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A Daylight Climate Chamber for Testing Greenhouse Climate Control Strategies and Calculating Canopy Carbon Dioxide Exchange

Lise T. Jensen¹, Eva Rosenqvist², and Jesper M. Aaslyng¹

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SUMMARY. A daylight climate chamber was designed with the aim of testing new greenhouse climate control strategies on a small scale. Precise control and measurement of the chamber climate and long-term measurement of canopy carbon dioxide (CO₂) exchange was possible. The software was capable of simulating a climate computer used in a full-scale greenhouse. The parameters controlled were air temperature, CO₂ concentration, irradiance, air flow, and irrigation. The chamber was equipped with a range of sensors measuring the climate in the air of the chamber and in the plant canopy. A chamber performance experiment with chrysanthemum (*Chrysanthemum grandiflorum* 'Coral Charm') plants grown in perlite was carried out over the course of 3 weeks. Five air temperature treatments at a day length of 13 hours were carried out, all with the same 24-hour mean temperature of 20 °C, but different day temperatures (18.0 to 25.1 °C) and night temperatures (14.0 to 22.4 °C). Rate of canopy CO₂ exchange in the chambers was calculated. In the range of day temperatures used, rates of canopy photosynthesis were almost equal. The results showed that leaf area and plant dry weight after 3 weeks were not significantly different among temperature treatments, which is promising for further investigations of how climate control can be used to decrease energy consumption in greenhouse production.

Greenhouse production is influenced by worldwide competition and increasing concern about the environment. There is a need for improved product quality, reduced production costs, and environmentally friendly production. In the northern hemisphere, research into greenhouse

production focuses on reducing energy consumption (e.g., Aaslyng et al., 2003; Hansen et al., 1996; Körner, 2003) and has resulted in proposals

for more dynamic temperature control strategies. The concept described by Aaslyng et al. (2003) is one of these; in this concept greenhouse climate was optimized to increase photosynthesis and plant quality and to decrease the load on the environment. Any new kind of climate control strategy for implementation in greenhouse production must be tested to find out how plant growth and development will respond, and how plant CO₂ exchange is affected if the climate control strategy is based on models of climate response on photosynthesis. A rapid and precise technique by relatively inexpensive means is testing on a small scale before testing in a full-scale experimental greenhouse and in commercial greenhouse production systems.

Although the climate response of CO₂ exchange is well understood at leaf level (von Caemmerer, 2000), we fall short of knowledge when it comes to evaluating the effects of climate patterns on canopy CO₂ exchange, since differences in plant architecture, internal shading in the canopy, and the contribution of other plant parts to the total CO₂ balance are not taken into account. Certain aspects of the use of a canopy model [e.g., a uniform, closed canopy and exponential profile of light in the canopy (e.g., Thornley, 2002)] are not true of the actual production cycle of pot plants. Production starts with rooted cuttings, and when the plants grow and the canopy closes, the distance between the pots is increased to prevent the plants from stretching. The canopy is therefore only temporarily closed and uniform. Small climate chamber systems containing a canopy are useful for testing climate effects on plant canopies on a small scale. However, an important difference in measuring CO₂ exchange at leaf and canopy level is the time factor. Most leaf cuvettes are relatively small, and the response time of entire CO₂ exchange systems optimized for a short response time is reduced to seconds (Pearcy, 1989). Depending on their

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
0.0283	ft ³	m ³	35.3147
2.5400	inch(es)	cm	0.3937
25.4000	inch(es)	mm	0.0394
28.3495	oz	g	0.0353
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

¹Crop Science, Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Højbakkegård Allé 21, DK-2630 Taastrup, Denmark.

²Department of Horticulture, Danish Institute of Agricultural Sciences, Kirstinebjergvej 10, DK-5862 Aarslev, Denmark.

volume, canopy chambers will create a time-lag in the measurements, and consequently, rapid changes in CO_2 exchange will go undetected. However, a chamber that contains a small canopy, and in which the climate can be closely controlled, is excellent for evaluating the effect of climate control strategies on the total daily CO_2 balance. In addition, when combined with leaf CO_2 exchange measurements, canopy chambers are powerful tools in scaling CO_2 exchange from leaves to canopies.

To meet the requirements for a complete small test greenhouse used for greenhouse climate control research, a climate chamber has to have the following features: 1) its dimensions must be commensurate with use of a small plant canopy; 2) it must provide precise measurement of the climate in the chamber and in the plant canopy; 3) it must be controllable to the desired climate; 4) the climate control principles of the software used for chamber climate control must correspond to principles used in a full-scale greenhouse; and 5) it must be capable of measuring long-term CO_2 exchange. Over the years, several climate chamber systems have been designed, all with different aims. In general, they are different in size, they have different ways of measuring and controlling the climate and CO_2 exchange, and they are different in terms of exposure to natural light. Climate chamber systems have been described by, among others, Andriolo et al. (1996), Dutton et al. (1988), Hand (1973), Mortensen (1982), and van Iersel and Bugbee (2000). All of these chambers, and many others described in the literature, meet many of the requirements for being a small test greenhouse, but none of them meet all requirements at the same time. Chambers are typically designed for plant response measurement, and not with a view to implementing a greenhouse climate control strategy in a full-scale greenhouse. Many chambers do not therefore have climate control software that can be used in both small-scale and large-scale greenhouses. The climate chamber system described in this paper is located in a greenhouse and is of a size that allows use of a small plant canopy. It has been designed to ensure precise control and measurement of the chamber climate and long-term measurement of the canopy CO_2 exchange, and is provided with software capable of

simulating a climate computer used in a full-scale greenhouse. It is therefore an indispensable tool in greenhouse climate control research.

The objective of this paper is to describe the canopy climate chamber: its design, how the chamber climate is controlled and measured, and how the canopy CO_2 exchange is calculated. Technical tests are described and the results from a chamber performance experiment with different temperature treatments in chrysanthemum are presented.

Materials and methods

SYSTEM DESIGN, CLIMATE CONTROL, AND SENSORS. The climate chamber described was an improved version of the chamber presented by Hansen and Hoegh-Schmidt (1996). The present design differed from the previous chamber in 1) having improved control and measurement of CO_2 , and thereby capable of calculating the CO_2 balance of the canopy inside the chamber;

2) having the same climate control software as in a full-scale greenhouse, which made it possible to directly scale up from test unit to full-scale units; and 3) being able to project several levels of supplementary light.

Each of the five climate chambers (Fig. 1) was rectangular, measuring 110×90 cm in ground area and 130 cm in height, giving a volume of 1.3 m^3 . The bench on which the plants were grown was about 0.5 m^2 in size. The chamber walls were of 6-mm clear polycarbonate (Lexan Margard; General Electric Plastics, Pittsfield, Mass.) and a horizontal air flow was ensured by clear, perforated polycarbonate plates (gap area 7%) on two opposite sides of the chamber, 10 cm from the chamber walls. The chamber could be accessed by a door in one side. The five climate chambers were placed in line in a standard greenhouse at the Royal Veterinary and Agricultural University in Taastrup, Denmark (lat. $55^\circ 40' \text{N}$, long. $12^\circ 18' \text{E}$).

Fig. 1. Design of the climate chamber constructed of clear polycarbonate plates (thick solid lines). Air was preconditioned [temperature and carbon dioxide (CO_2) concentration] in the air space below the plant bench and circulated through perforated polycarbonate plates (thick broken lines) on opposite sides of the chamber, thus ensuring an even, horizontal air flow at $0.3 \text{ m}\cdot\text{s}^{-1}$. Sensors were mounted above and in the plant canopy to measure the climate. Air from each chamber was pumped to an infrared gas analyser (IRGA) for CO_2 measurements, via valve switches creating a measuring cycle ($1 \text{ m}\cdot\text{s}^{-1} = 3.2808 \text{ ft/s}$).

The climate chambers were designed to ensure precise control of the climate in each chamber individually. The controlled climate parameters were air temperature, CO₂ concentration, air flow, irrigation, and, within certain limits, irradiance.

Air temperature was controlled by two separate systems for heating and cooling. The heating system consisted of a heating element (1250 W; Svend A. Nielsen A/S, Graested, Denmark), while the cooling system was based on continuously supplied chilled water running through a heat exchanger in each chamber. The cooling effect was adjusted by the speed of a fan regulating the air flow through the heat exchanger. The obtained temperature was a result of two simultaneous PI-regulations (Proportional–Integral) of the heating and cooling system.

The CO₂ concentration was controlled by the injection of pure CO₂ or renewal of chamber air with CO₂-free air. A mass flow controller (5850TR; Brooks Instrument, Hatfield, Pa.) and a magnetic valve (Z030C; Sirai, Bussero, Italy) controlled the injection of CO₂. An air pump (LP-60A; Yasunaga, Ueno City, Japan) with flow indicator (1355 Sho-Rate; Brooks Instrument) controlled by a magnetic valve (Z110A; Sirai) renewed the chamber air with CO₂-free air from outside pumped through a CO₂ absorber of soda lime. All tubes involved in CO₂ control were made of polyethylene.

The natural daylight of each chamber was supplemented by two high-pressure sodium lamps (SON-T Green Power; Philips, Eindhoven, The Netherlands) with a phase–phase system (H.G.W.-Electric ApS, Broby, Denmark). Each lamp could be used on two levels; it was thus possible to use supplementary light of five intensities: 0, 300, 600, 900, and 1200 W; 600 W corresponded to a photosynthetic photon flux density (*PPFD*) of about 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Horizontal air flow in the chamber was controlled by a fan ensuring air movement of up to 0.3 $\text{m}\cdot\text{s}^{-1}$.

Plants were fertigated by a timer-controlled ebb-flood system using a common storage tank for all five chambers.

Each chamber was equipped with a range of sensors. Air temperature was measured above the plant canopy with a thermistor (micro-BetaCHIP 10K3MCD1; BetaTHERM, Shrews-

bury, Mass.) positioned in a ventilated box. The same type of thermistor measured root temperature. Leaf temperature was measured with thermocouples (Sensycon type Cu/Con; ABB/Hartmann and Braun, Zurich, Switzerland). Global radiation was registered above the plant canopy by pyranometers (CM3; Kipp and Zonen, Delft, The Netherlands), whereas *PPFD* was measured with a quantum sensor (LI-190SA; LI-COR, Lincoln, Nebr.) and a photodiode [G1126-02; Hamamatsu Photonics, Hamamatsu City, Japan (described by Aaslyng et al., 1999)]. Chamber humidity above the plants was measured using a hygrometer (HygroClip S; Rotronic, Bassersdorf, Switzerland). Concentration of CO₂ above the plant canopy was measured by withdrawing an air sample to an infrared gas analyzer (IRGA) (CIRAS-SC CO₂/H₂O Analyser; PP Systems, Hertfordshire, U.K.). The measured air was recycled back to the chamber.

APPLYING CLIMATE CONTROL STRATEGIES IN THE CLIMATE CHAMBER AND GREENHOUSE. Input from the climate chamber sensors was measured with a data logger (CR10X; Campbell Scientific, North Logan, Utah) and

afterward data were transferred to the climate software IntelliGrow (Aaslyng et al., 2003), especially developed for controlling the climate inside the chamber. It was possible with this software to simulate a climate computer normally used in a full-scale greenhouse. The data exchange software for the climate chambers as well as the climate computer for a greenhouse could be used together with climate control software (IntelliGrow) by creating set points. The correlation between the climate chamber and the greenhouse in relation to applying climate control strategies is shown in Fig. 2.

CALCULATION OF NET CANOPY CO₂ EXCHANGE. The rate of net canopy CO₂ exchange, *A* ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), was calculated from the CO₂ balance of measured flow rates of CO₂ in and out of the chamber and nondestructive leaf area measurements. Similar equations of CO₂ balances of canopies in climate chamber systems have been used by, among others, Dutton et al. (1988), Ehler and Hansen (1998), and Hand et al. (1992), with some of the variables similar to equations used by Field et al. (1989), Long and Hällgren (1993), and Long et al. (1996) for closed and compensating gas exchange systems.

Fig. 2. Relationship between the daylight climate chamber and a full-scale greenhouse in the application of climate control strategies. Measurements from climate sensors in the chamber or in the greenhouse were sent via a data logger to the climate software IntelliGrow (Aaslyng et al., 2003). This software transferred calculated set points to software specially developed for the climate chambers or via interface to the greenhouse climate computer, respectively. Chamber climate or greenhouse climate was controlled from the chamber control program or the greenhouse climate computer (1 m³ = 35.3147 ft³).

CO₂ exchange equations for canopies in chamber systems could be based on ground area (Angell and Svejcar, 1999; Hand et al., 1992), number of plants (Andriolo et al., 1996) or, as in this paper, leaf area. To avoid disturbing the measurements of CO₂ exchange, leaf area was determined nondestructively by length and width measurements of leaf lamina. This method has been used in a range of plants [e.g., pepper (*Capsicum annuum*) (Ray and Singh, 1989) and cucumber (*Cucumis sativus*) (Robbins and Pharr, 1987)].

In the present experiment, the overall equation for the net canopy CO₂ exchange was:

$$A = \frac{CO_{2\text{ inj}} + \Delta CO_{2\text{ chamber}} - CO_{2\text{ leak}} - CO_{2\text{ out}}}{s} \quad [1]$$

where CO_{2 inj} was the amount of CO₂ injected to the climate chamber, ΔCO_{2 chamber} the change in CO₂ concentration of the chamber between two measurements, CO_{2 leak} the leakage of CO₂ from the chamber, CO_{2 out} the withdrawal of chamber air and renewal with CO₂-free air, and s leaf area of all plants in the chamber. Leaf area was described as an exponential increasing equation and determined once or twice per week on one-third of the plants, representative of all plants in a chamber. Respiration from microbial breakdown of organic matter derived from the rooting media was considered insignificant, as the growing medium was perlite. Rate of canopy CO₂ exchange was calculated on an hourly basis and treatment effects were analyzed following the General Linear Models procedure (PROC GLM) of SAS (SAS Institute, Cary, N.C.) (i.e., an F-test at the 5% probability level). Multiple comparisons between treatments were made using Tukey's honestly significantly different (HSD) test.

RESPONSE TIME OF THE CO₂ MEASURING SYSTEM. The time response of the CO₂ measuring system was tested by increasing the CO₂ concentration to 600 or 1200 μmol·mol⁻¹ by injection of pure CO₂ and placing a soda lime CO₂ absorber at the air outlet from the chamber to the IRGA. The response time of the IRGA and the tubes was determined as the time it took before the CO₂ concentration reached zero. This was the shortest possible measuring cycle for the IRGA when switching from one chamber to the next.

LEAKAGE OF CO₂ FROM THE

CLIMATE CHAMBERS. Leakage of CO₂ from the chambers to the surrounding greenhouse was measured with-out plants and without renewing the chamber air. The CO₂ concentration was increased by injecting pure CO₂ to about 1500 μmol·mol⁻¹ and the rate of decrease in CO₂ concentration to ambient concentration was followed. This was repeated three times in each chamber. Since the set point of the CO₂ concentration in the chamber performance experiment was 600 μmol·mol⁻¹, the parameter CO_{2 meas, leak} was estimated based on this concentration.

METHOD FOR DETERMINATION OF NONDESTRUCTIVE LEAF AREA. Nondestructive leaf area determination by leaf width and leaf length measurements necessitated determination of the relationship between leaf width, length, and area. This was established on 600 chrysanthemum leaves weeks before the start of the chamber performance experiment. Leaf width from the outermost right point to the outermost left point of leaf lamina, and leaf length from the highest point to the lowest point of leaf lamina were measured; the leaf was cut and actual leaf area was measured with a leaf area meter (3100 Area Meter; LI-COR).

CHAMBER PERFORMANCE EXPERIMENT WITH PLANTS. In the autumn of 2002, a chamber performance experiment, replicated twice with chrysanthemum, was carried out. Cuttings were rooted under white plastic in perlite in 10-cm-diameter plastic pots for about 20 d before they were selected for uniformity and transferred to the five climate chambers, each chamber containing 39 plants (corresponding to about 80 plants/m²). Five different treatments with the same 24-h mean air temperature of 20 °C and day and night temperatures ranging from 18.0 to 25.1 °C and 14.0 to 22.4 °C, respectively, were applied for 3 weeks (Table 1). Each treatment was carried out only once in a given chamber in the two replications. Set point of the CO₂ concentration was 600 μmol·mol⁻¹. Supplementary light was given continuously over a 13-h photoperiod using two high-pressure sodium lamps with a total effect of 600 W and a 60-W incandescent lamp placed above each chamber. The intensity of the supplementary light corresponded to a PPFD of about 200 μmol·m⁻²·s⁻¹. When natural day length was longer than 13 h, the climate chambers were

covered with black cloth to control the length of the photoperiod. Horizontal air flow was set to 0.3 m·s⁻¹. The plants were fertigated automatically once or twice a day at a given time interval using a standard nutrient solution with set points of pH 5.5 and electric conductivity 2 mS·cm⁻¹. The pot surfaces were covered with black plastic to reduce growth of algae. At the end of the chamber performance experiment, plant height, leaf area, and plant dry weight were measured on one-third of the plants representative of all plants in a chamber. The results were analyzed following the General Linear Models procedure (PROC GLM; SAS Institute) (i.e., an F-test at the 5% probability level). Multiple comparisons between treatments were made using Tukey's HSD test.

Results

RESPONSE TIME OF THE CO₂ MEASURING SYSTEM. In the time response test of the CO₂ measuring system, the CO₂ concentration began to decrease 30 s after the CO₂ absorber had been placed at the air outlet of the chamber (Fig. 3A). By 60 s, the CO₂ concentration had stabilized around 0 μmol·mol⁻¹. With a measuring time for each of the five chambers of 60 s and a sixth measurement of CO₂-free air from a separate soda lime tube, the total measuring cycle of the IRGA was 6 min.

LEAKAGE OF CO₂ FROM THE CLIMATE CHAMBERS. Leakage of CO₂ from the chambers to the surrounding greenhouse differed among the five climate chambers. An example of the rate of decrease in CO₂ concentration from 1500 μmol·mol⁻¹ to the ambient level is shown in Fig. 3B. At the set point of the CO₂ concentration in the chamber performance experiment at 600 μmol·mol⁻¹, CO₂ leakage

Table 1. The five air temperature treatments A–E at a day length of 13 h in the chamber performance experiments with chrysanthemum.

Treatment	Day temp	Night temp	24-h mean temp
	----- (°C)* -----		
A	25.1	14.0	20.0
B	23.4	16.0	20.0
C	21.7	18.0	20.0
D	20.0	20.0	20.0
E	18.0	22.4	20.0

* $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Fig. 3. Results of the technical test in the climate chambers. (A) Test of the response time of the carbon dioxide (CO₂) measuring system in climate chambers 2 (closed circles) and 3 (open circles) after a soda lime CO₂ absorber had been placed at the air outlet from the chamber to the infrared gas analyzer (IRGA) (time 0). (B) Example of the decrease in CO₂ concentration in a climate chamber due to leaking. Measurements were performed without plants and without renewing the chamber air. The two bumps during measurement were due to increased CO₂ concentration in the night in the surrounding greenhouse.

Fig. 4. Correlation between the product of leaf width and length and the leaf area measured by a leaf area meter. The solid line indicates the fitted linearly correlation given by Eq. [2]: leaf area = 0.62 (width × length) – 0.55. $R^2 = 0.99$. Leaf area could be determined nondestructively with this equation by measuring leaf width and length during chamber experiments (1 cm = 0.3937 inch; 1 cm² = 0.1550 inch²).

Fig. 5. Minute values of air temperature (A–B), leaf temperature measured by thermocouples inserted in leaves (C–D), carbon dioxide (CO₂) concentration (E–F), and photosynthetic photon flux density (PPFD) (G–H) during a September day for treatment C (left; day temperature 21.7 °C/night temperature 18.0 °C) and treatment E (right; day temperature 18.0 °C/night temperature 22.4 °C). Treatment C took place in climate chamber 2 and treatment E in climate chamber 3 [(1.8 × °C) + 32 = °F].

was found to be in the range 10 to 22 μmol·mol⁻¹·h⁻¹ in the five chambers.

METHOD FOR DETERMINING NONDESTRUCTIVE LEAF AREA. Analysis of 600 chrysanthemum leaves showed that leaf area could be described as a simple linear correlation ($R^2 = 0.99$) between leaf area (square centimeters) and the product of leaf width and leaf length (Fig. 4) according to Equation [2]:

$$\text{Leaf area} = 0.62 (\text{width} \times \text{length}) - 0.55 \quad [2]$$

With this equation leaf area was determined nondestructively by measuring leaf width and length during chamber experiments.

ACCURACY OF CLIMATE CONTROL. Air temperature was kept with maximum ± 0.5 °C deviations from the set points (Fig. 5A–B) and the desired differences in air temperature among the treatments were reflected in leaf temperatures measured by thermocouples inserted in the leaves (Fig. 5C–D). CO₂ concentration was generally kept at 600 μmol·mol⁻¹, with deviations between ± 30 –70 μmol·mol⁻¹ (Fig. 5E–F). Daily means of PPFD were in the range 350 to 650 μmol·m⁻²·s⁻¹ and were similar

among climate chambers, although differences could occur, depending on the natural light in combination with the greenhouse structure (Fig. 5G–H).

Humidity of the climate chambers was determined passively by the dew point temperature, which was dependent on the water temperature in the cooling system. To satisfy the cooling demand, the water temperature was 0 to 5 °C, resulting in a vapor pressure deficit on a daily basis of 0.9 to 1.4 kPa (data not shown).

EFFECT OF CLIMATE CONTROL STRATEGIES ON PLANT GROWTH. Measurements of plant height at the end of the chamber performance experiment showed an almost declining plant height with a decreasing positive difference between day and night temperature (DIF) (Table 2). Plant height was least in the negative DIF treatment (treatment E). Statistical analyses showed significant differences between some of the treatments. Leaf area was found to be similar among the five temperature treatments (Table 2). This was supported by statistical analyses showing no significant differences. Plant dry weight was also found to be similar among treatments (Table 2), with no significant differences.

CANOPY PHOTOSYNTHESIS RATE. When analyzing differences in the importance of variables in the canopy CO₂ exchange equation, Eq. [1], it became apparent that the calculated rate of canopy photosynthesis was determined primarily by the CO₂ injection rate ($F = 9848$; $P < 0.001$). However, the change in CO₂ concentration in the chamber ($F = 1269$; $P < 0.001$), and the renewal of chamber air ($F = 1633$; $P < 0.001$) and the leaf area ($F = 1683$; $P < 0.001$) also influenced the calculated rate of canopy photosynthesis. The leakage of CO₂ had no effect on the calculations ($F = 1$; $P > 0.5$).

Rate of canopy photosynthesis during the day in all five treatments varied primarily in relation to the fluctuations in PPFD (Fig. 6A–D). Despite the differences in leaf temperatures (Fig. 6G–H), rates of canopy photosynthesis were almost similar among treatments (Fig. 6A–B). The CO₂ concentrations were fairly equal among treatments (Fig. 6E–F) and did not affect rates of canopy photosynthesis. This pattern was supported by statistical analyses on means of both day values and experiment values showing

Table 2. Plant height, leaf area, and plant dry weight in the five temperature treatments A–E. Measurements were performed at the end of the chamber performance experiment on one-third of the plants representative of all plants in a chamber. Values with different letters indicate significant differences at the 5% level according to Tukey's honestly significantly different (HSD) test. DT = day temperature; NT = night temperature.

Treatment	(DT/NT)	Plant ht (cm/plant) ^z	Leaf area (cm ² /plant) ^z	Plant dry wt (g/plant) ^z
A	(25.1/14.0)	10.2 ab	182 a	1.61 a
B	(23.4/16.0)	10.8 a	203 a	1.60 a
C	(21.7/18.0)	9.3 bc	197 a	1.60 a
D	(20.0/20.0)	9.0 bc	191 a	1.67 a
E	(18.0/22.4)	8.5 c	182 a	1.53 a

^z1 cm = 0.3937 inch; 1 cm² = 0.1550 inch²; 1 g = 0.0353 oz.

Fig. 6. Correlations between 1-h based rates of canopy photosynthesis (A–B) and hourly means of photosynthetic photon flux density (PPFD) (C–D), carbon dioxide (CO₂) concentration (E–F), and leaf temperature measured by thermocouples inserted in leaves (G–H) during the photoperiod of a September day for treatment A (closed circles; day temperature 25.1 °C/night temperature 14.0 °C) and treatment D (open circles; day temperature 20.0 °C/night temperature 20.0 °C). Treatment A took place in climate chamber 5 and treatment D in climate chamber 1. Values for CO₂ concentration in treatment A were missing in the first 2 h. Mean values of the photoperiod for treatments A and D were: rate of photosynthesis = 9.5 and 8.4 μmol·m⁻²·s⁻¹; PPFD = 443 and 465 μmol·m⁻²·s⁻¹; CO₂ concentration = 629 and 563 μmol·mol⁻¹; leaf temperature = 23.3 and 19.1 °C [(1.8 × °C) + 32 = °F].

no significant differences in canopy photosynthesis rate among treatments (data not shown).

Discussion

PERFORMANCE OF CLIMATE CHAMBERS. Air temperature in the climate chambers could be controlled accurately. The changes between night and day temperature set points caused a short overshoot of temperature of only 1 to 1.5 °C. During sudden doubling of the natural *PPFD* during the day, the air temperature was still kept within ± 0.5 °C of the set point. Air flow decreased the boundary layer of the canopy, ensuring that the differences in air temperature among treatments were found in leaf temperatures. The low water temperature in the cooling system created a relatively dry climate in the chambers compared to full-scale greenhouses, because although the heat exchanger was designed to ensure a dew point temperature 1 °C below the chamber air temperature, this could not be achieved, resulting in large differences between temperature of the chamber air and temperature of the cooling system. The relatively low humidity meant that new plants introduced to the chamber system had to be well acclimated to varying climate conditions before being transferred from the high humidity propagation area to the chambers.

The calculation of canopy CO_2 exchange demanded accurate CO_2 measurement. As the most important variable was the rate of CO_2 injection, having very accurate mass flow controllers was a prerequisite. The response time of the CO_2 measuring system was relatively long, but this was probably only one part of the time delay of the climate chambers. Response time of a CO_2 exchange chamber in general depends on volume of the chamber and air flow rate through the chamber (van Iersel and Bugbee, 2000). The primary cause of the time lag of these chambers was the volume of 1.3 m³, which imposed a limit on how short the time span of the photosynthesis calculations could be. However, in the view of greenhouse climate control the response time of the climate chambers was acceptable. The leakage of CO_2 hardly influenced the rate of canopy photosynthesis in the present experiment, so any factors influencing the leakage (such as differences in CO_2 concentration and air pressure between the climate chamber

and the surrounding greenhouse) were assumed to be of minor importance. The variable describing air renewal was influenced by error, as flow indicators were unstable in periods. In future experiments, accuracy would be improved if mass flow controllers were installed in the air stream withdrawal from the chambers to measure the actual amount of air renewal. The leaf area variable determined nondestructively by measuring leaf width and length was found to be representative of the actual leaf area, as the correlation was based on measurements of 600 leaves from the same chrysanthemum cultivar. In addition, the description of the leaf area development as an exponential increasing equation was found to be well correlated (data not shown). Disadvantages of using the nondestructive method during experiments were that it was time-consuming, necessitated opening and thus interruption of the CO_2 balance in the chamber, and there was a risk of growth disturbances due to thigmomorphogenic effects (Kläring, 1999). However, these disadvantages were counterbalanced by the improved estimation of plant CO_2 exchange when based on proper estimations of the leaf area.

EFFECT OF CLIMATE CONTROL STRATEGIES ON PLANT GROWTH AND CANOPY PHOTOSYNTHESIS RATE. A plant height almost declining with decreasing positive DIF was in accordance with previous results of internode length in chrysanthemum grown at the same 24-h mean temperature but at different day and night temperatures (e.g., Calvalho et al., 2002; Langton and Cockshull, 1997). However, although significant differences occurred between some of the treatments, the differences in height were not substantial due to the relatively short growth period of 3 weeks.

Leaf area and plant dry weight were similar among treatments, indicating that the plants responded to the 24-h mean temperature rather than day or night temperatures. This was in accordance with the results of Cuijpers and Vogelezang (1992) with chrysanthemum. In addition, rates of canopy photosynthesis were found to be almost similar among treatments, although different leaf temperatures were measured. From our knowledge of the response of changes in temperature on rates of photosynthesis at leaf level, one might expect the higher day temperatures to increase the rate

of photosynthesis much more than the small differences shown in Fig. 6. Experiments similar to the present one are rarely reported in the literature, but the results of Warrington et al. (1977) support the indications of similar photosynthesis among temperature treatments with different combinations of day and night temperatures at the same 24-h mean temperature, whereas similar experiments show different rates of photosynthesis (Berhage et al., 1990; Friend and Helson, 1976). In these experiments, the day time rate of CO_2 exchange did not differ significantly between treatments.

It has to be kept in mind, however, that temperature response curves on leaf level are measured under conditions in which the other environmental factors are nonlimiting to photosynthesis (i.e., at high *PPFD*). The temperature optimum of photosynthesis of this cultivar of chrysanthemum grown in standard conditions for the species is in the range 21 to 23 °C (unpublished data). If *PPFD* is decreased during measurement, the temperature response curve will be lower and very flat, making the optimum difficult to estimate (unpublished data). In an intact canopy, both sunlit and shaded leaves contribute to the total CO_2 exchange. Since the day temperature range used here (Table 1) was about the expected optimum for photosynthesis at high *PPFD*, and a substantial part of the canopy will experience low *PPFD* due to internal shading, this can explain the virtual absence of any difference in CO_2 exchange between the treatments. The climate will therefore be slightly over-optimized when based on a leaf model in relation to what the plants need. However, by using a leaf model rather than a canopy model, other obvious errors are avoided, since the production practice of regularly repositioning pots at a larger distance prevents there being a closed, uniform canopy and an exponential profile of light, which are some of the primary assumptions in many canopy models (e.g., Thornley, 2002).

CLIMATE CONTROL STRATEGIES. As the climate chambers were designed to test new climate control strategies on a small scale, the software specially developed for the chambers provided the possibility of imitating a climate computer normally used in a full-scale greenhouse. The data exchange software for the climate chambers,

as well as the climate computer for a greenhouse, could be used, along with climate control software loaded with any mathematical model, as the basis for creating set points. It is thus easy first to test new climate strategies in small climate chambers and then to scale up and test them in the greenhouse. If successful, the climate strategy can be implemented in commercial greenhouse production.

An example is the development of a dynamic model-based climate control concept by which temperature and CO₂ concentration were controlled by natural irradiance using a leaf model. The concept was developed and tested in chambers (Hansen et al., 1996) and afterwards scaled up to greenhouse conditions (Aaslyng et al., 2003), mainly using the same control software in chambers and greenhouse. This paper describes the chamber system in operation with the software. For technical characterization of the chambers and investigation of how constant and comparable they were in respect to temperature and CO₂ control, a constant climate strategy for day and night, respectively, was used in the present experiment.

In this paper, the chamber performance experiment is an example of testing a climate strategy. With the aim of reducing energy consumption, the indications of no effect on rate of canopy photosynthesis and dry matter of different treatments are interesting. It might be possible to save energy in greenhouse production by increasing the use of free heat during daytime, having a higher ventilation limit, and lowering the night temperature set point to keep the 24-h mean temperature. Energy consumption can then be reduced. With the indications of the chamber performance experiment, it thus seems reasonable to test the climate strategy in a full-scale greenhouse.

This paper has illustrated some aspects of the design of climate chambers and of experiments in climate chamber systems investigating the effects of different climate control strategies. The climate chambers described here will be valuable tools in future research of greenhouse climate control, CO₂ exchange and plant growth.

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