Design for an improved temperature integration concept in greenhouse cultivation

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Abstract

The ability of crops to tolerate temperature deviations from the average set point could play an important role in energy saving greenhouse climate regimes. This principle is used in the so called temperature integration procedure, which is based on empirical knowledge and uses fixed maximum and minimum temperatures. More dynamic flexible boundaries depending on the underlying crop processes would probably increase the potential for energy saving in greenhouses. Therefore, our aim was to improve the temperature integration concept by introducing dynamic temperature constraints. Processes with a fast temperature response (e.g. photosynthesis or stress) were decoupled from developmental processes with a slow response time. A modified temperature integration procedure was designed combining the usual long-term integration over several days and fixed boundaries for daily average temperature with short-term integration over 24 h with flexible temperature limits. Because the optimum temperature for canopy photosynthesis rises with increasing concentration of atmospheric CO₂, this aspect was included in ventilation control. Because plants react not only to extreme temperatures but also to their duration, a dose concept was applied to stress-related temperature constraints. The desired mean temperature for the subsequent 24 h was calculated once in 24 h. Within this 24 h cycle, temperature set points for heating and ventilation were optimised in relation to the fast crop processes. The temperature regime was tested by simulations. Greenhouse climate, energy consumption and dry matter increase were simulated for complete years and different parameter settings for tomato as model crop. With the modified regime compared with regular temperature integration, with the same ±2 °C long-term temperature bandwidth 4.5% (normal secure settings) or up to 9% (extreme settings)

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more energy could be saved (on a yearly basis). Crop gross photosynthesis could increase by approximately 2.5%.

1. Introduction

To achieve a certain target temperature, greenhouses in The Netherlands are usually heated with a central boiler and cooled by ventilation. Set points for heating and ventilation with a narrow bandwidth (i.e. 1–2 °C) are set according to a blueprint (BP) regime, based on the experience of the individual grower and the computer manufacturer (Tap et al., 1996). Due to daily weather variations, heating and ventilation may alternate several times a day, leading to extra fossil energy consumption. Reduction of the amount of fossil energy used per unit produce and associated reduction of CO₂ emission is recently one of the major issues in greenhouse cultivation in moderate temperate climates such as in The Netherlands.

Climate control is necessary for attaining high crop growth, yield and quality, the major targets for the growers. Extreme temperatures may induce stress and associated damage to the plasmatic structures or the photosynthetic apparatus of the plant (Kaniuga et al., 1978; Al-Khatib and Paulsen, 1999). Less extreme sub-optimal temperatures may delay plant development and affect other plant characteristics such as dry matter distribution.

Climate regimes based on temperature integration (Hurd and Graves, 1984) that allow temperature fluctuations while respecting proper plant development and crop growth have been developed. Using temperature integration a certain mean temperature is maintained within upper and lower limits over specified time intervals. Intervals such as night time (Langhans et al., 1981), complete 24 h cycles (Cockshull et al., 1981; Rijsdijk and Vogelevang, 2000) and periods of several days (e.g. De Koning, 1990) have been successfully applied for a large variety of greenhouse crops. The maximum integration interval and temperature bandwidth for high quality crops are still fairly unknown. The concept in fact is based on empiricism and lacks physiological background. Fixed temperature bandwidths and integration intervals are commonly used. In regular temperature integration regimes fast (minutes) and slow (days) plant processes are not a matter of concern. Taking these into account could probably increase energy saving while maintaining crop yield and quality. Processes with a slow response time (e.g. plant development) probably respond primarily to average temperatures over prolonged periods and processes with a quick response (e.g. photosynthesis) may allow more extreme temperature deviations without losses in quality and growth (Rietze and Wiebe, 1989; Sato et al., 2000).

A more flexible temperature regime based on temperature integration could also improve the performance of optimal greenhouse climate control, because there is...
more freedom to generate optimal temperature trajectories outside the normal range. We, therefore, designed a regime with a wider short-term temperature bandwidth while maintaining the restrictions of long-term temperature integration over several days. The aim of this study was to describe and explain such a new temperature regime and to investigate its potential for energy saving and productivity. Therefore, the regime was tested with a greenhouse climate and crop photosynthesis model. Simulations were performed with different parameter settings for tomato to investigate the effects on greenhouse climate, energy consumption and photosynthesis as an indicator of crop growth.

2. Outline of the regime

2.1. Basis

The target greenhouse day and night temperature in common practice is usually not fixed. Temperature set points are modified automatically, such that e.g. ventilation temperature increases with instantaneous radiation or total daily radiation according to grower’s experience, based on rules of thumb (Tap et al., 1996). Increasing the bandwidth between ventilation and heating set points while controlling mean rather than instantaneous temperature is a further development of this BP regime and called temperature integration. Temperature integration is based on the assumption that within the limits considered the crop responds linearly to temperature. Maximum, minimum and mean temperature and averaging period are the key parameters for temperature integration. Freedom for temperature fluctuations, i.e. the possibilities for temperature to freely fluctuate due to the environment without being controlled by heating or ventilation, increases with longer averaging period and increasing temperature bandwidth. With a relatively short averaging period of 24 h, a cool day has to be compensated directly by a warm night or vice versa. Temperature integration over longer periods of several days enables compensation of warm or cold spells during one of the following days and higher energy savings are possible (Sigrimis et al., 2000). Whatever length of averaging period is used, mean temperature has to be attained within certain margins while actual heating can be shifted to periods of lower costs (Lacroix and Kok, 1999). Theoretically, three extreme (and many in-between) situations are possible with this regime. During sunny days and cold nights greenhouses heat up during daytime and cool down at night. In the most favourable conditions, greenhouse temperature stays above the heating set point and no energy for heating will be needed. With cold days, heating can be shifted to night-time under energy screens, which saves large amounts of energy (Rijsdijk and Vogezezang, 2000). In that case, more energy can be saved with increasing temperature compensation possibilities. Cold days can then be compensated later by warmer periods and there is no need to compensate high day temperatures during the following night when the integration period is longer than 1 day (e.g. the day after, with an integration period of 2 days). No temperature
compensation during night is possible when mean daytime greenhouse temperature is the same as the desired 24 h mean temperature.

2.2. Scheme

The regular temperature integration regime has a fixed averaging period, which is usually between 4 and 8 days. In this approach the existence of fast and slow plant processes is not considered. However, taking this distinction into account, new possibilities for energy saving become available. The regular concept of temperature integration was, therefore, modified to a system of two nested temperature integration regimes with different averaging periods, short-term (ST) (dedicated to fast plant processes) and long-term (LT) (dedicated to slow plant processes). LT corresponds to the averaging period of several days in regular temperature integration; ST corresponds to a 24 h period (Fig. 1). For ST, a target short-term temperature range rather than a fixed target temperature is used as control criterion. Temperature is allowed to fluctuate within this range but the average temperature should comply with the requirements of the LT regime (Fig. 2).

Temperature course a is with regular temperature integration; in b the temperature

![Fig. 1. Modified temperature integration regime with short-term (ST)-nested into long-term temperature integration regime (LT) as a function of time, with LT (---) in hourly scale (24 h) and ST (- - -) in days. With target mean temperature ($T_{\text{targ}}$); maximum and minimum temperatures for long-term control ($T_{\text{max,LT}}$ and $T_{\text{min,LT}}$), and short-term control ($T_{\text{max,ST}}$ and $T_{\text{min,ST}}$).](image-url)
boundaries are relaxed to ST boundaries while mean temperature is maintained. The cases c and d have different mean temperatures but are both within the acceptable range. The ST limits are adjusted if 24 h mean temperature exceeds the LT temperature integration boundaries.

Extreme temperatures are avoided by setting two thresholds on either side of the acceptable range. One threshold represents the absolute limit for temperature, after passing the other threshold stress may occur depending on the temperature dose. In fact, the effects of temperature extremes increase with duration and level of extremes and hence depend on the dose (Larcher and Bodner, 1980). We assume an exponential response between the two threshold levels.

A further element of the improved climate regime under consideration is optimisation of temperature for crop gross photosynthesis. Temperature for maximum gross photosynthesis increases with CO₂ concentration, as illustrated with model simulations according to Körner et al. (2003) (Fig. 3). Therefore, there is a benefit in allowing greenhouse air temperature to rise with radiation more than required for LT control, to prevent ventilation and associated drop in CO₂ concentration and due to photorespiration (Berry and Björkman, 1980). Introduction of photosynthesis optimisation will lead to a high CO₂ concentration that can be maintained at little or no ventilation, or atmospheric CO₂ with ample ventilation.
3. Materials and methods

3.1. Technical implementation

The proposed regime was implemented in a simulation model of the greenhouse crop system developed in the technical software environment MATLAB® (version 6.0, MathWorks, Natick, MA, USA) using greenhouse tomato as model crop. This programme, including a crop photosynthesis module, functioned as the set point generator.

Greenhouse air temperature, relative humidity and CO₂ concentration inside the greenhouse and outside global radiation were input with a fixed time step of 5 min. The set point generator was coupled with a greenhouse climate and control model (CCM) (De Zwart, 1996). Set points for heating, ventilation and CO₂ concentration were calculated by the set point generator and sent as input to the CCM. The CCM returned simulated greenhouse climate (relative humidity, air temperature and CO₂ concentration), while using the received set points for control of heating and
ventilation. The inner greenhouse climate was controlled by a replica of commercially available climate controllers.

The CCM provided simulations for a 2 ha Venlo-type greenhouse with single glass cover with a diffuse short-wave radiation transmission of 78.5%. Transmission of direct sunlight was calculated as a function of azimuth and elevation of the sun (De Zwart, 1993). The CCM controlled greenhouse climate through heating and ventilation, and simulated energy consumption with a 2-min time step. Energy input to the greenhouse was calculated taking incoming solar short-wave radiation into account (no assimilation lamps were used) and required direct heat supply from the heating unit. Heat was provided by a natural gas fired hot water boiler (maximum of 94 °C). Natural gas consumption was simulated with a heat content of 35.17 MJ m⁻³ natural gas (Van de Braak, 1995). Energy losses were calculated from radiative, convective and latent heat fluxes through the greenhouse cover and conduction through the ground below the greenhouse. Energy loss from heating pipes was calculated by sensible heat flux through convection to the greenhouse air and by radiative heat exchange to greenhouse elements and the crop. Radiative heat exchange processes were governed by the Stefan–Boltzmann equation. An effective sky temperature ($T_{sky}$) as the temperature of a black hemisphere exchanging thermal radiation with the greenhouse cover was calculated according to De Zwart (1996). Latent heat loss by crop transpiration was calculated according to Stanghellini (1987) and natural ventilation was computed according to De Jong (1990). An energy saving screen was used that reduced short-wave transmission to the crop canopy by 70% when it was closed. Air exchange between the compartment beneath and above the screen was simulated by convective heat flux through openings in the fabric (De Zwart, 1996).

Validations of the CCM in four semi-commercial Venlo-type greenhouse compartments of 192 m² ground cover with a full-grown rose stand have been performed (De Zwart, 1996). Greenhouse climate on a short time scale (minutes) was well predicted and simulated and measured annual energy consumption differed only by 2%. In addition, simulations done with the CCM agreed well with reported gas consumption calculated with the regularly validated greenhouse climate model Pregas (Woerden and Bakker, 2000). Natural gas consumptions for commercial year-round tomato cultivation without screen were 2.15 and 2.16 GJ m⁻² per year for Pregas and CCM, respectively.

3.2. Reference climate regime

Two reference temperature regimes were used for comparison. The heating set points were 18 and 19 °C and ventilation set points were 19 and 20 °C for night and day, respectively. The first reference regime (BP) was according to commercial practice and included adaptation of temperature set points in relation to instantaneous radiation and daily radiation. Daytime ventilation set points increased linearly with outside global radiation (0.5 °C per 100 W m⁻² between 400 and 800 W m⁻²) and night-time ventilation and heating set points increased linearly with daily global radiation sum (0.25 °C per 1 MJ m⁻² per day between of 6 and 16 MJ
m$^{-2}$ per day). In the second reference temperature regime (BPfix) night- and daytime heating and ventilation temperature set points were fixed, as is uncommon in commercial practice.

### 3.3. Specification of the long-term temperature integration regime

The averaging period for temperature integration was 6 days. A post hoc procedure for temperature integration was used, i.e. deviations from mean target temperature were compensated afterwards rather than using an optimal forecasted temperature trajectory for determining temperature set points. Deviations of mean temperature of the preceding 5 days were compensated during the last 24-h of the averaging period. Temperatures before 5 days were no longer taken into account. Within the 24 h of day 6 of the integration interval there were several constraints, (a) constraints to attain the target average temperature over the full integration period, (b) constraints to avoid extreme temperatures and (c) constraints for optimisation of crop gross photosynthesis.

The target 24-h mean temperature ($T_{\text{targ},24}$) at day 6 ($d$) of the averaging period ($t_{\text{int}}$) was obtained from the difference between the sums of the 24-h means of desired temperatures ($T_{\text{des}}$) over $t_{\text{int}}$ and previous realised temperatures ($T_{\text{real}}$) over the preceding 5 days ($t_{\text{int}}-1$).

$$T_{\text{targ},24}(d) = \sum_{1}^{t_{\text{int}}} \bar{T}_{\text{des}} - \sum_{1}^{t_{\text{int}}-1} \bar{T}_{\text{real}}$$  

### 3.4. Specification of the short-term temperature regime

The ST averaging period was 24 h. First, the greenhouse temperature without control (i.e. neither ventilation nor heating through temperature set points) for ST was estimated at the start of each new averaging period (0:00 h) with a simple $K$-value model (Eq. (2)). In semi-commercial greenhouses this equation described greenhouse temperature well (De Zwart, IMAG, Wageningen, personal communication).

$$T_{\text{in}} = T_{\text{out}} + \frac{1}{3} \tau_{\text{dif}} \frac{I_{\text{out}}}{K}$$  

with inside greenhouse temperature ($T_{\text{in}}$ (°C)), outside temperature ($T_{\text{out}}$ (°C)), fraction of greenhouse transmission for diffuse short-wave radiation ($\tau_{\text{dif}}$), outside global radiation ($I_{\text{out}}$ (W m$^{-2}$)) and overall greenhouse heat transmission coefficient ($K$ (W m$^{-2}$ °C$^{-1}$)). $K$ was set to 4 and 8 W m$^{-2}$ °C$^{-1}$, respectively, with and without energy screen.

Eq. (2) was compared with simulations with the CCM with relative passive heating and ventilation temperature set points of 10 and 34 °C, respectively. Relative humidity set point was 85%. Hourly mean temperatures of the CCM were on
average underestimated by 2.5, 3.4, 1.3 and 0.7 °C in spring, summer, autumn and winter, respectively. This was sufficient for the purpose of planning. The equation was only used for a rough estimation of greenhouse temperature in the next 24 h without concern about temperature control, although the absolute ST temperature thresholds ($T_{\text{max,ST}}$, $T_{\text{min,ST}}$) were respected to avoid temperature extremes. Once the planning for the next 24 h had been made, the greenhouse environment during simulation was actively controlled by heating and ventilation. As Eq. (2) was only used for planning, the actual greenhouse mean temperature was continuously updated with realised temperature.

We used the lazy-man weather prediction (Tap et al., 1996), where weather at day $d$ was assumed to be the same at day $d - 1$. Twenty four h mean greenhouse temperature at day $d$ was updated every 5 min with the actual greenhouse temperatures. To protect the crop against excessive high or low temperatures due to radiation or too strong compensation, maximum and minimum heating (24, 10 °C) and ventilation temperatures (34, 14 °C) were set initially, and adapted during cultivation according to Eqs. (3) and (4) (Fig. 4).

$$dose_{\text{max}} = \frac{(T - T_{\text{max,rel}}) \exp(160(1/T_{\text{max,abs}} - 1/T))}{(T_{\text{max,abs}} - T_{\text{max,rel}})} \frac{t_{\text{dose, max}}}{t_{\text{sample}}}$$

Fig. 4. Principle of temperature dose without time factor. An example is given for relative maximum temperature ($T_{\text{max,rel}}$); relative minimum temperature ($T_{\text{min,rel}}$); absolute maximum temperature ($T_{\text{max,abs}}$) and absolute minimum temperature threshold ($T_{\text{min,abs}}$) which are 30, 14, 34 and 10 °C, respectively.
dose_{min} = \frac{(T_{\text{min,rel}} - T)\exp(-30(1/T_{\text{min,abs}} - 1/T))}{(T_{\text{min,rel}} - T_{\text{min,abs}})} t_{\text{dose}_{\text{min}}} t_{\text{sample}} \tag{4}

with upper and lower relative thresholds ($T_{\text{max,rel}}$ and $T_{\text{min,rel}}$ ($^\circ$C)), upper and lower absolute thresholds ($T_{\text{max,abs}}$ and $T_{\text{min,abs}}$ ($^\circ$C)), greenhouse air temperature ($T$ ($^\circ$C)), dose for maximum and minimum temperature boundaries (dose$_{\text{max}}$ and dose$_{\text{min}}$), sample time ($t_{\text{sample}}$ (min)) and maximum and minimum exposure at $T_{\text{max,abs}}$ or $T_{\text{min,abs}}$ ($t_{\text{dose}_{\text{max}}}$ or $t_{\text{dose}_{\text{min}}}$ (min)); $t_{\text{dose}_{\text{max}}}$ and $t_{\text{dose}_{\text{min}}}$ were set 30 min for standard conditions. Single values taken each $t_{\text{sample}}$ were integrated over time. If the integrated value exceeded 1, the corresponding relative threshold was held for the duration of a refresh time of 6 h and was then reset. This was due to regeneration of plant tissue at non-extreme temperatures.

Crop gross photosynthesis ($P_{gc}$) was calculated according to Goudriaan and Van Laar (1994) based on leaf photosynthesis and radiation distribution within the canopy. Leaf photosynthesis was described with the two parameter (maximum gross photosynthesis and photochemical efficiency), negative exponential light–response curve (Thornley, 1976). Biochemical based equations derived by Farquhar et al. (1980) were used as described by Körner et al. (2003).

The upper threshold for greenhouse CO$_2$ concentration was 1000 μmol mol$^{-1}$ and set when vents were closed. Temperature giving rise to maximum gross photosynthesis at 1000 μmol mol$^{-1}$ (under prevailing light conditions) was used as ventilation set point. CO$_2$ set point was 350 μmol mol$^{-1}$ when vents were open or when outside global radiation was below the threshold of 40 W m$^{-2}$.

3.5. Set points

Temperature in a commercial control system is controlled by set points for heating and ventilation. Heating set point ($T_{\text{heat}}$) was obtained according to Eq. (5) and ventilation set point ($T_{\text{vent}}$) according to Eq. (6). Default values were absolute extreme temperatures thresholds (i.e. $T_{\text{max,abs}}$ or $T_{\text{min,abs}}$).

\[
T_{\text{heat}} = \max(T_{\text{min,ST}}, T_{\text{min,dose}}) \tag{5}
\]

\[
T_{\text{vent}} = \min(T_{\text{max,ST}}, T_{\text{max,dose}}, T_{\text{max,phot}}) \tag{6}
\]

with minimum and maximum temperature according to the dose concept ($T_{\text{min,dose}}$ and $T_{\text{max,dose}}$, respectively); minimum and maximum temperature determined in the ST loop ($T_{\text{min,ST}}$ and $T_{\text{max,ST}}$, respectively); and temperature for maximum photosynthesis ($T_{\text{max,phot}}$).

3.6. Simulations

Greenhouse tomato cultivation was simulated for a crop grown as usual in practice in The Netherlands. However, a 365 days cultivation period with planting date 1 January ignoring the normal 2–3 weeks interruption for cleaning and replanting was used. A representative 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 yearly dynamics of greenhouse climate, energy consumption and crop growth. The reference year consisted of a typical Dutch climate data set with hourly values of air temperature, relative humidity, direct and diffuse global radiation, CO₂ concentration, wind speed, wind direction and soil temperature. An energy screen was used and controlled as in commercial practice. For dehumidification, the screen was opened to a maximum of 4%. Gas was burned for CO₂ supply with the heater. Excess heat was stored in a heat buffer of 120 m³. When the buffer was completely filled, CO₂ supply stopped. Target mean greenhouse temperature was 19 °C for all simulations. Different settings for the modified and the regular temperature integration regime (Table 1) were compared with each other and to the two reference climate regimes BP and BPfix. Relative humidity set points were 85 or 99% for separate simulations and controlled by ventilation.

The same back-regulation (Fig. 5, Eqs. (7) and (8)) was used for all simulations with temperature integration. Minimum and maximum average target temperature were set according to the difference between realised and target mean temperature and vice versa. The offset-factors \( f_h \) and \( f_v \) (heating and ventilation) were proportional to the deviation from the mean target temperature (\( \Delta \bar{T} \)) and controlled its realisation.

\[
f_h = x + \left( xt_{\text{int}} + (xt_{\text{int}})\exp\frac{\Delta \bar{T}}{r_h} \right)
\]

\[
f_v = y\left( yt_{\text{int}} - (yt_{\text{int}})\exp\frac{-\Delta \bar{T}}{r_v} \right)
\]

with length of averaging period (\( t_{\text{int}} \)), maximum allowed positive and negative deviation from the target temperature (i.e. half temperature bandwidth, \( x \) and \( y \), respectively) and factors for the strength of back regulation for heating and ventilation (\( r_h \) and \( r_v \), respectively). The stronger the back regulation (i.e. the lower \( r_h \) or \( r_v \)), the more conservative the system is. To achieve the targeted mean

Table 1
Simulated regular and modified temperature integration regimes with \( P_{gc} \) optimal (+) and non-optimal (0)

<table>
<thead>
<tr>
<th>Temperature integration regime (bandwidth)</th>
<th>Regime settings</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( t_{\text{dose}} ) (min)</td>
<td>( P_{gc} )-optimisation</td>
</tr>
<tr>
<td>Modified ((\pm 2, \pm 4, \pm 6 \degree C))</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>+</td>
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<tr>
<td></td>
<td>30</td>
<td>+</td>
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<td></td>
<td>30</td>
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<td></td>
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<td>180</td>
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<td>360</td>
<td>+</td>
</tr>
<tr>
<td>Regular ((\pm 2, \pm 4, \pm 6 \degree C))</td>
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<td>0</td>
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<tr>
<td></td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>
4. Results

4.1. General regime behaviour and energy saving

Mean temperature for the reference regime was lower when the temperature set points were independent of radiation (Table 2). Since these influences accounted for an increase in energy consumption of 0.8% (data not presented), energy consumption of BPfix was used for comparisons to the different temperature integration regimes. The yearly mean temperatures varied with about 1 °C between temperature integration and BP regimes. The BP regimes had higher temperatures in summer and this accounted for the higher yearly mean temperatures. Monthly mean temperatures differed only slightly in winter, spring and autumn. During these seasons energy consumption in greenhouses is highest. Therefore, energy saving of...
Table 2
Annual mean temperature and mean temperature per month for simulated climate regimes

<table>
<thead>
<tr>
<th>Regime</th>
<th>Year</th>
<th>Month</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
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<th>September</th>
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<tr>
<td>Mean temperature (°C)</td>
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<td>18.7</td>
<td>19.2</td>
<td>20.6</td>
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<td>22.8</td>
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<td>19.6</td>
<td>18.7</td>
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the temperature integration regimes compared with BP fix (Fig. 6) was not due to a lower mean temperature.

In the modified regime more energy was saved than with regular temperature integration (Fig. 6). Energy saving increased with temperature bandwidth in all cases evaluated. This increase, however, was less than proportional to temperature bandwidth. Yearly greenhouse energy saving increased by up to 23% compared with the BP regime (temperature bandwidth of ±6 °C). Compared with regular temperature integration energy saving increased relatively with 14% (3% absolute) (Fig. 6).

The set point for relative humidity highly influenced energy saving. Without humidity control (i.e. set-point relative humidity of 99%), energy saving increased for all investigated cases compared with the control with a set point of 85% (Fig. 6). This increase was fairly insensitive to temperature bandwidth.

Energy consumption was mainly reduced between early spring and late autumn (Fig. 7). During the first 2 months of cultivation (i.e. January and February), energy consumption for both regular and modified temperature integration regime even

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**Fig. 6.** Simulated yearly energy saving of regular temperature integration with 85 and 99% relative humidity set point (○, △, respectively), and modified temperature integration ($t_{dose_{max}}$ and $t_{dose_{min}} = 30$ min) with 85 and 99% relative humidity set point (●, ▲, respectively) compared with BP fix with 85 and 99% relative humidity set point ($a, b$).
exceeded the BP regime very slightly. The implemented control for temperature integration was too rigid since no optimal temperature trajectory was calculated for the future, and back-regulation (Eqs. (7) and (8)) was too strong during winter months (Fig. 8). In this period temperature integration pays when shifting heating to night under energy screens (Bailey and Seginer, 1989). This was not implemented in

Fig. 7. Simulated cumulative energy consumption (GJ m$^{-2}$) of a BP temperature regime (—, upper bold line), regular temperature integration (- - -) and modified temperature integration (—) with temperature bandwidths of ±2 °C (a), ±4 °C (b) and ±6 °C (c). A 6 day averaging period for tomato crop cultivation in The Netherlands according to a reference climate year was used (RH set point 85%).

Fig. 8. Simulated heating set point (bold line) and greenhouse temperature (thin line) during 21 typical autumn days for the modified temperature integration regime with standard settings and LT temperature bandwidth of ±2 °C.
the control and heating set point alternated between its highest and lowest limits (i.e. 24 and 10 °C). The difference in energy saving between the two energy saving regimes was most extreme at the lower temperature bandwidth. The larger the temperature bandwidth, the more similar were the yearly energy consumption patterns.

4.2. Crop gross photosynthesis module

In the modified climate regime, crop gross photosynthesis was higher than with the reference regime and regular temperature integration (Table 3). \( P_{gc} \) with the modified regime increased with temperature bandwidth from ±2 to ±4 °C and stabilised after that; regular temperature integration had its highest \( P_{gc} \) at temperature bandwidth of ±2 °C and continuously decreased thereafter. The control algorithm was probably the reason for that. As mentioned above, temperature integration control was not implemented optimally. With increasing freedom for temperature compensation, periods of extreme high temperatures were either compensated by short periods of extreme low temperatures or by long periods of low temperatures. Photosynthesis increase at high temperature periods was later overcompensated by very low or long lasting low photosynthesis levels (data not presented). Comparing simulations with and without the optimising photosynthesis module proved that energy consumption and crop gross photosynthesis slightly increased when applying the maximisation procedure (Table 3).

4.3. Temperature–dose response module

Increasing the duration of absolute maximum and minimum temperatures (\( T_{abs} \)) increased energy saving and \( P_{gc} \) (Fig. 9a). The modified regime with ±2 °C temperature bandwidth increased energy saving by 4.5% (\( T_{abs} = 30 \) min) or 9% (\( T_{abs} = 360 \) min) compared with regular temperature integration. The percentage energy saving was higher with larger maximum temperature bandwidths over the complete range (Fig. 9b). The increase in energy saving decreased with increasing

<table>
<thead>
<tr>
<th>Temperature bandwidth (°C)</th>
<th>(A) Increase in comparison to BP ( (BP_{fix}) ) (%)</th>
<th>(B) Increase in comparison to MTI <em>nonopt( P</em>{gc} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RTI</td>
<td>MTI</td>
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<tr>
<td>±2</td>
<td>2.1</td>
<td>3.5</td>
</tr>
<tr>
<td>±4</td>
<td>2.0</td>
<td>3.9</td>
</tr>
<tr>
<td>±6</td>
<td>1.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 3

Crop gross photosynthesis (\( P_{gc} \)) increase with regular and modified temperature integration (RTI, MTI) in comparison to the fixed BP regime (BPfix) (A). Difference \( P_{gc} \) and energy consumption (\( E_{cons} \)) influenced by non-maximised \( P_{gc} \) in MTI (MTI _nonopt\( P_{gc} \) ) (B)
maximum duration and decreased stronger with larger temperature bandwidths. Percentage difference in $P_{gc}$ between the different maximum temperature bandwidths did not change significantly with permissible duration for the absolute temperature extreme.

5. Discussion

A conceptual design for a more advanced temperature integration control was shown. Simulations indicated that energy consumption could be reduced further with the new regime. Energy consumption, nevertheless, was evaluated with simulations. As mentioned earlier, the greenhouse CCM agreed closely with measured gas consumption (De Zwart, 1996). Less than 0.5% deviation from a commercial greenhouse climate model (Woerden and Bakker, 2000) was found, too. This supports the validity of the greenhouse simulation model for comparing simulated energy consumption.
The most crucial part in temperature integration is achieving the desired mean temperature without losses in crop development, quality and/or growth. Yearly mean temperatures of both evaluated temperature integration regimes, nevertheless, was lower than with the reference temperature regimes. This was due to summer situations when temperature integration was able to compensate warm days by cooler nights, whereas in the reference regimes the temperature would not drop below 18 °C. An overall more constant yearly week-average temperature course for temperature integration regimes was the result of that, too. This could probably result in better tomato fruit yield since tomato cultivation is optimal around a mean temperature between 18 and 19 °C. Higher temperature enhances early fruit growth at the expense of vegetative growth (De Koning, 1989).

The proposed modified temperature integration regime enabled an additional increase in absolute energy saving of up to 9% compared with the regular regime. This maximum energy saving was only possible with the most extreme setting for temperature-dosage (i.e. 360 min). These settings, in fact, should give rise to crops with high quality and yield. Rietze and Wiebe (1989), for example, reported that cucumber plants could repeatedly bridge a period of 360 min at 8 °C during a period of 24 h if the temperature rises to 20 °C after that. In the modified regime the temperature increased only to 14 °C after a cool period. The findings of Rietze and Wiebe (1989), however, indicate that the applied 30 min at 10 °C for the standard settings in the proposed modified temperature integration regime was safe and that the most extreme dose of 360 min at 10 °C may be feasible.

The combination of the lowest long-term temperature bandwidth (±2 °C) with the longest permissible exposure to the absolute temperature threshold, yielded the highest relative increase in energy saving compared with regular temperature integration. This was due to the increase in freedom for instantaneous temperature fluctuation, which was most beneficial at safe long-term settings. The implemented control algorithm for the modified regime gives already most of its freedom for temperature fluctuation at low long-term bandwidths. This is due to the strong effect of the nested-time regime. Regular temperature integration with higher temperature bandwidths of ±4 and ±6 °C buffers many short-term fluctuations already. With smaller bandwidths, however, instantaneous temperature is almost constantly controlled and this control decreased with the modified regime. Regular temperature integration with small bandwidth was very close to the reference regime, and therefore, energy saving was low.

Energy consumption increased when applying the photosynthesis maximisation procedure. Photosynthesis on the other hand increased only slightly. Compared with the reference regime and regular temperature integration, nevertheless, photosynthesis with modified temperature integration increased much more. This was most probably due to less window opening and longer time at high CO₂ dosage (data not shown). To increase the positive effect of photosynthesis maximisation the procedure could probably be improved, because the control was too rigid.

The proposed regime could probably be improved with better parameter estimation, e.g. a deeper insight into plant physiology could improve the exponential model for temperature–dose response. Also the crop photosynthesis model was not
properly validated for extreme temperature conditions. However, a theoretical photosynthesis model evaluation study has been performed (Körner et al., 2003) and the one applied here was promising. In addition, a better greenhouse climate model for calculating subsequent 24 h greenhouse temperature could probably improve the climate control possibilities. The application of simple models, however, was sufficient for the aim of the present research to show and evaluate the new design of a temperature integration regime.

A high freedom in temperature set point determination has been achieved and this makes the regime valuable for optimal climate control. However, before implementing this regime as a module into an optimal climate control programme, it should further be improved by longer greenhouse climate predictions than 24 h (i.e. several days) and by calculating an optimal temperature trajectory for this period. The longer the period is for which conditions are predicted and analysed the greater are the opportunities for optimal control (Lacroix and Kok, 1999).

Highest energy saving was achieved when no humidity control was used. An improvement of humidity control as, e.g. based on the underlying processes rather than an overall low relative humidity set point could, therefore, most probably increase energy saving and possibilities for optimal climate control. Until now energy saving strategies have mainly been focussed on temperature and more advanced humidity control was mainly developed in relation to disease control (Jewett and Jarvis, 2001). For an overall approach, one should take both advanced temperature and advanced humidity control into account.

6. Conclusions

The presented modified temperature integration regime is a promising starting point for further development. The distinction between short- and long-term processes in temperature integration lead to an increase in energy saving compared with a regular temperature integration regime. The modified regime increased crop photosynthesis slightly. A more advanced CO₂ control could probably improve this. With more knowledge about the hard limits in time and quantity for short temperature drops and increases, with this system energy saving and options for optimal climate control could probably increase. Humidity control, furthermore, is still limiting energy saving possibilities with temperature integration. A more advanced flexible humidity control concept based on the underlying processes rather than using fixed values could probably help to further decrease energy consumption and give more freedom for optimal climate control.

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References


