Effect of misting on transpiration and conductances of a greenhouse rose canopy

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Received 7 March 2000; received in revised form 31 July 2000; accepted 17 August 2000

Abstract

The influence of greenhouse humidity control on the transpiration rate ($E_c$), sensible heat flux ($H_c$) and bulk stomatal conductance ($g_c$) of a soilless rose canopy (Rosa hybrida, cv. First Red) was studied in a greenhouse located in the coastal area of eastern Greece. Measurements were carried out during several days in the summer (i) without air humidity control and (ii) with a mist system operating when the relative humidity of the greenhouse air was lower than 75%. The diurnal course of $g_c$ was determined from the relation linking $E_c$ to canopy-to-air vapour pressure deficit ($D_c$) or from inversion of the Penman–Monteith equation. The two ways of estimating $g_c$ were in good agreement, showing a significant increase of $g_c$ under mist conditions. Covariation of radiation and humidity during the day caused diurnal hysteresis in $E_c$ and $g_c$. The hysteresis phenomena were less marked when the mist system was operating. Normalising $g_c$ by radiation removed most of the hysteresis and indicated a curvilinear stomatal response to vapour pressure deficit. The analysis of the energy partition at the canopy showed high negative values of the Bowen ratio ($\beta \approx -0.7$) in both conditions, indicating that canopy transpiration played a major role in cooling the greenhouse atmosphere. The contribution of the mist system to total evaporative cooling was estimated to be about 20%, with only 40–50% of the mist water being effectively used in cooling. Calculation of the crop water stress index confirmed that the crop was less stressed under misting conditions. It was concluded that the prediction of short-term variations of $E_c$ and $g_c$ in greenhouse environments must account for the magnitude and diurnal variation of air VPD. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Rose; Greenhouse; Transpiration; Humidity; Bulk conductance; Mist system

1. Introduction

In Mediterranean countries, high temperature ($T > 35^\circ$C) and vapour pressure deficit (VPD $> 3$ kPa) are currently observed in greenhouses during summer. These conditions are responsible for the decrease in yield and quality of greenhouse production. Various methods for cooling the greenhouse atmosphere may be used to maintain more suitable conditions for plant growth. Natural ventilation is usually the first step due to its low cost and simplicity, but is generally not sufficient for extracting the excess energy during sunny summer days (Baille, 1999). Therefore, other cooling methods must be used in combination with ventilation. One of the most efficient solutions for alleviating the climatic conditions is to use evaporative cooling systems, based on the conversion of sensible heat into...
latent heat by means of evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or through evaporative pads (wet pads). Evaporative cooling allows simultaneous lowering of temperature and vapour pressure deficit (Cohen et al., 1983; Arbel et al., 1999; Willits, 1999) and can lead to greenhouse air temperatures lower than the outside air temperature. Its efficiency is higher in dry environments, but it also gives satisfactory results in humid coastal environments (Montero et al., 1990; Montero and Segal, 1993). The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, therefore eliminating the need for forced ventilation and airtight enclosure.

Concerning rose plants response to evaporative cooling, Plaut et al. (1979) observed a significant improvement of flower quality under evaporative cooling conditions. However, Plaut and Zieslin (1977) reported that canopy wetting decreased transpiration rate and increased the diffusive resistance to water vapour transfer. More recent works have focused on the effect of mist systems on crop transpiration (tomato: Boulard et al., 1991; rose: Baille et al., 1994). The latter authors found that the use of a mist system strongly affects the diurnal course of transpiration ($\lambda E$) and VPD. Particularly, the diurnal hysteresis between $\lambda E$ and VPD, or $\lambda E$ and solar radiation ($R_s$), was modified. A more detailed study of this phenomena would supply useful information on the effect of air VPD on the physiological response of the crop. In this paper we investigated the effects of a mist system on canopy transpiration and water vapour conductance ($g_c$) and compared the results with the case of a non-misted greenhouse.

2. Materials and methods

2.1. Greenhouse facilities and plant material

The experiments were carried out during August 1998 in a 200 m$^2$ experimental glass-covered greenhouse, N–S oriented, located at the University of Thessaly near Volos (latitude 39°44’, longitude 22°79’, altitude 85 m) on the coastal area of eastern Greece. The geometrical characteristics of the greenhouse were as follows: eaves height = 2.9 m, span angle = 20°, total width = 6.5 m, total length = 31 m, ground area ($A_g$) = 200 m$^2$, volume ($V_g$) = 690 m$^3$. During the period of measurements (summer 1998), the cover was whitened with white-paint on 15th of June in order to alleviate the radiation load inside the greenhouse. Two methods were used for greenhouse cooling:

1. Natural ventilation only, by means of a continuous roof vent (Fig. 1). Due to the high outside temperature during the periods of measurements, the roof vent was opened at 100% from 9:00 to 19:00 h.

2. Natural ventilation associated with evaporative cooling. During some periods of the summer, a mist system, installed in the greenhouse, was operated in order to maintain 75% relative humidity during the day.

The evaporative cooling equipment was a high-pressure water misting system, consisting of two fan and mist modules (Fig. 1), each module covering the cooling needs for 100 m$^2$. The fans, in vertical position, provided a good air mixing and homogeneity of water distribution inside the greenhouse. A circular ring with eight nozzles for the distribution of atomised water was placed above the fan outlet. Each module had a rate of about 45 l h$^{-1}$ per 100 m$^2$ of ground area or 10$^{-4}$ l s$^{-1}$ per m$^2$ of ground area. If all the misted water was evaporated the equivalent amount of latent heat would represent the evaporative cooling potential of the misting system, which is calculated as the total rate of missed water multiplied by the latent heat of vapourisation of water. Thereby, by the use of misting system, an evaporative cooling potential of 245 W m$^{-2}$ of ground area was allowed. The system was controlled through a humidity sensor (hygrostat) and operated whenever the relative humidity was lower than 75%. During operation of the mist system the roof vent was opened at about 20% of its maximum aperture.

The row rose crop (cv. First Red) was planted on March 1997 in containers (1 m length and 0.3 m width) filled with perlite, and the plant density was 6 plants m$^{-2}$. The distance between rows was 1 m. Water and fertilisers were supplied every hour from 6:00 to 21:00 h via a drip-system, which was automatically controlled by a fertirrigation computer. The drainage rate was maintained near 30%, as usually
practised by growers, in order to maintain optimal conditions of water supply to the plants.

The plants were grown following the “bending” technique (Kool and van de Pol, 1996), which consists in bending the stems that are not considered useful to flower production. This technique allows to obtain more leaf area for sustaining photosynthesis and increasing the contribution of the canopy transpiration to greenhouse cooling. The leaf area of the bent shoots was approximately 70–80% of the total canopy leaf area. During the period of measurements, the area of ground covered by the crop, (projected leaf area), \(A_c\) was about 100 m², thus giving a ratio \(p = 0.5\) for the fraction of soil covered by the crop.

2.2. Measurements

The following climatic data inside the greenhouse were recorded:
- internal temperature \((T_i, \degree\text{C})\) and vapour pressure \((e_i, \text{kPa})\), by means of a psychrometer located in the middle of the greenhouse at the level of the upper bent shoots (0.50 m),
- incoming solar radiation over and under the rose crop \(R_{s,a}\) and \(R_{s,b}\), respectively, \(\text{W m}^{-2}\) by means of two solar pyranometers,
- net radiation over the crop \(R_n, \text{W m}^{-2}\), by means of a net pyrradiometer.

Simultaneously to the measurements of inside climatic variables, outside variables were recorded: solar radiation, air temperature and vapour pressure \((R_{s,o}, T_o,\text{ and } e_o, \text{ respectively})\), and wind speed.

Leaf temperature \((T_l)\) was measured by means of copper-constantan thermocouples, (wire diameter = 0.1 mm). The thermocouple junctions were glued to the back side of leaves. The canopy temperature \((T_c)\) was calculated as the mean value of measurements on seven healthy and mature leaves distributed randomly along the different layers of the canopy (bent shoots and flower stems).

All measurements were collected on a data logger system. Measurements took place every 30 s and the 10 min average values were recorded.
The leaf area index (LAI: m² leaf m⁻² ground) was estimated from leaf length measurements (L, cm). After laboratory estimation of leaf area, a simple relationship linking the area \( S \) (cm²) of a leaf to its length \( L \) (cm) was established:

\[
S = 0.26 L^2
\]  

(1)

During the period of measurements, the leaf area index referred to \( A_c \) (LAI_c) was about 4. Transpiration rate was measured every 10 min by means of a weighing lysimeter (Fig. 1), located in a central row of the greenhouse compartment. The device included an electronic balance (scale capacity \( D_{12} \): 1 kg, resolution \( D_0 \): 1 g) equipped with a tray carrying two plants, and an independent system of water supply and drainage. Considering that the evaporation loss from the perlite substrate was negligible, the weight loss measured by the electronic balance was assumed equal to the crop transpiration. In the following, we expressed the transpiration with respect to the area of ground covered by the crop (\( E_c \), W m⁻²).

2.3. Calculations

2.3.1. Aerodynamic conductance of the canopy

The sensible heat flux (\( H_c \), W m⁻²) exchanged between the canopy and the air was estimated from

\[
H_c = R_n - \lambda E_c
\]

(2)

assuming that the absorbed net radiation was equal to the net radiation measured above the crop. This assumption could be considered valid as the LAI was high (\( \geq 4 \)) and the bent shoots of the plants covered completely the alleys between rows. Like \( \lambda E_c \), \( H_c \) referred to the area of ground covered by the crop.

The aerodynamic conductance, \( g_a \), was calculated from the relationship linking \( H_c \) to the canopy-to-air temperature difference, \( \delta T_c = T_c - T_i \). By convention, \( \lambda E_c \) is considered positive, and \( H_c \) is positive when \( T_c > T_i \), therefore

\[
g_a = \frac{H_c}{\rho C_p \delta T_c}
\]

(3)

2.3.2. Total and stomatal conductance of the canopy

The total canopy conductance to water vapour transfer, \( g_t \) (mm s⁻¹), was estimated from the direct formula:

\[
\lambda E_c = \frac{\rho C_p}{\gamma} g_t D_c
\]

(4)

where \( \lambda \) is the latent heat of vaporisation (J g⁻¹), \( \gamma \) the psychrometric constant (kPa K⁻¹), \( \rho \) and \( C_p \) are respectively the density (kg m⁻³) and specific heat (J kg⁻¹ K⁻¹) of air, \( D_c \) the canopy-to-air VPD. The bulk stomatal conductance, \( g_c \), was derived from the knowledge of \( g_t \) and \( g_a \) from

\[
g_c = \frac{g_a g_t}{g_a - g_t}
\]

(5)

The estimation of \( g_c \) was also performed by inversion of the Penman–Monteith equation:

\[
\lambda E_c = \frac{\Delta R_n + \rho C_p D_i g_a}{\Delta + \gamma (1 + g_a/g_c)}
\]

(6)

where \( \Delta \) (kPa K⁻¹) is the slope of the saturation vapour pressure deficit at \( T_i \).

2.3.3. Bowen ratio

The canopy Bowen ratio was estimated as

\[
\beta = \frac{H_c}{\lambda E_c}
\]

2.3.4. Crop water stress index

The crop water stress index (CWSI) was calculated as proposed by Jackson et al. (1981). The highest possible temperature a canopy can achieve (\( T_M \)) is given by

\[
T_M = T_i + \frac{R_n}{g_a \rho C_p}
\]

(7)

The lower limit, \( T_m \), was assumed to be achieved for a maximum canopy conductance, \( g_M \), and was calculated as

\[
T_m = T_i + \frac{(1/g_a + 1/g_M)(R_n/\rho C_p) - D_i/\gamma}{1 + \Delta/\gamma + g_a/g_M}
\]

(8)

Then, CWSI was given by

\[
W = \frac{T_c - T_m}{T_M - T_m}
\]

(9)

where \( W \) is the CWSI.
3. Results

The results presented in the following section concerned two consecutive 3-day periods of measurements obtained during August 1998.

- a sunny period without misting (19–21 August),
- a sunny period with misting (25–27 August).

The data were averaged on 30 min and covered the period 8:00–19:00 h local time. Solar noon corresponded approximately to 13:30 h solar time.

3.1. Outside conditions

The characteristics of outside climatic variables (average over the period 8:00–19:00 h local time) during the two periods are presented in Table 1. There were no significant differences in outdoor conditions between the two periods.

3.2. Inside microclimate

The daily variation of the air VPD is presented in Fig. 2. The average greenhouse air temperature between 8:00 and 19:00 h was about 32°C without misting, and about 29.6°C when the mist system was operating. The average air VPD during the same time interval was respectively near 2.7 and 1.1 kPa.

3.3. Transpiration rate

The daily variation of the canopy transpiration rate, $E_c$, is presented in Fig. 3. It can be observed that $E_c$ was lower under misting conditions, but the difference was relatively small, reaching about 10–15% on a daily scale. The highest difference was mainly seen during the morning period.

The dependence of $E_c$ versus solar radiation and vapour pressure deficit is presented in Fig. 4a and b, respectively. Both figures evidence of hysteresis, the curves being counter-clockwise in the case of solar operating.
radiation while clockwise in the case of air VPD. It can be seen that misting affected only slightly the relation between $\lambda E_c$ and solar radiation, while modifying strongly the relation between $\lambda E_c$ and air VPD.

3.4. Canopy-to-air temperature difference

Fig. 5 shows the variation of the canopy-to-air temperature difference, $\delta T_c$, versus $D_i$. Under misting, the data appeared to follow a unique trend, represented by the continuous straight line. The linear regression obtained with all points ($n = 67$), when the mist system was used, was

$$\delta T_c = 0.99 - 1.49 D_i, \quad R^2 = 0.85$$

(9)

When the mist system was off, different trends can be distinguished with respect to the period of day: (i) during the morning until 10:00 h, the points were close to the regression line obtained under misting conditions (ii) after 10:00 h until 17:00 h, $\delta T_c$ continued to decrease, but more slowly (dashed arrow) and (iii) in the late afternoon, $\delta T_c$ reversed the tendency and became less negative (dotted arrow), reaching slightly positive values at sunset.

3.5. Sensible heat flux and Bowen ratio

Fig. 6 presents the diurnal variation of the sensible heat flux, $H_c$, on days 19 August (no-misting) and 27 August (misting). It can be seen that $H_c$ reached very large negative values, with maximum at about $-360$ and $-300$ W m$^{-2}$ respectively for no-mist and mist conditions. On average $H_c$ was about 100 W m$^{-2}$ lower under misting than under no-misting conditions, the difference being greatest in the early morning. The diurnal variation of the Bowen ratio (Fig. 7) was similar in the two treatments after 12:00 h. Except on the early morning $\beta$ was found negative and relatively constant throughout the day ($\beta \approx -0.6$–$0.7$).

3.6. Bulk aerodynamic conductance

The relationship between $H_c$ and $\delta T_c$ is shown in Fig. 8 for the days 19 and 27 August. It can be seen that the relationships were approximately linear, with the following regression equations:

No-mist : $H_c = 78.0 \delta T_c - 19.2, \quad R^2 = 0.77$

Mist : $H_c = 150.1 \delta T_c - 7.5, \quad R^2 = 0.79$
The slope of the regression lines supplied an estimation of the average bulk aerodynamic conductance, with $g_a = 62$ and $120 \text{ mm s}^{-1}$ in no-misting and misting conditions, respectively. Similar linear trends were observed for the other days, with some slight variations in the fitted coefficients (slope and offset). For each day, an average value of $g_a$ was calculated in this way and used further in the estimation of the bulk stomatal canopy conductance.
Fig. 5. Canopy-to-air temperature difference ($\delta T_c$) versus air vapour pressure deficit ($D_i$). The measurements were made from 8:00 to 19:00 h. (—) misting (all day long during 27 August), and no-misting during the morning till 10:00 h (19 August), (---) no-misting 10:00 to 17:00 h (19 August), (-----) no-misting 17:00 to 19:00 h (19 August); (○) 19 August, no-misting, (●) 27 August, misting.

Fig. 6. Canopy sensible heat flux ($H_c$) versus hour of the day: (○) 19 August, no-misting; (●) 27 August, misting.
Fig. 7. Bowen ratio ($\beta$) versus hour of the day: (⊙) 19 August, no-misting; (●) 27 August, misting.

Fig. 8. Canopy sensible heat flux ($H_c$) versus canopy-to-air temperature difference ($\delta T_c$): straight lines represent linear regressions of the experimental data; (⊙) 19 August, no-misting; (●) 27 August, misting.
3.7. Bulk stomatal conductance

The two ways of estimating $g_c$ (Eqs. (4) and (6)) were in good agreement for both data obtained under misting and no-misting (Fig. 9), with a slope near 1 and a coefficient of determination $R^2 = 0.96$ for 147 observations. In the following, the direct estimation from $\lambda E_c$ (Eq. (4)) was used for the bulk canopy conductance.

The diurnal variation of $g_c$ under mist and no-mist conditions is presented in Fig. 10. In both cases, an initial sharpen increase in $g_c$ followed by a more progressive decrease in the afternoon was observed. The maximum canopy conductance under misting was about 30 mm s$^{-1}$ (or 7.5 mm s$^{-1}$ if referred to unit leaf area) and was reached near 13 h while, under no-mist conditions, the maximum was about 15 mm s$^{-1}$ (or 3.8 mm s$^{-1}$ if referred to unit leaf area) and was reached sooner (11:00 h). Until 10:00 h, $g_c$ was nearly similar with and without misting.

The change in canopy conductance with respect to $R_s$ and air VPD is presented in Fig. 11a and b, respectively. As for transpiration rate, hysteresis were observed between $g_c$ and the two climatic variables, both being clockwise. It can be seen that, for a same value of $R_s$ or $D_i$, $g_c$ was significantly higher in the morning than in the afternoon.

3.8. Crop water stress index

The diurnal variation of CWSI, calculated with $g_M = 30$ mm s$^{-1}$, is presented in Fig. 12. The higher values of CWSI in the early morning and late afternoon were due to the low radiation levels and should not be taken into account in the evaluation of the level of water or heat stress. It can be seen that, according to this index, the canopy was not stressed under misting conditions (CWSI near 0) and only slightly stressed under no-mist conditions, with an increase from near 0.10 in the early morning to 0.15 in the late afternoon.

4. Discussion

4.1. Changes in microclimate

As illustrated in Fig. 2, the air VPD was strongly affected by the mist system, which allowed keeping the air VPD under 2 kPa, while a maximum value of about 5 kPa was reached under no-mist conditions. The air
Fig. 10. Canopy stomatal conductance ($g_c$) versus hour of the day: (○) 19–21 August, no-misting; (●) 25–27 August, misting.

temperature was also significantly reduced under mist conditions (not shown). These contrasted trends of air temperature and air VPD were expected and confirmed that evaporative cooling is effective for lowering both temperature and air VPD.

4.2. Energy partitioning

The levels of transpiration rate reached by the canopy were very high (up to 600 W m$^{-2}$, Fig. 3). The sensible heat flux $H_c$ also reached high levels (Fig. 6), as the Bowen ration was about −0.6 throughout the day (Fig. 7). Such high values of $\lambda E_c$ and $H_c$, overcoming the net radiation of the canopy by a factor 2, or even more in the case of $\lambda E_c$, can be explained by the “oasis effect” induced by the presence of a large fraction of dry ground ($p = 0.5$) not covered by the canopy (Seginer, 1994). Much of the net radiation absorbed by the uncovered ground was converted into sensible heat and contributed to the transpiration of the canopy. Assuming as a first estimation that the sensible heat of the uncovered dry ground was equal to the net radiation $R_n$, we can deduce that the canopy has to convert into latent energy a heat load of about $2 \times R_n$, which corresponds roughly to the order of magnitude of $\lambda E_c$.

The difference of $H_c$ between no-misting and misting periods was on average about 100 W m$^{-2}$ (Fig. 6). That means that misting contributed to alleviate the heat load by this amount of sensible energy. As the cooling potential was about 240 W m$^{-2}$, it can be concluded that only a part (about 40–50%) of the mist water contributed to the actual cooling of the greenhouse. It appears therefore that (i) a significant fraction of mist water was probably transferred directly to the outside atmosphere through the aperture of the vents and (ii) the contribution of misting to evaporative cooling is only a small fraction (about 0.15–0.25) of the contribution due to canopy transpiration.

It has to be noticed that the average bulk aerodynamic conductance $g_a$ was double under misting (120 mm s$^{-1}$) compared to that under no-misting (about 60 mm s$^{-1}$). This was due to the effect of the fan-and-mist system that increased air mixing and turbulence above the canopy.

4.3. Bulk stomatal conductance

The transpiration rate (Fig. 3) was not affected to such an extent as the air VPD by misting. Although $\lambda E_c$ was lower under mist conditions, the difference observed with the values of $\lambda E_c$ under no-mist con-
ditions was moderate. The maximum values of $\lambda E_c$ observed during the two periods of measurements were relatively close, and occurred at the same hour. This can be explained by the values reached by the bulk stomatal conductance (Fig. 10), which was about double under mist conditions. Therefore, as the canopy-to-air VPD followed the air VPD trend and was about half under misting, the transpiration rate was not significantly changed. In fact, there was a compensatory effect between VPD and bulk stomatal conductance.
Fig. 12. CWSI versus hour of the day. CWSI was calculated with $\delta_{\text{SM}} = 30 \, \text{mm} \, \text{s}^{-1}$: (○) 19–21 August, no-misting; (●) 25–27 August, misting.

resistance that allowed the canopy to keep similar levels of $\lambda E$.

It has to be pointed out that, during the period without misting, the decrease in $g_c$ started at the value of 2 kPa (Fig. 11b), which was reached near 10:00 h. During days with misting, the maximum values of $g_c$ were reached near 13:00–14:00 h, when air VPD was also near 2 kPa, and decreased afterwards. This critical value of 2 kPa was mentioned by Baille et al. (1994) as a reference value (or set-point) for actuating the mist system in order to avoid stomatal closure.

4.4. Canopy water stress index

The difference between canopy and air temperature as a function of vapour pressure deficit can be used as an index of the water status of the crop (Jackson et al., 1981; Idso et al., 1990). The results presented in Fig. 12 indicate that the canopy was more stressed under no-mist conditions. In Fig. 5 three different phases can be distinguished in the relationship linking $\delta T_c$ to air VPD. The first phase, corresponding to the morning period until 10:00–11:00 h, the relationship was nearly the same under mist and no-mist conditions, and could be considered as the “baseline” corresponding to no-stress conditions (Idso, 1982). In the second phase (11:00–17:00 h), $\delta T_c$ under no-misting conditions still decreased, with increasing air VPD, but the slope of the regression line was lower, therefore inducing an increase of CWSI. The third phase (after 17:00 h) corresponds mainly to the progressive response of stomata to the steep decrease in radiation, while the more progressive decrease in VPD during this period did not seem to play a major role. These results were consistent with the evolution of $g_c$ versus time under mist and no-mist conditions (Fig. 9).

It can be underlined that the CWSI of the misted canopy was very low (between 0 and 0.05), and that the CWSI values for the no-mist canopy were not very high (maximum of about 0.20 in the late afternoon). The latter suggest that high LAI associated with an adequate water supply was quite effective in avoiding strong canopy stress in greenhouse summer conditions, even when artificial evaporative cooling was not available.

4.5. Analysis and interpretation of the hysteresis phenomena

The hysteresis of $\lambda E_c$ with respect to the environmental variables $R_s$ and VPD (Fig. 4) was previously observed in rose greenhouse conditions (Baille
Fig. 13. Normalised conductance, $g_c^*$ ($=g_c/R_{s,a}$, arbitrary units) against canopy surface vapour pressure deficit, $D_s$: (○) 19–21 August, no-misting; (●) 25–27 August, misting. The curve is a power function fitted to all data ($g_c^* = 0.0756 D_s^{-0.504}$, $R^2 = 0.62$).

The hysteresis of canopy conductance was previously demonstrated for other species under field conditions, e.g. by Gutierrez et al. (1994), who found similar trends as observed in this study for the transpiration and canopy conductance of coffee hedgerows, and by Takagi et al. (1998), on wetland species. The first authors attributed the diurnal hysteresis to the effects of covariation of $R_s$ and VPD on the stomatal response. They presented the results in a non-dimensional form, normalising the canopy conductance by the photosynthetic active radiation, $I$, and the transpiration rate by the net radiation, $R_n$. The normalisation removed the hysteresis and revealed a strong stomatal response to humidity, showing that the normalised conductance, $g_c^*$, decreased exponentially with increasing evaporative demand. We applied the same type of normalisation to the values of $g_c$ obtained in this study. Fig. 13 presents the relationship between $g_c^*$ ($=g_c/R_{s,a}$) and the VPD at the canopy surface, $D_s$, for misting and no-misting conditions. The variable $D_s$ was chosen as it is commonly used as the reference VPD in studies dealing with the response of stomata to humidity (Aphalo and Jarvis, 1993). When all experimental points were grouped together, we effectively found a curvilinear decrease of the normalised conductance when $D_s$ increases, with a relative high scattering, mainly due to the data corresponding to misting conditions (Fig. 13).

5. Concluding remarks

In this study, the hysteresis curves observed for transpiration rate and canopy conductance versus vapour pressure deficit and radiation were characterised under mist and no-mist conditions. The influence of environmental variables on the hysteresis curves was demonstrated and discussed.

In the conditions prevailing during the experiments (summer sunny days, high LAI canopy) the use of a mist system for greenhouse cooling, when compared with no-mist conditions, showed that:

1. The air temperature and vapour pressure deficit significantly decreased, while maintaining a relatively high level of transpiration rate. The low VPD levels allowed the plants to maintain higher stomatal conductance during the major part of the day.
2. The crop physiological status improved as indicated by the higher canopy stomatal conductance prevailing under misting conditions, and by the calculation of the canopy water stress index.

It was also found that high LAI associated with an adequate water supply was quite effective in avoiding strong canopy stress in greenhouse summer conditions, even when artificial evaporative cooling was not available.

Finally, the results presented in this study suggest that, in order to accurately predict short-term variations of canopy transpiration rate and conductance from greenhouse environmental conditions, the magnitude and diurnal variation of VPD during the day must be accounted for. Therefore, on-line measurements of VPD in greenhouse appear to be a prerequisite for improving irrigation or climate control algorithms based on canopy transpiration predictive models.

References


