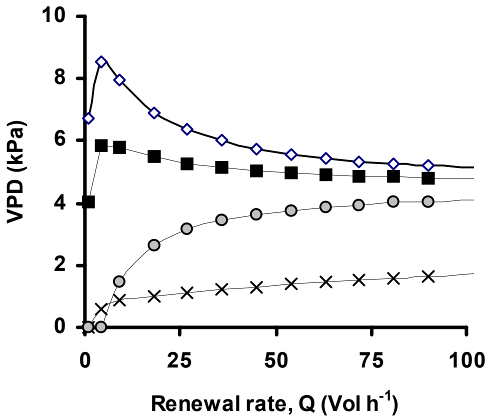

Figure 3 c. Greenhouse VPD (D_g) vs Q. LT crop

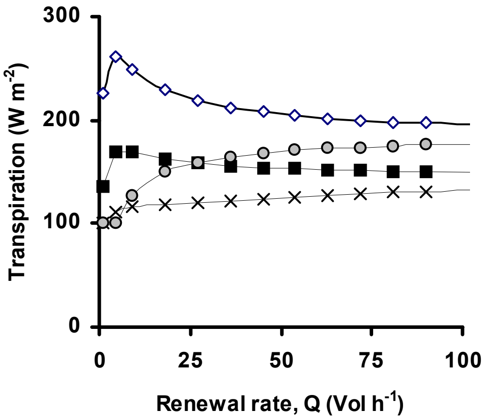

Figure 3d. Canopy transpiration (λE_c) vs Q. LT crop

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 10ºC 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 B_0 (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.

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