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CONTROL OF EVAPORATIVE DEMAND ON TRANSPIRING PLANTS II. CONTROL ALGORITHM AND PERFORMANCE

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KITANO M, HAMAKOGA M. and EGUCHI H. *Control of evaporative demand on transpiring plants. II. Control algorithm and performance.* BIOTRONICS 21, 61–68, 1992. The control of evaporative demand (ED_A) was performed on the basis of the control algorithm developed. ED_A can be controlled by manipulating environmental factors of short wave irradiance, air temperature, humidity and wind velocity. In this experiment, relative humidity (*RH*) was manipulated in consideration of the higher sensitivity of ED_A to *RH*. In a natural light growth chamber, ED_A was controlled at a desired value of 73 mg/m^2/s with an accuracy of $\pm$4 mg/m^2/s by manipulating *RH* in the range from 45 to 90% according to diurnal variation in solar irradiance on a fair day. Under higher solar irradiance around the fair midday, the ED_A control brought smaller water loss and higher stomatal conductance in a cucumber plant as compared with those under the ED_A-uncontrolled condition where ED_A was increased to the higher level with solar irradiance under a constant *RH* of 70%. Thus, it can be conceivable that the developed algorithm is useful for optimalizing plant water relations.

Key Words : *Cucumis sativus* L. ; evaporative demand ; control algorithm ; growth chamber; water relations.

INTRODUCTION

Evaporative demand of the environment induces transpiration stream in plants and directly affects plant water relations responsible for stomatal response and water uptake in roots(*1, 2, 5, 6, 8, 9, 11–14*). We have evaluated evaporative demand (ED_A) on unit leaf area by using physical environmental factors of short wave irradiance, air temperature, humidity and wind velocity as follows(*8–10*)

$$ED_A = \frac{2C_P \rho G_E SD + \Delta\{\alpha R_S - 2\sigma\varepsilon_L(1-\varepsilon_A)T_A^4\}}{\{(2/n)\gamma(G_E/G_{AV}) + \Delta\}\lambda} \tag{1}$$

where the symbols are explanied in APPENDIX. ED_A related to transpiration rate (E_A) per unit leaf area as follows

$$E_A = \frac{C}{C + G_{AV}/G_S} \times ED_A \tag{2}$$

where C is the physical parameter defined as $1+(n\Delta G_{AV})/(2\gamma G_E)$. Thus, ED_A can be a quantitative measure of evaporative demand as a physical input to plant hydraulic system, and E_A can be an output regulated by stomatal function. From this input–output relationship between ED_A and E_A, it can be supposed that control of ED_A is one of the reliable methods for optimalizing plant water relations (*3, 4*). In the preceding paper (*10*), the sensitivity of ED_A to each environmental factor was analyzed, and ED_A was indicated to be more sensitive to short wave irradiance (R_S) and relative humidity (RH) than to air temperature (T_A) and wind velocity (U).

The present paper deals with algorithm and performance of the ED_A control by manipulating a given environmental factor responsible for ED_A in a natural light growth chamber.

CONTROL ALGORITHM

Evaporative demand can be controlled by manipulating one of the environmental factors responsible for ED_A of Eq. (1). Figure 1 shows a flow chart for the ED_A control by manipulating a given environmental factor responsible for ED_A. The environmental factors $X=\{x_i\}$ of R_S, R_A, RH and U were measured and transmitted to CPU through an interface. The present value of ED_A was evaluated by Eq. (1) and compared with the desired value ($SV\ (ED_A)$) of ED_A. If the deviation ($|\Delta ED_A|=|ED_A-SV(ED_A)|$) was larger than 1 mg/m^2/s, the adjustment of x_i was repeated by the following treatment

$$x_i = x_i + \frac{\partial x_i}{\partial ED_A}\Delta ED_A \tag{3}$$

where $\partial x_i/\partial ED_A$ is the reciprocal of the sensitivity ($\partial ED_A/\partial x_i$) of ED_A to x_i, as evaluated in the preceding paper (*10*). After several repetitions of this treatment with Eq. (3), the x_i which brought $|\Delta ED_A| < 1$ mg/m^2/s was obtained and transmitted to the x_i controller of the growth chamber for use as the desired value ($SV(x_i)$) of x_i.

The control range of ED_A depends on the sensitivity of ED_A to x_i and on the control range of x_i in the growth chamber. The manipulation of RH is considered to be an effectual method for the ED_A control, for the reason that ED_A is more sensitive to RH which is a controlled variable in growth chambers. In this experiment, we tried to control ED_A by manipulating RH in a natural light growth chamber, which was equipped with T_A and RH control units (*15*): One or two sets of cooling coils were operated continuously for cooling and dehumidifying, and an electric heater and a modutrol vapor valve were manipurated by P. I. D. controllers for heating and humidifying, respectively. This system made it possibe to control dew point in a range from 8 to 33℃ under the dark condition. This control capacity was estimated to be enough to control RH in a range from 40 to 90% at T_A from 20 to 30℃ even under higher solar irradiance.

Environmental factors of R_S, T_A, RH and U were measured with the

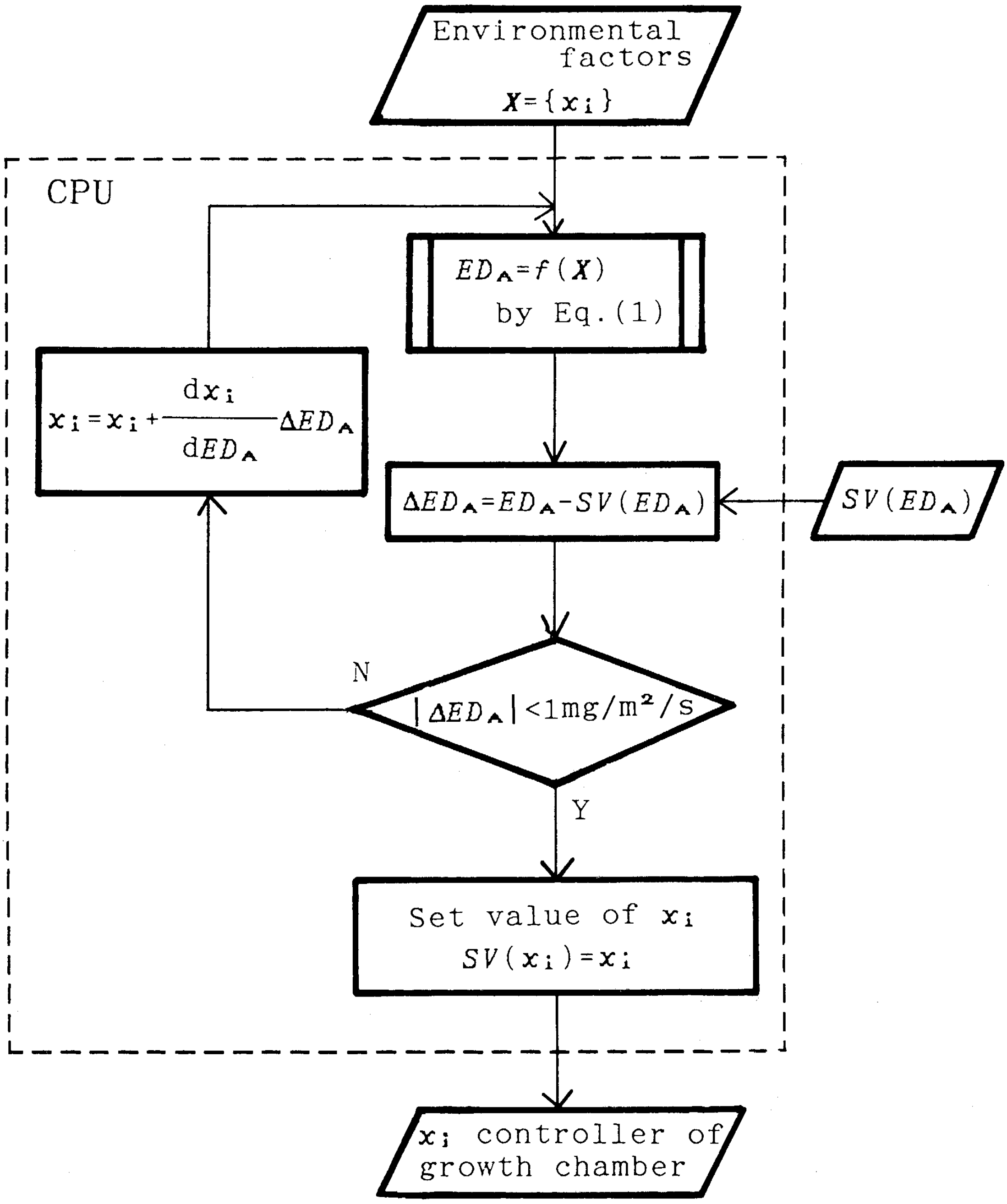

Fig. 1 A flow chart for the control of evaporative demand by manipulating one of the environmental factors responsible for evaporative demand: ED_A, evaporative demand by Eq. (1) ; X, environmental factors responsible for ED_A ; x_i, short wave irradiance or air temperature or humidity or wind velocity ; SV (ED_A), desired value of ED_A ; SV (x_i), desired value of the environmental factor of x_i.

respective sensors of a tube solarimeter, a resistance thermometer of Pt–100 Ω, a psychrometer with the resistance thermometers and a hot wire anemometer. The interval of maniulating RH was determined in consideration of the response characteritics of the tube solarimeter and the modutrol vapor valve: The solarimeter has a time constant of 40s, and modutrol moter for humidifying takes 1 min for one stroke. Therefore, RH was measured and SV (RH) was transmitted from CPU to the humidity controller with an interval of 1 min.

PERFORMANCE

In the previous study(*8*) in a phytotron glass room at T_A of 23℃, RH of 70% and U of 25 cm/s, it has been found that ED_A varies with R_S of solar irradiance and reaches the higher levels around the fair midday. Under such higher ED_A condition, water deficit has been found to be induced in a 10 leaf stage cucumber plant, and stomatal conductance has been known to be depressed from 10 : 00 by the water deficit.

Therefore, on a fair day, ED_A was controlled to keep ED_A constant by manipulating RH according to diurnal variation of R_S in the natural light growth chamber: T_A and U were set at 23℃ and 25 cm/s respectively, and ED_A was set at SV (ED_A) of 73 mg/m^2/s which was estimated to be equal to ED_A at 10 : 00 on the fair day. At the same time, in another growth chamber, RH was kept constant at 70% under T_A of 23℃ and U of 25 cm/s, and the variation in ED_A with R_S was evaluated. In both of the ED_A–controlled and the ED_A–uncontrolled growth chambers, diurnal variations of transpiration rate (E_A) and stomatal conductance (G_S) were evaluated on–line in a 6 leaf stage cucumber plant potted in vermiculite filled with sufficient nutrient solution : E_A was measured by weighing the plant and the pot, and G_S was evaluated from E_A and leaf temperature measured by thermocouples inserted into leaves(*5, 8, 9*).

Figure 2 shows diurnal variations of R_S, RH, ED_A, E_A and G_S on the fair day in both of the ED_A–controlled and the ED_A–uncontrolled growth chambers: RH, ED_A, E_A and G_S with the subscripts $_C$ and $_U$ indicate those under the respective conditions of the controlled ED_A and the uncontrolled ED_A. R_S started to increase at 6 : 00 and reached the maximum of 565 W/m^2 at 13 : 00. In the ED_A–controlled growth chamber, RH_C was manipulated in the range from 45% in the nighttime to 90% around the midday according to the diurnal variation of R_S, and ED_{AC} was always kept constant at SV (ED_A) of 73 mg/m^2/s with an accuracy of ±4 mg/m^2/s. On the other hand, in the ED_A–uncontrolled growth chamber RH_U was kept constant at 70%, and consequently ED_{AU} remarkably varied from 30 to 96 mg/m^2/s in the daytime according to increase in R_S: ED_{AU} was 30 mg/m^2/s in the nighttime under R_S=0 W/m^2 and reached the maximum of 96 mg/m^2/s at 13 : 00.

In the morning (6 : 00–9 : 00) and the late afternoon (15 : 00–18 : 00), variation in transpiration rates of E_{AC} and E_{AU} depended mainly on those in stomatal conductances of G_{SC} and G_{SU}. Around the midday (9 : 00–15 : 00), evaporative demands of ED_{AC} and ED_{AU} regulated the respective transpiration rates of E_{AC}

and E_{AU}, and differences in transpiration rate and stomatal conductance between the ED_A-controlled and the ED_A-uncontrolled conditions appeared more remarkable: E_{AC} was leveled off at a constant value of about 40 mg/m^2/s by the controlled ED_{AC}, while E_{AU} increased to 56 mg/m^2/s according to the increase of ED_{AU}, and furthermore G_{SC} was kept 1.5 times higher than G_{SU}: The G_{SU} was estimated to be depressed by the higher ED_{AU}. These differences imply that

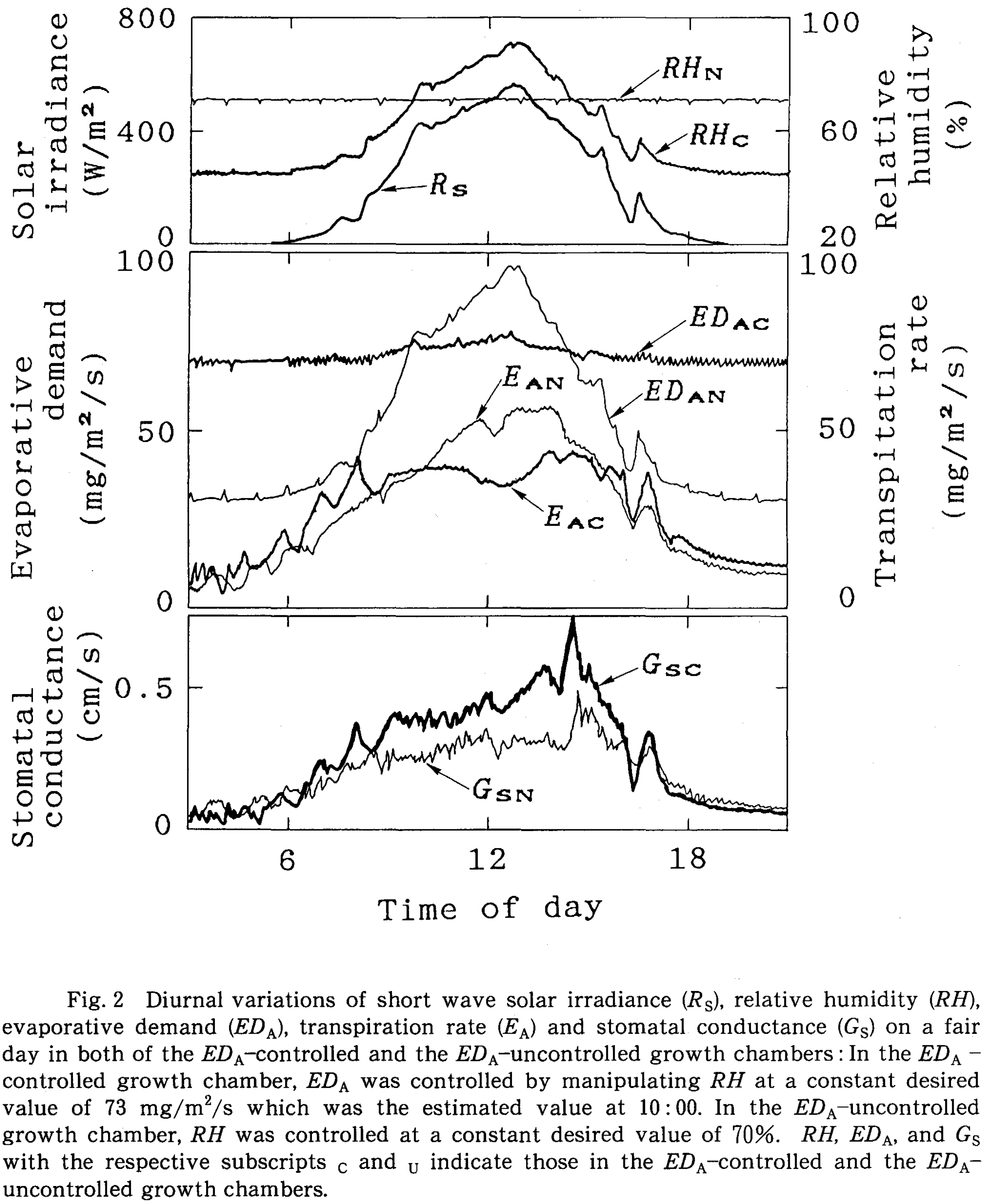

Fig. 2 Diurnal variations of short wave solar irradiance (R_S), relative humidity (RH), evaporative demand (ED_A), transpiration rate (E_A) and stomatal conductance (G_S) on a fair day in both of the ED_A-controlled and the ED_A-uncontrolled growth chambers: In the ED_A-controlled growth chamber, ED_A was controlled by manipulating RH at a constant desired value of 73 mg/m^2/s which was the estimated value at 10:00. In the ED_A-uncontrolled growth chamber, RH was controlled at a constant desired value of 70%. RH, ED_A, and G_S with the respective subscripts $_C$ and $_U$ indicate those in the ED_A-controlled and the ED_A-uncontrolled growth chambers.

transpitation and stomatal function can be modulated by controlling the evaporative demand.

Thus, it can be conceivable that evaporative demand can be controlled in a growth chamber by manipulating air humidity, and the developed algorithm is useful for optimalizing plant water relations.

APPENDIX : List of symbols

a	short wave absorption coefficient of a leaf.
C	physical parameter defined by $1 + (n\Delta G_{AV})/(2\gamma G_E)$.
C_P	specific heat of air at a constant pressure.
E_A	transpiration rate per unit leaf area.
E_{AC}	E_A under the controlled ED_A condition.
E_{AC}	E_A under the uncontrolled ED_A condition.
ED_A	evaporative demand per unit leaf area.
ED_{AC}	controlled ED_A.
ED_{AU}	uncontrolled ED_A.
G_{AH}	leaf boundary layer conductance for heat transfer by mixed convection ($G_{AH}=G_{FO}+G_{FR}$) (5, 7).
G_{AV}	leaf boundary layer conductance for vapor transfer by mixed convection ($G_{AV}=G_{FO}/\mathrm{Le}^{0.67}+G_{FR}/\mathrm{Le}^{0.75}$).
G_E	parallel conductance of G_{AH} and G_R.
G_{FO}	leaf boundary layer conductance for forced convection which depends on U.
G_{FR}	leaf boundary layer conductance for free convection which depends on T_L-T_A.
G_R	radiative transfer conductance ($4\varepsilon_L\sigma T_E{}^3/C_P\rho$).
G_S	stomatal conductance.
G_{SC}	G_S under the controlled ED_A condition.
G_{SU}	G_S under the uncontrolled ED_A condition.
Le	Lewis number.
n	constant ($n=2$ in an amphistomatous leaf and $n=1$ in a hypostomatous leaf).
RH	relative humidity of ambient air.
RH_C	RH under the controlled ED_A condition.
RH_U	RH under the uncontrolled ED_A condition.

R_S	short wave irradiance.
SVA	saturation vapor density of air.
SD	saturation deficit of ambient air $(1\text{–}RH/100)\times SAV$.
T_A	temperature of ambient air.
T_L	leaf temperature.
T_{LP}	estimated temperature of a wetted surface (*8, 9*).
T_E	$(T_A+T_{LP})/2$.
U	wind velocity of ambient air.
X	environmental factors responsible for ED_A, which consists of R_S, T_A, RH and U.
x_i	R_S or T_A or RH or U.
γ	thermodynamic psychrometer constant $(C_P\rho/\lambda)$.
Δ	slope of the saturation vapor density curve at T_E.
ε_A	emissivity of environment.
ε_L	emissivity of a leaf.
λ	latent heat of vaporization of water.
ρ	density of air.
σ	Stefan–Boltzmann constant $(5.67\times10^{-8}\mathrm{W/m^2/K^4})$.

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