Process-based humidity control regime for greenhouse crops

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Abstract

Modern greenhouses in The Netherlands are designed for efficient use of energy. Climate control traditionally aims at optimal crop performance. However, energy saving is a major issue for the development of new temperature regimes. Temperature integration (TI) results in fluctuating and often high relative humidity (RH) levels in modern, highly insulated greenhouses. At high temperature, water vapour pressure deficit (VPD) is usually high and RH consequently low and vice versa. Relatively low fixed set points (80–85% RH) for air humidity as is common practice, may strongly influence the efficiency of TI, because heating and/or ventilation actions are required to control humidity rather than temperature. This requires much energy. Fluctuating RH may affect crop performance in several ways. Too low VPD may reduce growth due to low transpiration and associated physiological disorders. Water vapour pressure above the dew point leads to condensation on the relative cooler plant tissue and this may give rise to diseases. High VPD, on the other hand, may induce high stomatal resistance and plant water stress (PWS). The aim of the present research was the design of a process-based humidity control concept for a reference cut chrysanthemum crop cultivated with TI. RH control set points were generated as function of underlying processes. Greenhouse performance with this humidity regime and different temperature regimes were simulated with respect to greenhouse climate, energy consumption and photosynthesis. Compared with a fixed 80% RH set point, annual energy consumption of a year-round cut chrysanthemum cultivation could be reduced by 18% for TI with ±2 °C temperature bandwidth as well as for regular temperature control. For separate 12 week cultivations with planting date 1 March, energy saving could increase up to 27 or 23% for TI and regular temperature control, respectively.

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1. Introduction

Future greenhouse systems in moderate climates will have to be energy efficient. Greenhouses will have decreased transmission for long-wave- and increased transmission for short-wave-radiation compared with common shelters (Bot, 2001). Improved heat insulation will lead to more fixation of solar energy. For optimal use of these greenhouse systems and for maximum energy saving and optimal crop growth, climate regimes should be designed especially for this type of greenhouses (Bot, 2001). For this purpose, the temperature integration principle (TI) could be used. With TI, mean temperature is controlled rather than instantaneous temperature, allowing temperature fluctuations within a certain bandwidth (Cockshull et al., 1981; Hurd and Graves, 1984). However, when applying TI (especially in highly insulated greenhouses) humidity is a limiting factor for energy saving. With TI, heating and ventilation are minimised leading to more temperature fluctuations. In this situation with reduced ventilation and heating, relative humidity (RH) increases when temperature drops and vice versa. Water vapour pressure deficit between greenhouse air and crop (VPD) may affect transpiration and consequently absolute air humidity. The low fixed set points for humidity control used in common practice (80–85% RH) counteract the positive effect of TI on energy consumption. Vents will open at lower temperatures than required for TI or heating will decrease RH or both. This problem will be even more pronounced in future highly insulated greenhouses (Bakker and De Zwart, 1999).

Humidity control, nevertheless, is very important for achieving high quality crop yield. Without humidity control, high RH levels may lead to loss of crop quality due to fungal diseases, leaf necrosis, calcium deficiencies and soft and thin leaves (e.g. Kranz, 1996). Crop growth may decrease (Mortensen, 1986), anatomical changes may occur and plant development can be disturbed or delayed (Hand et al., 1996; Mortensen, 2000). High humidity conditions can further hamper pollination in fruit vegetables, as pollen grains tend to remain inside, or stick to the anthers (Van Koot and Van Ravestijn, 1963; Bakker, 1991) and vase life in ornamental plants may be shortened (De Gelder, 2000). Too low RH conditions on the other hand (high VPD), can lead to plant water stress (PWS).

By using flexible humidity constraints, significant reductions in energy consumption could be realised (De Gelder, 2000). To this end dynamic humidity ranges should be established for different underlying humidity-related crop processes. The constraints formulated in this way together determine the acceptable range. In this research, such a humidity regime is proposed. A first design with roughly estimated parameters was introduced to show the possibilities of such a regime. Processes were
identified and constraints were formulated on the basis of literature for the case of cut chrysanthemum. Processes related to PWS, calcium deficiencies, crop growth and development and major airborne fungal diseases were distinguished. The regime was investigated in simulations with a greenhouse climate and control model (De Zwart, 1996). The effect of the regime on energy consumption, greenhouse climate and crop photosynthesis with different TI regimes was evaluated.

2. Humidity regime

The regime is based on the response of crop processes that are affected by greenhouse atmospheric humidity (PWS, calcium deficiencies, crop growth, crop development and fungal diseases). These processes by their nature react to different aspects of atmospheric humidity, either to VPD, to absolute humidity or to RH. Fungal diseases probably react to a combination of RH and leaf wetness (LW). LW (i.e. condensation) occurs when temperature drops below the dew point. This value depends on absolute humidity. PWS and calcium deficiencies are related to transpiration whose climate determinants are VPD, radiation and CO₂ concentration (i.e. influence on stomatal conductance). Crop growth and development are probably also mainly affected by an indirect effect of VPD on transpiration.

2.1. Crop growth and development

Humidity affects growth of greenhouse crops mainly through its impact on leaf size and light interception rather than through a direct impact on photosynthesis by increased stomatal conductance at low VPD (Gislerød and Nelson, 1989; Bakker, 1991). Leaf area can either increase or decrease under long-term high humidity exposure (Bakker, 1991). Increased leaf area was found in cucumber (Bakker et al., 1987) or chrysanthemum (Mortensen, 2000) and leaf area decreased in tomato (Bakker, 1990; Holder and Cockshull, 1990). Due to that, tomato fruit yield also decreased when exposed to 28 days at 0.15 kPa VPD (Holder and Cockshull, 1990). The smaller leaf area was associated with low calcium concentrations in the leaf laminae and calcium deficiency symptoms (Holder and Cockshull, 1990; Bakker, 1990). Holder and Cockshull (1990) concluded that the cost of reducing humidity to VPD greater than 0.3 kPa was likely to exceed any economic gain. However, crop growth in cut chrysanthemum is relatively insensitive to a continuous atmospheric vapour pressure deficit (VPD_air) between 0.1 and 1.2 kPa (Hand et al., 1996). This was also supported by Mortensen (2000), who did not find any significant dry weight increase with chrysanthemum long-term exposure to 0.155 kPa. But in chrysanthemum, plant development can be affected by low VPD conditions. Applying a continuous VPD_air of 0.1 or 0.155 kPa delayed flower development of cut chrysanthemum by 4–5 or 3–4 days (Hand et al., 1996; Mortensen, 2000). The delays, however, are cultivar dependent (Hand et al., 1996). Although humidity conditions < 0.2 kPa VPD are likely to occur in chrysanthemum cultivation when short-day is induced with blackout screens or during winter at reduced ventilation.
(Hand et al., 1996), those investigations concerned continuous high humidity situations and that is much more extreme than would probably ever be encountered in commercial growing (Hand et al., 1996).

The underlying processes leading to delayed flower development in cut chrysanthemum exposed to low VPD are obscure (Hand et al., 1996). Although the response of crop growth to humidity is probably based on more underlying processes as transpiration and calcium transport, an overall rule was applied combining growth and development as first general protection. Because plants are able to compensate unfavourable climate conditions, a mean VPD for control in greenhouse conditions was applied. A simple rule with a 24 h VPD integral with upper and lower boundary was used for that. Since the literature review on effects of humidity on greenhouse crops by Hand (1988) revealed that for most greenhouse crops, growth and development are unaffected between 0.3 and 1.0 kPa VPD, and only one of six tested cut chrysanthemum cultivars delayed flower development when continuously exposed to 1.1 kPa VPD (Hand et al., 1996), the two boundaries for the 24 h VPD integral were chosen as 0.3 and 1.1 kPa to maintain crop growth and development at a high level.

2.2. Plant water stress and calcium deficiencies

Increasing VPD enhances potential crop transpiration (λE) and xylem water flux and, therefore, import of calcium ions into leaves. A too high VPD in combination with high radiation leads to higher λE than the plants can handle (Nederhoff, 1998). With too high potential λE, water loss may exceed water uptake. This discrepancy between water uptake through the roots and transpiration from the leaves may occur at VPD levels higher than 1 kPa (Hand, 1988). Then, plant water potential may decrease below the acceptable range and plants may start wilting. Permanent leaf-damage may occur (especially in combination with high radiation). Stanghellini and Van Meurs (1997) suggested a transpiration integral with upper and lower boundary to adequately deal with this problem. Transpiration related disorders, could then be controlled by integrating λE. Plants integrate long high humidity periods without negative consequences, whereas PWS can occur in minutes or hours.

A minimum and maximum transpiration mean was set to control PWS and calcium deficiencies. A lower boundary on 24 h transpiration mean was defined to prevent calcium deficiencies. To prevent PWS, an upper threshold on the 1 h mean transpiration was applied. To set boundaries, two λE extremes were calculated with climate conditions that may occur when TI is applied with large temperature bandwidths as presented by Körner and Challa (2003). Equations derived by Stanghellini (1987) were used for that. The upper boundary was established for a situation with 30 °C, 65% RH and high irradiation, the lower boundary for 14 °C, 93% RH and low irradiation. This corresponded to 12 and 300 J m⁻² s⁻¹ λE at leaf area index (LAI) of 3, respectively. When λE exceeded the lower threshold, transpiration had to reach the threshold within 1 h. When λE exceeded the upper threshold, this had to occur within 5 min. Forecasted transpiration was checked for
that. If the requirement could not be met, a transpiration set point was chosen such that satisfied the integral requirement.

2.3. Fungal diseases

In commercial chrysanthemum production in greenhouses grey mould (GM) (*Botrytis cinerea*), powdery mildew (PM) (*Erysiphe cichoracearum*) and chrysanthemum white rust (WR) (*Puccinia horiana*) are the major air-borne plant pathogenic fungi. For control of fungi, RH and leaf wetness duration (LWD, i.e. the time integral of LW) are most important (Huber and Gillespie, 1992).

2.3.1. Chrysanthemum white rust

Chrysanthemum WR (*P. horiana*) causes pale areas on the upper leaf surface, with powdery orange pustules or spots directly beneath on the undersides of the leaves. Severely infected plants are much weakened and fail to bloom properly. High humidity over 90% and a film of moisture appear to be necessary for germination of both teliospores and basidiospores (Uchida, 1983). However, no new infection occurs at LWD less than 5 h (Krebs, 1991) and at least 2–3 h LWD is necessary for penetration of existing infections (Uchida, 1983). Basidiospores, nevertheless, are very sensitive to desiccation (Horst and Nelson, 1997). According to Dickens and Potter (1983) the survival of spores is both time and dose dependent. *P. horiana* spores survive for 5 min at 80% RH and for 1 h at 90% RH. Assuming a greenhouse temperature of 20 °C, this corresponds to 0.48 and 0.25 kPa VPD as a more direct measure of desiccation. These values were used for control. LWD was restricted to 3 h followed by a VPD dependent desiccation time (as dose–response) using an arbitrary exponential function fitting the two mentioned control values.

2.3.2. Grey mould

GM is caused by *B. cinerea*. It attacks ornamentals as chrysanthemum (D’Aulerio and De Polzer, 1982), roses and gerbera (Kerssies, 1994) as well as vegetables as tomato (Meneses et al., 1994). In Dutch greenhouse environment, conidia of *B. cinerea* are always present (Kerssies, 1994). The fungus sporulates on infected tissues under high RH conditions. Usually *B. cinerea* does not invade healthy green tissue such as leaves and stems unless an injured or dead area is present. However, lower leaves in the canopy are often attacked and then the fungus can spread. The spores contain little water and need to absorb it from the environment (Nederhoff, 1997a) and due to that condensation provokes spore germination (Nederhoff, 1997a,b). It is, however, difficult to predict at what RH level spores germinate and infect plants (Nederhoff, 1997a). Free moisture is probably necessary for fast germination and infection, and a minimum LWD may provoke growth and development. As with chrysanthemum WR, spores are sensitive to desiccation and die after longer periods of low RH (Nederhoff, 1997a). After short periods (about 2 h) spores continue germinating when humidity gets very high again (Nederhoff, 1997a). However, RH > 93% is at least necessary for spore development and infection can occur with RH higher than 95% (Kerssies, 1993). To control *B. cinerea* in chrysanthemum, first a
long-term RH boundary of 93% must be respected (De Gelder, 2000; Spaargaren, 2002) and secondly LWD must stay below a certain limit. The same LWD threshold as for chrysanthemum WR was used. In addition, a long-term integral of RH was applied. RH was not allowed to be higher than 93% for maximum of 48 successive hours. When this happened, RH was set to 85% until a minimum of 4 h (arbitrarily) below 93% RH was achieved.

2.3.3. Powdery mildew

Chrysanthemum PM is caused by *E. cichoracearum* with its anamorph *Oidium chrysanthemi* DC. Conidia of the family Erysiphales consist of 50–70% of water and can germinate and infect without dew and condensation is not required for growth (Verhaar, 1998). Once infection occurs it develops rapidly under dry conditions (Watterson, 1986). However, water sprays or rain reduces PM in roses (Sivapalan, 1993b; Liu, 2001) and squash (Coelho et al., 2000). In fact, dew after sporulation may kill spores due to lack of oxygen, but spores may become more resistant when LWD is too short (Yarwood, 1978). Different species of PM differ widely in their ability to germinate in water (Sivapalan, 1993a) and survival greatly depends on intensity of conidia adhesion to the plant tissue (Yamaoka and Takeuchi, 1999). However, to include this as a first approximation into control, a minimum LWD of 1 h was applied in each 24 h cycle to kill possible *O. chrysanthemi* spores.

3. Materials and methods

3.1. Determination of RH set point

The processes affected by humidity control (calcium deficiencies, PWS, crop growth and development, chrysanthemum WR, PM and GM) all require a separate, process related RH window. A 24 h course of greenhouse temperature was calculated once a day (0:00 h) with a simple greenhouse model as reported by Körner and Challa (2003) and weather forecast according to the lazy-man weather prediction (Tap et al., 1996). Future and recorded climate data were used for control.

Humidity in greenhouses is commonly controlled by set points for RH or VPD. From that decisions on ventilation or heating or a combination of these two measures are made by the climate computer. In the present approach, set points for RH were created and used as input for a climate computer. Set points were clustered into lower and upper RH thresholds (RH$_{set}^-$ and RH$_{set}^+$, respectively). Lower thresholds deal with humidity related problematic processes that are susceptible to low humidity conditions such as PM, PWS, and the maximum level for growth and development (GD$_{max}$). Upper thresholds deal with humidity related problematic processes that are susceptible to high humidity conditions such as chrysanthemum WR, Calcium deficiencies (Ca$_{Def}$), GM and minimum level for growth and development (GD$_{min}$).

PM and PWS can occur at relatively low humidity conditions and chrysanthemum WR, GM and calcium deficiencies can occur at high RH conditions. Developmental
delay and growth reductions can occur under both circumstances. Conflicts between humidity requirements of different processes may occur. Sporulation probability for PM, for instance, is reduced by setting a minimum LWD and for chrysanthemum WR (and GM) by setting a maximum LWD (Fig. 1). In addition, also spore survival requirements are conflicting, and depend on desiccation time of these two fungi (Fig. 2). Solving these problems would lead to conflicting climate set points. To cope with that conflict, priorities were given to different processes. To implement control of humidity including the rules for all processes, the two clusters of rules were distinguished. RH$_{set}$ is dealing with maximum RH constraints and RH$_{set}^-$ with minimum constraints. For priority assignment, an approach according to response times was used (Challa and Van Straten, 1993). PWS has the fastest response time as it is controlled with a 1 h integral and is to be compensated within 5 min. This is controlled first. Then, because high humidity conditions and a relatively short minimum leaf condensation (i.e. short response time) are necessary to control PM, this process was controlled second and maximum VPD integral for growth and development was third. Active dehumidification follows only after control measures for PWS, PM and maximum VPD for growth and development have been taken. Constraints for those processes have equal priority.

Constraints for each cluster were determined first (Eq. (1)), where lower constraints had priority over upper constraints (Eq. (2)). Default values for RH$_{set}^-$ and RH$_{set}^+$ were, respectively, 70% and 99%.

$$\begin{align*}
\text{RH}_{set}^- &= \max(\text{RH}_{set,PM}^-; \text{RH}_{set,LWS}^-; \text{RH}_{set,GD_{max}}^-) \\
\text{RH}_{set}^+ &= \min(\text{RH}_{set,WR}^+; \text{RH}_{set,GM}^+; \text{RH}_{set,CaDef}^+; \text{RH}_{set,GD_{min}}^-) \\
\text{RH}_{set} &= \max(\text{RH}_{set}^+; \text{RH}_{set}^-)
\end{align*}$$

(1)

(2)

With these rules, RH was set to 99% until a complete LWD of 1 h was achieved for

Fig. 1. Theoretical example of the relationship between LWD and sporulation probability for PM (O. chrysanthemi) (---) and chrysanthemum WR (P. horiana) or GM (B. cinerea) (—). Applied models were arbitrarily chosen respecting only the boundaries. PM: 100(1+exp((t−P_{50})/x)), t is time in hours, P_{50} is time of reduction to 50% sporulation probability and x is a form parameter. Chrysanthemum WR and GM: $P_{RH}=(100-P_{RH})(1+\exp((-t-P_{50,LWD})/y))$, P_{RH} is the threshold probability that is determined by the relative humidity integral (\int RH) and P_{50,LWD} is the time reduction to 50% of the LWD influence.
PM control in each 24 h cycle. The upper threshold for growth and development had second order priority as this was controlled after PWS and PM. Processes of RH_set/C27 had third and fourth order priority, because all processes of RH_set/C28 were controlled first. Therefore, e.g. desiccation-time for chrysanthemum WR was immediately applied after control for RH_set/C28 was terminated. An overview of the different processes and their constraints is illustrated in Table 1.

3.2. Calculation of microclimate

In a fixed time sequence, static values of different microclimate parameters were calculated from greenhouse climate data. To this end, crop transpiration (i.e. latent

Table 1
Humidity related crop processes in cut chrysanthemum process-based humidity control, their controlling factors (VPD, RH, LWD and λE), control criteria and applied priority for set point determination

<table>
<thead>
<tr>
<th>Process</th>
<th>Control factors and criteria</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VPD (kPa)</td>
<td>RH (%)</td>
</tr>
<tr>
<td>Growth</td>
<td>24 h ≥ 0.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>24 h ≤ 1.1</td>
<td>–</td>
</tr>
<tr>
<td>Development</td>
<td>24 h ≥ 0.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>24 h ≤ 1.1</td>
<td>–</td>
</tr>
<tr>
<td>Water stress</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ca deficiencies</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>WR</td>
<td>Desiccation</td>
<td>–</td>
</tr>
<tr>
<td>GM</td>
<td>–</td>
<td>48 h ≤ 93</td>
</tr>
<tr>
<td>PM</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
heat of evaporation, $\lambda E$), crop temperature ($T_c$), dew point temperature of the greenhouse air ($T_{dp}$) and LWD were the most important factors.

Within a greenhouse, $\lambda E$ normally is the major process contributing to accumulation of water vapour in the greenhouse atmosphere. $\lambda E$ increases with LAI, $T_c$, VPD (Pa), and net short wave radiation (Stanghellini and Van Meurs, 1997). $\lambda E$ (W m$^{-2}$) of a canopy was obtained by a simplified approximation of the Penman–Monteith equation (Monteith, 1973) for a greenhouse tomato crop (Stanghellini, 1987).

$$\lambda E \approx \frac{12 \text{LAI}}{3 + r_{h_{2}o}/r_{b_{2}o}} \left( \frac{I_c}{40} + \frac{T_h - T_{air} + \text{VPD}}{3} \right)$$

This equation contains internal and external resistance to $H_2O$ ($r_{h_{2}o}$, $r_{b_{2}o}$ s m$^{-1}$), short-wave radiation on the top of the canopy ($I_c$, W m$^{-2}$), temperature of surfaces and greenhouse air ($T_h$ and $T_{air}$, K) and the psychrometric constant ($\gamma$, Pa K$^{-1}$). The symbol $\sim$ denotes to a rough approximation of this relationship. The internal resistance (stomatal) was calculated as function of temperature, CO$_2$ concentration ($\mu$mol mol$^{-1}$) and RH; and the boundary layer resistance (external) was assumed constant and calculated from the specific heat capacity of the air, the density of the air and the convective heat transfer coefficient between greenhouse air and canopy (Stanghellini, 1987). $T_c$ was calculated as proposed by Stanghellini (1987) for a tomato crop, based on the energy balance separated for day and night. The night equation was used whenever $I_c$ was lower than 10 W m$^{-2}$.

$$T_c - T_{air} \approx \begin{cases} 0.006I_c + 0.08(T_h - T_{air}) - 0.25 \frac{\text{VPD}_{air}}{\gamma} & \text{if } I_c \geq 10 \text{ W m}^{-2} \\ 0.16(T_h - T_{air}) - 0.1 \frac{\text{VPD}_{air}}{\gamma} & \text{if } I_c < 10 \text{ W m}^{-2} \end{cases}$$

Equations that were used to calculate $\lambda E$ and $T_c$ were originally designed for a dense stand of a tomato crop and were only a rough approximation to the sample crop cut chrysanthemum as used here. However, since $T_c$ may vary with the position of leaves within the canopy three leaf layers of equal partial LAI were distinguished to represent this heterogeneity in the chrysanthemum crop. To estimate $T_c$ and leaf condensation in different layers of the crop, the Beer–Lambert Law was applied according to Monsi and Saeki (1953). It was assumed that only $I_c$ changed with LAI while $\text{VPD}_{air}$, $T_h$ and $T_{air}$ were the same at all locations in the crop.

$T_{dp}$ ($^\circ C$) was calculated by a function containing RH (%), saturated vapour pressure of the crop ($\text{VP}_{\text{sat,c}}$, Pa) and constants in similarity to Zolnier et al. (2000).

$$T_{dp} = 237.3 \log_{10} \left( \frac{\text{VP}_{\text{sat,c}} \text{RH}/100}{610.78} \right) / \left( 7.5 - \log_{10} \left( \frac{\text{VP}_{\text{sat,c}} \text{RH}/100}{610.78} \right) \right)$$

It was assumed that condensation occurred when the difference between crop and dew point temperature was smaller than 1.5 K (Avissar and Mahrer, 1982; Zhang et al., 1997).
Because the distinction between a completely wet and a completely dry leaf layer was important with this regime (i.e. relationship between LWD and desiccation time for PM and WR control) a state variable, LW was introduced that could assume only three states (wet, intermediate and dry).

\[
LW = \begin{cases} 
-1 & \text{if } T_c - T_{dp} \geq 2 \\
0 & \text{if } 1.5 < T_c - T_{dp} < 2 \\
+1 & \text{if } T_c - T_{dp} < 1.5 
\end{cases}
\]  

(6)

LW was set according to that and integrated over time to LWD for three levels in the crop separately. If one layer exceeded a specific threshold, RH set point for this process decreased. The strength of decrease depended on the number of wet leaf layers. For, e.g. B. cinerea, RH set point was calculated from setting \(T_c - T_{dp}\) to 0.75, 1.5 and 2.25 for one, two and three wet layers, respectively. The highest RH that satisfied this value was calculated and used as partial set point.

3.3. Technical implementation

The humidity control regime was implemented in the software environment MATLAB® (version 6.0, MathWorks, Natick, MA, USA) and used in simulations with a greenhouse climate and control model (De Zwart, 1996) with cut chrysanthemum as test crop. A 1 year reference climate data set for De Bilt (The Netherlands, lat. 52° N) (Breuer and Van de Braak, 1989) was used for simulations on greenhouse climate, energy consumption and crop growth for a whole growing season. The model consisted of a typical 1 ha Venlo-type greenhouse with a single glass cover (transmission for diffuse radiation of 78.5%) and a blackout screen. A set point controller was implemented that used the set points calculated by the MATLAB® programme in 5 min intervals. Greenhouse air temperature, RH and CO₂ concentration inside the greenhouse and outside global radiation were input to the model. RH set points were calculated by the humidity control regime and sent together with set points for temperature control as input for simulation to the greenhouse climate model. The control system in the greenhouse model used the set points and the model returned simulated realised greenhouse climate (RH, temperature and CO₂ concentration). CO₂ set point was 1000 μmol mol⁻¹ when vents were closed and 350 μmol mol⁻¹ when vents were open or when the outside global radiation was below the threshold of 40 W m⁻². Crop gross photosynthesis was calculated according to Goudriaan and Van Laar (1994) based on leaf photosynthesis and radiation distribution within the canopy. Leaf photosynthesis was described by the two parameter (maximum gross photosynthesis and photochemical efficiency), negative exponential light-response curve (Thornley, 1976) and applied as reported by Körner et al. (2003).

3.4. Simulations

Cultivation of cut chrysanthemum was simulated with set points according to common practice in The Netherlands (blueprint) and with flexible humidity and
temperature regimes (Table 2). Targeted mean temperature over the 6 day averaging period was set to 19°C. The blueprint consisted of initial set points of 18.5 and 19.5°C for heating and ventilation, respectively, and influences through global radiation. Daytime ventilation set points increased linearly with outside global radiation level (0.5 K per 100 W m$^{-2}$ between 800 and 1200 W m$^{-2}$) and nighttime heating and ventilation set points increased linearly with daily global radiation sum (0.25 K per 1 MJ m$^{-2}$ per day between 12 and 16 MJ m$^{-2}$ per day). TI was applied over a 6 day averaging period according to the procedure for regular TI as described by Körner and Challa (2003).

Two types of simulations were performed on crop growth, greenhouse climate and energy consumption. First, a year-round cultivation starting 1 January was simulated. Short-day was induced with blackout screens. For this, 25% of the greenhouse area was assumed under long-day and 75% under short-day (day-time 06:00–00:00 and 08:00–19:00 h, respectively). During long-day, an energy saving screen (SLS 10 plus, Ludvig Svensson, Kinna, Sweden) was applied between 19:00 and 08:00 h when sunset was earlier than 19:00 h or between sunset and 08:00 h when sunset was later than that. In addition to that, 12 separate cultivations were simulated with monthly plantings. For simplification, the cultivation period was 12 weeks independent of the season. Long-day was maintained during the first 3 weeks and short-days between week 4 and 12 after planting. Simulations were performed for a regular temperature regime and for TI with different temperature bandwidths with fixed 70, 80, 90 and 99% RH set points.

4. Results

4.1. Energy saving and crop gross photosynthesis

Yearly energy consumption was strongly reduced with increasing RH set points up to 99% for all TI regimes. Increasing temperature bandwidths decreased energy
consumption. With set points in the range 90 and 99% RH the effect of RH on energy consumption was small compared with RH < 90% (Fig. 3).

Applying process-based humidity control compared with a humidity regime with fixed RH set points of about, 90% and lower reduced energy consumption (Table 3). Applying TI, energy saving with the process-based humidity regime compared with the same regime with a fixed humidity set point of 80% RH decreased with increasing temperature bandwidths. However, combining the process-based humidity regime with TI yields in increasing energy saving with increasing bandwidth compared with a blueprint regime (data not presented).

Yearly crop gross photosynthesis with process-based humidity control increased compared with a fixed RH set point of 80% as commonly used in practice between 1.8 and 3.3% depending on temperature control (Table 4).

Table 3
Percent energy saving for year-round cut chrysanthemum with different temperature regimes combined with the process-based humidity control compared with the same temperature regimes with fixed RH set points of 70, 80, 90 and 99%; with regular temperature control (Regular) and TI with 6 day averaging period and different temperature bandwidths of ±2, ±4 and ±6 °C (TI±2, TI±4, TI±6).

<table>
<thead>
<tr>
<th>RH set point (%)</th>
<th>Temperature control</th>
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<tr>
<td></td>
<td>Regular</td>
</tr>
<tr>
<td>70</td>
<td>31.6</td>
</tr>
<tr>
<td>80</td>
<td>18.2</td>
</tr>
<tr>
<td>90</td>
<td>1.9</td>
</tr>
<tr>
<td>99</td>
<td>−0.9</td>
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separate 12 week cultivations with TI (Table 5). In summer plantings (May and June), the new humidity regime had no or marginal consequences on TI. This was less pronounced with the blueprint temperature control.

The highest absolute savings on energy consumption were obtained in winter but in spring relative savings were highest, e.g. 27% for TI with planting in March. Applying the process-based humidity regime with regular temperature control resulted in yearly energy saving of 18% compared with a fixed RH set point of 80% and only a little difference to a set point of 90% RH (Table 3, Fig. 4). Combining the process-based humidity regime with a 6 day TI regime (with, e.g. temperature bandwidth of $9\pm 4^\circ C$) increased energy saving compared with regular temperature control with 80% RH set point up to 40% during one 12 week cultivation period in spring (Table 5).

Table 4
Crop gross photosynthesis for year-round cut chrysanthemum with different temperature regimes with different RH set points compared with the same temperature regimes with a fixed RH set point of 80%; with TI with $\pm 2$, $\pm 4$, $\pm 6^\circ C$ temperature bandwidth (TI$_{\pm 2}$, TI$_{\pm 4}$, TI$_{\pm 6}$) and normal temperature regime (Regular)

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<thead>
<tr>
<th>RH set point (%)</th>
<th>Temperature control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
</tr>
<tr>
<td>70</td>
<td>0.3</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>90</td>
<td>1.3</td>
</tr>
<tr>
<td>99</td>
<td>2.0</td>
</tr>
<tr>
<td>Flexible</td>
<td>1.8</td>
</tr>
</tbody>
</table>
4.2. General behaviour of the greenhouse climate

In winter, average RH with a year-round chrysanthemum crop was slightly higher in the process-based humidity control regime compared with a regime with a fixed set point of 80% RH for all investigated temperature controls (Fig. 5). In summer, weekly mean RH did not differ for any temperature control. Instantaneous RH in winter, nevertheless, fluctuated much more and was often very high (i.e. condensation) with the process-based humidity regime (Figs. 6 and 7). Ventilation was reduced and average CO₂ concentration was higher for the process-based humidity regime for normal temperature control and TI (Table 6).

Table 5
Simulations on cumulative energy consumption (MJ m⁻²) for a 12 week cut chrysanthemum cultivation with different planting dates for a regular temperature regime (Regular) and TI with 6 day averaging period and ±4 °C temperature bandwidth (TI ±4) with fixed (80%) and process-based humidity regime

<table>
<thead>
<tr>
<th>Planting date</th>
<th>Climate regime</th>
<th>TI ±4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular RH fixed (80%)</td>
<td>RH process-based</td>
</tr>
<tr>
<td>1 February</td>
<td>416</td>
<td>332</td>
</tr>
<tr>
<td>1 March</td>
<td>267</td>
<td>205</td>
</tr>
<tr>
<td>1 April</td>
<td>148</td>
<td>113</td>
</tr>
<tr>
<td>1 May</td>
<td>79</td>
<td>66</td>
</tr>
<tr>
<td>1 June</td>
<td>58</td>
<td>55</td>
</tr>
</tbody>
</table>

Fig. 5. Weekly mean RH for simulations of greenhouse climate for year-round cut chrysanthemum cultivation with normal temperature control with fixed RH set point of 80% (lower line) and process-based humidity regime (upper line). Hatched field is difference in weekly mean RH.
Fig. 6. Instantaneous RH values (i.e. 5 min averages) for day 40–41 after planting for normal temperature regime with fixed 80% RH set point (---) and process-based humidity control (-----) for four separate 12 week cultivations of cut chrysanthemum with different planting dates 1 January, (a), 1 March (b), 1 May (c) and 1 July (d).

Fig. 7. Instantaneous RH values (i.e. 5 min averages) for day 40–41 after planting for TI with 6 day averaging period and temperature bandwidths of ±6 °C with fixed 80% RH set point (---) and process-based humidity control (-----) for four separate 12 week cultivations of cut chrysanthemum with different planting dates 1 January, (a), 1 March (b), 1 May (c) and 1 July (d).
Table 6
Monthly average percent daytime (short-day) lee vent-opening (V) and average daytime greenhouse CO₂ concentration [CO₂] for regular temperature control and TI with 6 day averaging period and temperature bandwidths of ±4 °C with fixed RH set point of 80% and process-based humidity control for year-round cultivation.

| Month | Climate regime | Normal | | | | TI ±4 | | | | |
|-------|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|       | RH fixed (80%) | V (%)  | [CO₂] (ppm) | V (%)  | [CO₂] (ppm) | RH fixed (80%) | [CO₂] (ppm) | RH fixed (80%) | [CO₂] (ppm) | RH process-based | [CO₂] (ppm) |
| 1     | 4.3            | 524    | 0.2     | 799    | 2.6     | 530    | 0.1     | 753    | 5.8     | 551    |
| 2     | 7.1            | 485    | 2.8     | 740    | 5.7     | 471    | 0.5     | 743    | 11.1    | 434    |
| 3     | 19.3           | 483    | 15.0    | 680    | 11.1    | 470    | 5.9     | 773    | 31.3    | 431    |
| 4     | 29.2           | 442    | 24.6    | 571    | 31.3    | 431    | 26.7    | 590    | 40.4    | 397    |
| 5     | 42.4           | 421    | 39.3    | 465    | 40.4    | 397    | 37.6    | 467    | 50.4    | 379    |
| 6     | 51.8           | 416    | 49.4    | 434    | 70.4    | 379    | 69.8    | 382    | 65.1    | 379    |
| 7     | 56.0           | 418    | 53.6    | 434    | 65.1    | 379    | 64.9    | 381    | 71.9    | 383    |
| 8     | 60.7           | 423    | 59.7    | 434    | 71.9    | 383    | 71.5    | 386    | 53.1    | 404    |
| 9     | 40.3           | 435    | 34.3    | 497    | 53.1    | 404    | 52.0    | 436    | 21.6    | 435    |
| 10    | 22.8           | 463    | 16.3    | 602    | 21.6    | 435    | 17.3    | 621    | 11.1    | 434    |
| 11    | 8.8            | 489    | 2.5     | 725    | 9.5     | 471    | 5.1     | 742    | 5.8     | 551    |
| 12    | 5.5            | 557    | 0.2     | 849    | 5.8     | 551    | 0.2     | 852    | 4.3     | 524    |
5. Discussion

With the new humidity regime simulated energy consumption decreased strongly. Simulated energy consumption was in the same order of magnitude as in commercial practice in The Netherlands. Simulated yearly energy consumption for a normal temperature regime with a fixed RH set point of 80% was 1.34 GJ m\(^{-2}\) per year and reported values from practice were 1.41 and 1.55 GJ m\(^{-2}\) per year (Woerden and Bakker, 2000; Spaargaren, 2002). The small discrepancy supports the validity of the greenhouse simulation model for comparing energy consumption.

The new regime gave rise to a strong reduction in energy consumption compared with a regular humidity regime, in particular during winter. During this season, temperature control has little effect on ventilation because low outside global radiation and temperature do not heat up greenhouses above the temperature ventilation set point. Therefore, humidity control is basically the only cause for ventilation. When humidity levels are above the set point, opening of vents lead to extra energy consumption for maintaining temperature. Reduced ventilation was, therefore, the major cause of energy saving in winter.

Temperature and humidity controls interact in ventilation towards the summer. When outside global radiation and temperature increase, greenhouse temperature control gets stronger impact on the rate of ventilation and the role of humidity control diminishes. TI in summer contributes only little to yearly energy saving, because greenhouses heat up during daytime but do not cool down at night. A low night temperature, nevertheless, is indispensable to compensate for the high day temperatures. Because cut chrysanthemum is partly cultivated under blackout screens temperature will not drop much during the night. With TI, there is more night ventilation than in normal temperature control, because elevated day temperatures have to be compensated during the night. Therefore, process-based humidity control had an impact on energy saving during summer when temperature was controlled normally and not when it was controlled by TI.

The described humidity regime is a first approach to control greenhouse humidity according to their underlying processes concerning crop requirements. Parameter values were chosen from empirical results or arbitrarily in many cases (e.g. transpiration set points) and were not validated. Results rather indicate the value of such a regime for future climate control rather than being quantitatively correct. The system was not controlled optimally and before strong conclusions on the value of the new regime could be made, greenhouse experiments are necessary. First experimental results for complete cultivations with cut chrysanthemum in spring and autumn controlled by the process-based humidity regime combined with TI with different bandwidths (Körner and Challa, 2003) did not show any negative consequences on plant growth, development or quality.

There is little doubt that the approach of controlling greenhouse humidity according to the response of individual processes that are affected by humidity is promising in terms of energy saving.
Acknowledgements

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References


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