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MEDEDELINGEN LANDBOUWHOGESCHOOL
WAGENINGEN • NEDERLAND • 79-10 (1979)

A CLOSED SYSTEM FOR MEASUREMENT OF PHOTOSYNTHESIS, RESPIRATION AND CO_2 COMPENSATION POINTS

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(Received 2-IV-79)
Publication 459

H. VEENMAN & ZONEN B.V. – WAGENINGEN – 1979

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INTRODUCTION

Fundamental data for the production of glass-house crops in relation to temperature, light and CO_2-conc. are greatly needed. Nowadays, advanced equipment is available to control temperature and CO_2-conc. in the glass-house climate. An efficient temperature regulation is now extremely important, because of the amount of energy required to heat the glass-house. In practice the application of artificial light is useful but depends to a large extent on economic factors. Data about the relation between temperature, light and CO_2 on photosynthesis of glass-house crops are scanty.

Many research workers have built open, semi-closed or closed systems or have discussed aspects, which have to be considered in building such a system (ACOCK 1974; JARVIS et al. 1971). At the Agricultural University and Research Institutes in Wageningen, The Netherlands, open systems have been built for measurements of leaves (CHALLA 1976; GAASTRA 1959; PIETERS 1974), whole plants (LOUWERSE and VAN OORSCHOT 1969) or stands (LOUWERSE and EIKHOUDT 1975). VERFAILLIE (1972) constructed a closed system in which the environmental control of the aerial part and the control of the roots was separated. The equipment was used for grains (e.g. rice) and could not be applied to vegetables such as lettuce and sweet pepper. A closed system facilitates the measurement of CO_2-exchange from high external CO_2-conc. to levels as low as the CO_2-compensation point. HEATH and MEIDNER (1967) stated that data obtained in that way give information about possible practical use of CO_2-application. The CO_2-compensation point gives information about the photosynthetic efficiency of plants. For these reasons a relatively simple and cheap apparatus is constructed, based on the principle of a closed system and suitable for glass-house crops.

METHODS AND APPARATUS

General description

Fig. 1 is a diagram of the equipment which consists of the following components: plant chamber and pot chamber, the equipment for light- and temperature control. The infra-red gas-analyser and a 24 channel mV-recorder are not shown in Fig. 1. The closed circuit with the perspex plant chamber (Pl.ch.) and the temperature control equipment is placed on a metal trolley (g; 800 × 880 × 960 mm) with universal wheels (h_1–h_4). This trolley can be pushed under and beside the frame (e). Details of the perspex chamber and temperature control equipment will be given in subsequent paragraphs.

The light equipment consists of 5 Philips high intensity mercury vapour lamps (a_1–a_5; HPLR of 400 W each), arranged at 250 mm from each other,

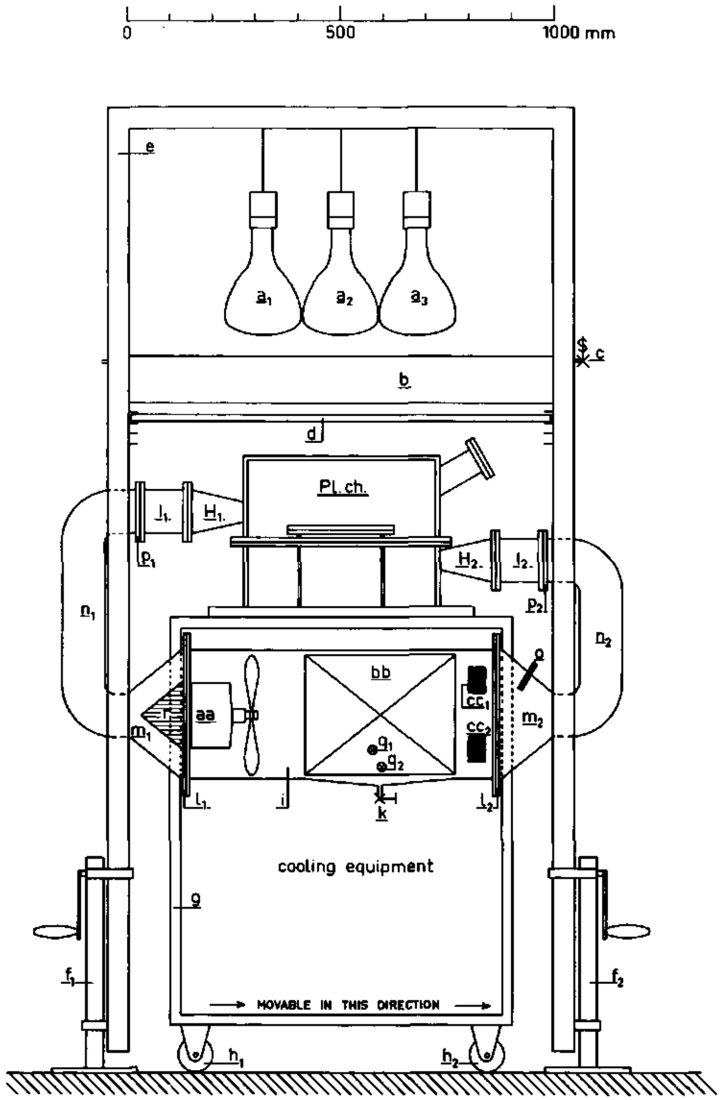

Fig. 1. Diagram of the equipment. All sizes in mm. a_1–a_5 = lamps, aa = fan and motor, b = water bath, bb = cooling coil, c = valve, cc_1 and cc_2 = air-heating elements, d_1–d_5 = metal screens, e = metal frame, f_1–f_4 = screw jacks, g = metal trolley, h_1–h_4 = universal wheels, i = copper duct, I_1–I_2 = perspex interunits, k = drain cock, l_1–l_2 = copper flanges, m_1–m_2 = copper interunits, n_1–n_2 = flexible tubes, o = temperature sensor, p_1–p_2 = perspex flanges, Pl.ch = plant chamber, q_1–q_2 = places of transits through the copper duct, r = copper cone fixed on aa.

measured from the central lamp. Light intensity is regulated by movable metal screens (d) with a different size and a different number of perforations. A range of irradiance between 0 and 215 W m^{-2} (400–700 nm) at plant level can be realized. The difference in light intensity at the horizontal direction in the plant chamber is less than 15%. A water bath (b) was installed in order to reduce the long wave radiation. The distance from the water bath to the lamps is 50 mm and from the water bath to the plant chamber 120 mm. The temperature in the water bath is regulated between 12° and 35°C with a thermostat, which operates a valve (c) for the tap-water supply. Lamps, water bath and screens are mounted on a metal frame (e; U-tube, 2250 × 1090 × 1090 mm), the height of which can be increased 400 mm by 4 hand-operated screw jacks (f_1–f_4). More details of the equipment are given in the Appendix.

A copper duct i (700 × 320 × 424 mm) is equipped with a fan (aa), a cooling coil (bb) and 2 air-heating elements (cc_1 and cc_2). A copper cone r is fixed on aa and placed in the airstream. The drain cock (k) is inserted at the lowest point of the duct in order to drain superfluous water. At points q_1 and q_2, 2 copper tubes connect the cooling coil with the cooling equipment at the bottom of the trolley. The copper tubes and 3 transits for electric wires through the copper duct are hermetically sealed with Bucarit-aquarium putty. The duct is connected at both ends to sloping copper units (m_1 and m_2) by means of copper flanges (l_1 and l_2) and bolts and hermetically clothed with foamed cellrubber. The sloping units are connected with flexible tubes (∅ 100 mm) to the inlet (n_2) and to the outlet (n_1) of the plant chamber. The copper part is isolated with Armaflex rubber and the flexible tubes are wrapped in Virginia foam rubber tape. A temperature sensor (o) for the temperature control equipment is placed at unit m_2. The length of tube n_1 can be varied for various heights of the plant chamber. Both tubes (n_1 and n_2) have perspex flanges (p_1 and p_2) which connect the perspex interunits I_1 and I_2 by means of bolts and a quad ring (∅ 113 × 6 mm). The room temperature can be varied between 10° and 34°C with an accuracy of ± 0.8°C by means of thermostatic controlled electric heaters and a cooling battery (s).

Details of the plant chamber

The plant chamber (Fig. 2) consists of a perspex (polymethylmethacrylate) cylinder (A; h = 150 mm) mounted on a solid perspex bottom plate (B; ∅ 620 mm; h = 25 mm) and an upper unit (C) with an internal height of 190 mm. The height of the cylinder can be increased with 2 interunits (D and E) with heights of 100 and 250 mm, resp. (not shown in Fig. 2). The inner diameter of the cylinders (A, C, D, E) is 441 mm and the wall thickness 8 mm. The units are airtight connected with O-rings (∅ 480 × 6 mm) and 6 adjustable metal clips (F). The total volume of the closed circuit with A and C is 180 litres. This volume (b) was calculated from the increase of the CO_2-concentration (ΔCO_2) after injection of a known volume (Δv) of pure CO_2 into the system according to the equation $\Delta v = a + b\Delta CO_2$. In plotting Δv against ΔCO_2 a straight line was obtained from which the volume was calculated. When there is no leakage, the symbol a is zero in the equation.

Cylinder A is provided with perspex tubes (G_1–G_4) which are used to insert wires for sensor elements, electrical cables and copper tubes conducting the

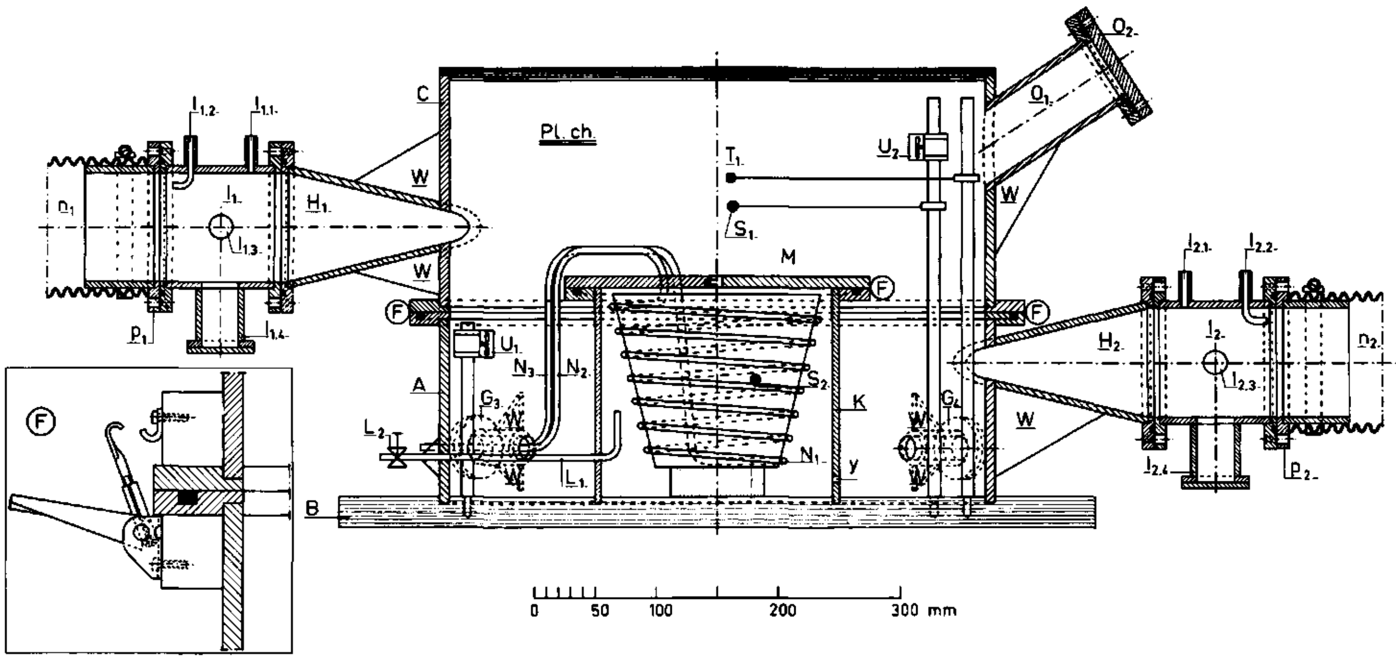

Fig. 2. Diagram of the plant chamber. All sizes in mm. A = perspex basal unit, B = solid perspex bottom plate, C = perspex upper unit, D and E = perspex interunits, F = metal clips (see detail), G = perspex tubes (ø 40 × 30; l = 32), H_2 = perspex air inlet (opening with Pl.ch.: 210 wide and maximally 40 high), H_1 perspex air outlet, I_1 and I_2 = perspex interunits (ø 110 × 100, l = 100), I_1I_1, I_1I_2, I_2I_1 and I_2I_2 = perspex tubes (ø 8 × 5), I_1I_3 and I_2I_3 = perspex tubes (ø 24 × 12; l = 15), I_1I_4 and I_2I_4 = perspex tubes, similar to G, K = perspex pot chamber (ø 200 × 190; h = 190), L_1 = perspex tube (ø 5 × 3 mm; l = 180 mm), L_2 = valve, M = perspex disk (ø 250; thickness 10), n_1 and n_2 = flexible tubing, N_1 = copper spiral (ø 6 × 4), N_2–N_3 = plastic tubes, O_1 = perspex tube (ø 60 × 50; = 75), O_2 = perspex flange, p_1–p_2 = perspex flanges, Pl.ch. = plant chamber, S_1 and S_2 = thermocouples, T_1 = photocells, U_1 and U_2 = fans, W = perspex supports, Y = place of transit for a thermocouple wire.

thermostat controlled water to achieve any desired temperature of the pot in the chamber. The tubes G_1–G_4 are filled with perspex stops to prevent CO_2-pockets in the closed circuit. Air leakage is prevented by use of perspex stop flanges, bolts and airtight foamed cell rubber. The air inlet (H_2) is connected to the interunit I_2 by a flange and a quad ring (⌀ 113 × 6 mm). In the subscript of Fig. 2 those dimensions of the various parts are given, which have not been mentioned here. The bottom plate is provided with holes with screw thread to insert PVC bars on which sensors can be fitted. A perspex cylinder (K), the pot chamber, is glued onto the bottom plate in which a pot with a soil-volume of almost 2,3 litres can be inserted. The cylinder is provided with a perspex tube (L_1) for supply of water and air via a valve (L_2). W are perspex supports. Point Y is the place for a transit of themocouple wires.

An airtight seal of the pot chamber with the pot is obtained by means of a flat disk (M) of 2 segments, an O-ring (⌀ 226 × 6 mm) and metal clips (F). Disks with different slot sizes are used because of various thicknesses of the plant stems. The slot is sealed with aquarium putty after inserting the pot with the plant in the pot chamber. The temperature of the pot can be regulated in a range between 15–35°C by a copper tube (N_1) bent into a spiral (l = 225 or 315 cm) and connected to an isolated water bath (N_4) of 10 litres which contains a portable thermoregulator (N_5) and a cooling unit (N_6). N_2 and N_3 are plastic tubes. N_4–N_6 are mentioned in the Appendix. The difference in temperature between the pot and the water bath depends mainly on the applied difference in air and soil temperature.

The upper unit C is provided with an air outlet H_1, constructed in the same way as the air inlet H_2. Opposite to H_1 a perspex tube (O_1) with a flange (O_2), a perspex stop and an O-ring (⌀ 63 × 4 mm) are attached. Through this tube the leaf temperature of a plant can be measured with an infra-red thermometer (P; see Appendix) before or after the CO_2-exchange measurements.

H_1 and H_2 are connected by perspex flanges (p_1 and p_2) with the interunits (I_1 and I_2) and flexible tubes (n_1 and n_2). The interunit I_2 is provided with perspex tubes I_2I_1 and I_2I_2 (both $l = 50$ mm), I_2I_3 and I_2I_4. I_2I_1 is connected by means of a threeway valve onto a CO_2-injector and a CO_2-cylinder. In this way pure CO_2 can be injected in the circulating airstream with an accuracy of 5%. The time needed after injection to achieve a steady mixture is about 4 minutes. I_2I_2 is connected to a U-shaped glass tube (not shown) filled with paraffin oil, which indicates the pressure difference between the closed circuit and the ambient air and prevents damage to the equipment in case of excessive under or over pressure.

Through tube I_2I_3 a humidity sensor (Q; see Appendix) can be inserted in the airstream. I_2I_4 is used for wires. Interunit I_1 has similar tubes (I_1I_1, I_1I_2, I_1I_3, I_1I_4) as I_2. Tubes I_1I_1 and I_1I_2 are connected via nyloseal tubes to the in- and outlet of the URAS (R_4). The nyloseal tubes are impermeable for CO_2. Nyloseal flareless tube fittings were used for the connections. The circuit is provided with a filter (R_1), a membrane pump (R_2) and a flowmeter (R_3; see Appendix). In tube I_1I_3 a humidity sensor (Q) has been inserted.

Transpiration is determined by measuring in- and outgoing air of the plant chamber by the humidity sensors. The temperatures of the air in cylinder K and in the soil of the pot are measured by copper-constantan thermocouples (S_1; 0.5 mm^2). The air and leaf temperature is measured by manganin-constantan thermocouples (S_2; 0.2 mm^2) fixed on thin aluminium bars and movable in all directions. The irradiance at various horizontal and vertical positions in the empty plant chamber was measured with a flat photometer for visible light (type TFDL – 65 – 2020) and a Kipp solarimeter (type cc_1). The maximum irradiance at plant level is 215 W m^{-2}. The difference in horizontal distribution was less than 15% and the vertical measurements showed a quadratic relation. During CO_2-exchange measurements the irradiance is recorded continuously by photocells (T_1) which are fixed on the thin aluminium bars.

To improve the turbulence in the plant chamber 2 small fans (U_1 and U_2) are used. Usually the wind-speed is not recorded during CO_2-exchange measurements. The wind-speed in the centre of the interunits is about 4.80 m s^{-1}. In the plant chamber without a plant it was 0.60–0.95 m s^{-1} with units A and C (in the centre 0.8 m s^{-1}) and 0.50–1.10 m s^{-1} with units A, C, D and E. Wind-speed was measured by a heatball anemometer, constructed at the Department of Physics and Meteorology, Agricultural University. Because of the relatively high wind-speed the difference between leaf and ambient air temperature was small, which is in accordance with results obtained by PAPENHAGEN (1974).

The URAS, thermocouples, photocells and humidity sensors are connected to a 24 channel mV-recorder (Philips, type PR 3500) or to a datalogger (Fluke, type 2240 A).

Principle of the temperature control system

A diagram of the temperature control system is given in Fig. 3. The copper-duct i of the closed circuit (see Fig. 1.) is provided with a fan (aa), a cooling coil (bb), 2 air-heating elements (cc_1 and cc_2) and the temperature sensor (o).

Glycol is circulated through the cooling coil. The glycol circuit consists of an expansion vessel (dd) with pressure gauge (ee), a threeway valve with servomotor (ff), a pump (gg) for circulating the glycol through the glycol circuit and a valve (hh). The threeway valve determines the distribution of glycol through the evaporator (ii) and a bypass. In this way the cooling capacity is adapted continuously to the cooling requirement. Temperature is regulated proportionally. The valve hh is used for filling the circuit with glycol.

The freon circuit consists of a freon compressor (kk_1), an air cooled condensor (kk_2), a liquid vessel (kk_3), a filter drier (ll), a sight glass (rr), double tubes evaporator (ii), thermostatic expansion valves (mm_1 and nn_1) with bulb sensors (mm_2 and nn_2), a liquid separator (oo) and a filter drier (pp); qq and ss are pressure valves.

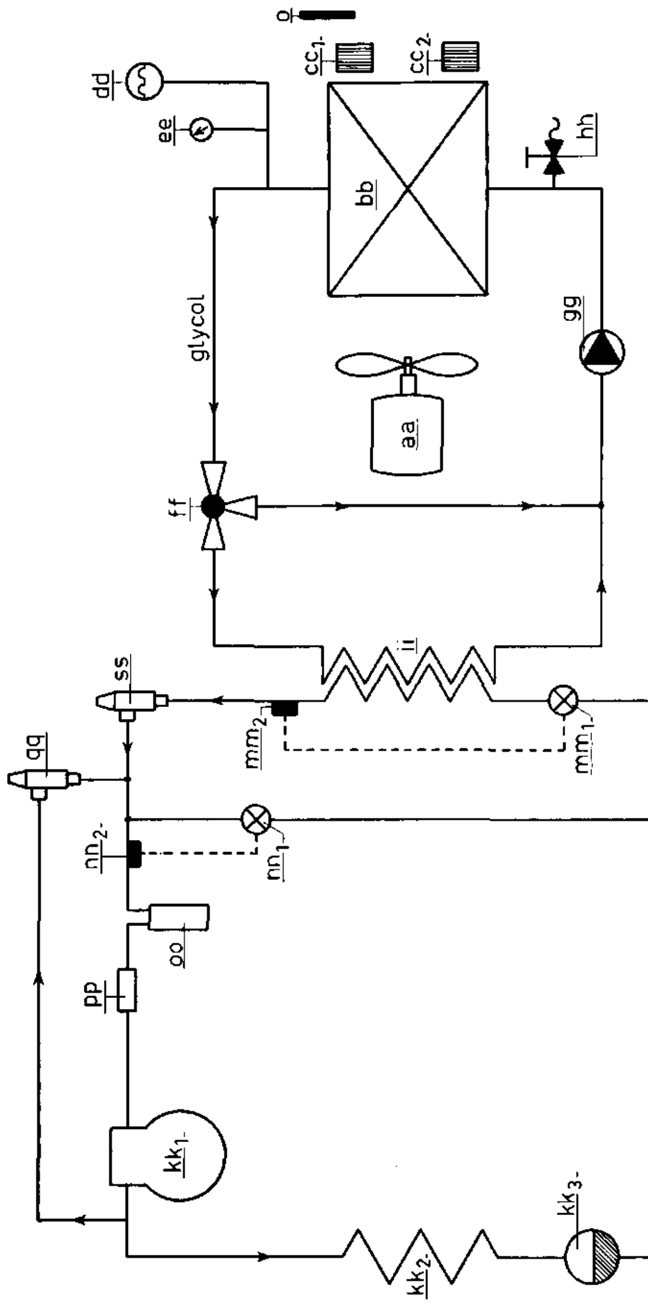

Fig. 3. Diagram of the temperature controlsystem, aa = fan and motor, bb = cooling coil, cc_1 and cc_2 = air-heating elements, dd = expansion vessel, ee = pressure gauge, ff = threeway valve and servo motor, gg = pump, hh = valve, ii = double tubes evaporator (condensor), kk_1 = freon compressor, kk_2 = condensor, kk_3 = cooling vessel, ll = filter drier, mm_1 and nn_1 = thermostatic expansion valves, mm_2 and nn_2 = pressure bulb sensors, o = temperature sensor, oo = liquid separator, pp = filter drier, qq = pressure valve, rr = sight glass, ss = constant pressure valve.

A high pressure and high temperature exist in compressor kk_1. In kk_2 the pressure is still high but the temperature becomes lower, due to the cooling by ventilators with ambient air. A high pressure exists from kk_1 till mm_1 and nn_1. The pressure difference between the high pressure and low pressure part (ii) is provided by mm_1. A low pressure and low temperature exist at ii. Freon evaporates in ii and takes heat off from the glycol circuit.

The freon system is continuously operating but below full capacity. Pressure valve ss regulates the pressure in ii in such way that the temperature in ii never becomes too low. When ss is closing, an extreme low pressure between ss and kk_1 can exist, because the capacity of kk_1 remains unchanged. For the protection of the compressor the extreme low pressure is taken off via a gas short-circuit, regulated by qq. Expansion valve nn_1 is necessary to prevent high temperatures in the short-circuit in a period of prolonged low cooling capacity at ii. Temperature sensor bulb nn_2 regulates nn_1 in such way that the temperature in the shortcircuit never becomes too high and the compressor is protected against burning. The evaporation of freon after nn_1 in the low pressure part cools the short-circuit.

Since the room temperature can be controlled in a range between 10 and 34°C, the temperature in the plant chamber can be chosen between 5 and 32°C. Usually the room temperature was kept a few degrees above the plant chamber temperature in order to prevent condensation on the plant chamber wall. The temperature of the plant chamber could be kept constant with an accuracy of $\pm$ 0.5°C. With rapid changes in irradiance manual control of the temperature can be applied in order to achieve more quickly the desired temperature.

In case the equipment fails, a safety fuse will cut the current in order to prevent damage.

Some preliminary results on photosynthesis and transpiration

During preliminary experiments it appeared that the humidity sensors were accurate and sufficiently sensitive. The difficulty of exactly calibrating the sensors at the high air humidity and of the high wind-speed applied in the plant chamber, which gives a small difference in water vapour between the in- and outgoing air, resulted in a less accurate recording of transpiration than desired. At present data on transpiration can be obtained only under steady conditions (Acock et al. 1977; King et al. 1977) by measuring the amount of water condensed at point k (see Fig. 1.). Measurement of transpiration by humidity sensors would have been cheap. In the near future we hope to use a URAS for continuous recording of transpiration.

The rates of photosynthesis and respiration are determined in a closed system by measuring the CO_2-content of the circulating air by infra-red gas-analysis. The rate of photosynthesis (Pn) depends on the decline in CO_2-concentration (ΔCO_2) per unit time (Δt) and the volume (b) of the closed circuit according to $Pn = b.\Delta CO_2/\Delta t.c$. Symbol c contains a factor for the calibration of the URAS and the density of CO_2 at the measured temperature. Analogue to the measurements of Heath and Meidner (1967) with lettuce leaves

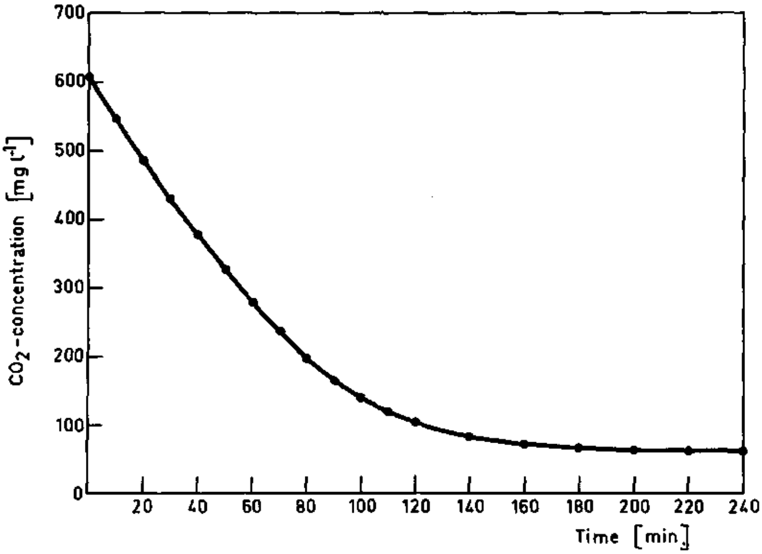

Fig. 4. Decrease of CO_2-concentration during 4 hours in a closed circuit with a sweet pepper plant cv. Bruinsma Wonder at irradiance of 61 W m^{-2} at plant level. The injected CO_2-conc. was about 620 mg l^{-1}. Plant chamber and pot chamber temperature was 25.5°C ±0.5°C during the measurement. The plant was grown at day-night temperatures of 26–21°C in a glass-house in April-May 1977. The leaf area was 23.3 dm^2 and the plant had 3 small fruits.

or VERFAILLIE (1972) with rice plants, the CO_2-exchange can be measured at any external CO_2-concentration. Fig. 4 shows the decrease in CO_2-concentration against time for a sweet pepper plant cv. Bruinsma Wonder. It is evident from Fig. 4 that below a concentration of 300 mg l^{-1} the rate of photosynthesis declines until a steady condition is achieved and the net CO_2-exchange is zero. The CO_2-concentration at the compensation point, which was 62 mg l^{-1} in this particular case, can be read directly from the chart. Leakage in a short period is neglectable. If there was some leakage of CO_2, the CO_2-compensation point would actually be lower than on the chart.

When knowledge regarding photosynthesis at only one CO_2-concentration is required, a calculated amount of CO_2 can be injected each time to obtain the desired CO_2-concentration. Fig. 5a shows an example with lettuce cv. Amanda Plus at various light intensities. The figure shows that within a few minutes after injection a gradual decline in CO_2-concentration set in and ΔCO_2 can be measured. The data of Fig. 5a were used to calculate the CO_2-exchange rates, which are presented in Fig. 5b, showing the photosynthesis-light response curve.

It should be mentioned that the volume of the plant chamber can be varied depending on the height of the plant. With the smallest volume, plants should have a leaf area of at least 5 dm^2 in order to obtain accurate data.

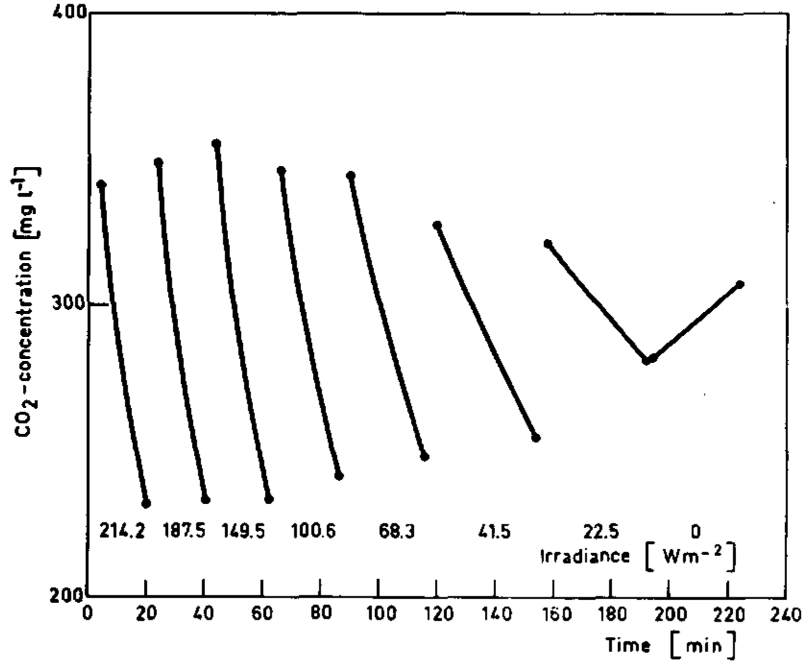

Fig. 5a. Decrease of CO_2-concentration in a closed circuit with a lettuce plant cv. Amanda Plus during short periods at various irradiance levels. The CO_2-conc. was between 350 and 250 mg l^{-1}. Plant chamber and pot chamber temperature was 14 ± 0.5°C during the measurement. The plant was grown at day-night temperatures of 16–11°C in a glass-house in Februari-March 1977 with 30 W m^{-2} (400–700 nm) artificial illumination and the last two weeks before the measurement 65 W m^{-2}. The fresh weight was 52.4 g and the leaf area 18.0 dm^2.

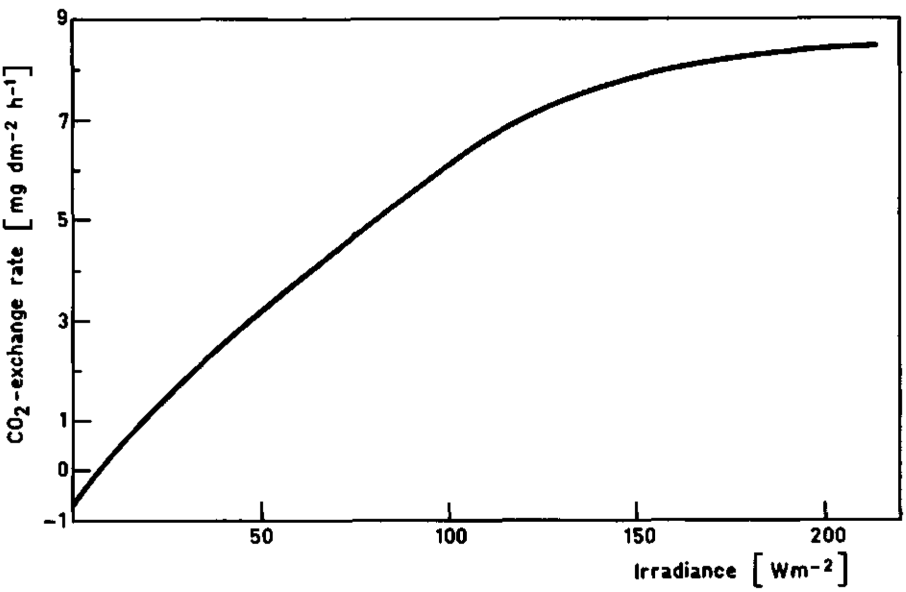

Fig. 5b. CO_2-exchange rate (mg CO_2 dm^{-2} h^{-1}) of a lettuce plant cv. Amanda Plus at various irradiance levels.

SUMMARY

A closed system for determination of photosynthesis, respiration and CO_2-compensation points is described. The internal gaseous volume of the closed circuit is 180 litres. It consists of a plant chamber, a copper duct with built-in fan, cooling coil and air-heating elements and connecting flexible tubes. The cylindrical perspex plant chamber has an internal diameter of 441 mm and a height of 340 mm, which can be enlarged to 690 mm. The cylindrical perspex pot chamber has an internal diameter of 190 mm and a height of 190 mm.

Temperature in the plant chamber can be kept constant in the range between 5 and 32°C and in the pot chamber between 15 and 35°C with an accuracy of ±0.5°C. Temperatures are measured by thermocouples. The maximum irradiance on plant level is 215 W m^{-2} (400–700 nm). Irradiance is measured by selenium photocells and air humidity with thin film humidity sensors. Windspeed in the centre of the plant chamber is about 0.8 m s^{-1}. The rate of CO_2-exchange is determined by an infra-red gas-analyser. Injection of pure CO_2 or a gas mixture facilitates continuous monitoring of photosynthesis and respiration. During short periods leakage can be neglected.

All measurements are recorded on a 24 channel mV-recorder or a data-logger. The equipment has been used in a controlled environment room but can be transferred to the field. Since 1976 this closed system has been used for CO_2-exchange measurements with lettuce and sweet pepper plants.

ACKNOWLEDGEMENTS

I gratefully acknowledge the valuable advice of the technical staff of Wientjes, Roden, The Netherlands, and Mr. L. v.d. Meiden of ITHO, Schiedam, The Netherlands. I'm much indebted to the Technical Service of the Department of Horticulture, especially to Mr. H. ten Böhmer for his technical assistance. Grateful acknowledgement is also due to Mr. H. v. Lent for the preparation of the drawings.

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aa	Ventilator motor. Küba, type EA-24, with Küba–wings 300KS 15/12 and stepless revolution regulator, type VRH-502.
b	Water bath of aluminium plate (h = 110 mm) with a glass plate (d = 10 mm) on the bottom.
bb	Cooling coil Küba, type 6 × 7 (0.3) B6. Total cooling area is 10 m^2. At a temperature difference of 10°C the capacity with forced cooling is about 5040 kJ h^{-1}.
c	Water bath thermostat. Danfoss solenoid valve, type EVJD 15.
cc_1 and cc_2	Air-heating elements. Küba, type HR300. Power 315 W.
dd	Expansion vessel. Flexon, type 2/0.5.
ee	Flexon pressure gauge with a range of 0.1–0.4 g m^{-2}.
f_1–f_4	Old screw jacks, used for cars.
ff	Servomotor. Zentra, type VM-13P and a threeway valve, Zentra type DRK-15.
F	Metal clips. Camloc, type 5 IL 7–IBF.
gg	Pump. SMC, Commander 'S', with a maximal working pressure of 6. 10^5Pa.
ii	Double tubes evaporator (condensor). Küba, type G3. Capacity at a temperature difference of 10 °C is 7350 kJ h^{-1}.
kk_1–kk_3	Compressor unit L'unité hermétique, type TAH4518/AHR. This fan-cooled condensing unit consists out of the freon compressor kk_1, condensor kk_2 and cooling unit kk_3. Airflow of 23.10^5 1 h^{-1}.
ll	Filter drier. Danfoss, type DC-0833.
mm_1	Thermostatic expansion valve, Danfoss, type TF2–0.5 with pressure sensor mm_2. Capacity max. 6300 kJ h^{-1}.
n_1–n_2	Flexible tubes Flexofit, type NG2M (∅ 100 mm).
nn_1	Thermostatic expansion valve, Danfoss, type TF2–0.2 with pressure sensor nn_2. Capacity: max. 3780 kJ h^{-1}.
N_5	Portable thermoregulator. Braun, type Thermomix II. Capacity: 800 l h^{-1}. Temperature range 0–40°C.
N_6	Cooling unit. Grant, type CC15. Cooling power of 295 kJ h^{-1} at 0 °C and of 590 kJ h^{-1} at 25 °C.
o	Temperature sensor. Zentra, type GF–11 with selector, type FG–2. The temperature in the closed circuit is regulated proportionally by the Zentra thermostat type 2G13/TE3/TK, (ES) with above mentioned sensor and selector by switching the cooling coil bb and air-heating elements cc_1 and cc_2 simultaneously.
oo	Liquid separator (a suction line accumulator), Virginia, type VA32–55.
pp	Lo-side filter drier, Virginia, type AL 24–5SV.
p	Infra-red thermometer, Heimann, type KT with objective A. Temperature range 0–60°C.
qq	Capacity regulator/receiver pressure valve. Danfoss, type CPC-15.

Q	The Vaisala humidity sensor has been described by SUATOLA and ANTSON (1973). The electronical circuit is changed by Hoogendoorn B.V. 's-Gravenzande, The Netherlands.
rr	Sight glass. Danfoss, type SGI-10S.
R_2	Membrane pump. Hartmann und Braun, type 2-Wisa.
R_3	Flowmeter. Brooks, type E/C, model 1550-V. Capacity: 0–115 l h^{-1}.
R_4	Infra-red gas-analyser, Hartmann und Braun, URAS-2. The URAS has a measuring cuvette of 21 cm with an optical H_2O-filter in order to reduce interference with the water vapour content of the air sample. Applied flow rate is about 40 l h^{-1}. The URAS is weekly calibrated with gas mixtures mixed by 2 mixing pumps (R_5 and R_6), set in series. Variations in sensivity of the URAS are always less than 3%.
R_5 and R_6	Gas mixing pumps. Wöstoff, type SA 27/2a and SA 27/3a.
s	Searle-Bush refrigerators, type SR-240.
ss	Constant pressure valve. Danfoss, type CPP-15.
T_2–T_6	Small selenium cells. Megatron, type B (⌀ 7 mm). The photocells are calibrated with a flat photometer and the Kipp solarimeter, mentioned in the text.
U_1–U_2	Fans. Micronell, type V361 M. Maximal capacity 50.10^4 l h^{-1}.