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<http://hdl.handle.net/2324/8183>

出版情報 : BIOTRONICS. 21, pp.61-68, 1992-12. Biotron Institute, Kyushu University
バージョン :
権利関係 :



CONTROL OF EVAPORATIVE DEMAND ON TRANSPIRING PLANTS

II. CONTROL ALGORITHM AND PERFORMANCE

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(Received August 5, 1992; accepted August 28, 1992)

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 $73 \text{ mg/m}^2/\text{s}$ with an accuracy of $\pm 4 \text{ mg/m}^2/\text{s}$ 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 optimizing 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)

$$ED_A = \frac{2C_p \rho G_E SD + \Delta \{ \alpha R_s - 2\sigma \epsilon_L (1 - \epsilon_A) T_A^4 \}}{\{(2/n)\gamma (G_E/G_{AV}) + \Delta\} \lambda} \quad (1)$$

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

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

where C is the physical parameter defined as $1+(nAG_{AV})/(2\gamma G_E)$. 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 optimizing 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 $1 \text{ mg/m}^2/\text{s}$, the adjustment of x_i was repeated by the following treatment

$$x_i = x_i + \frac{\partial x_i}{\partial ED_A} \Delta ED_A \quad (3)$$

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 $|\Delta ED_A| < 1 \text{ mg/m}^2/\text{s}$ 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 manipulated by P. I. D. controllers for heating and humidifying, respectively. This system made it possible to control dew point in a range from 8 to 33°C 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°C even under higher solar irradiance.

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

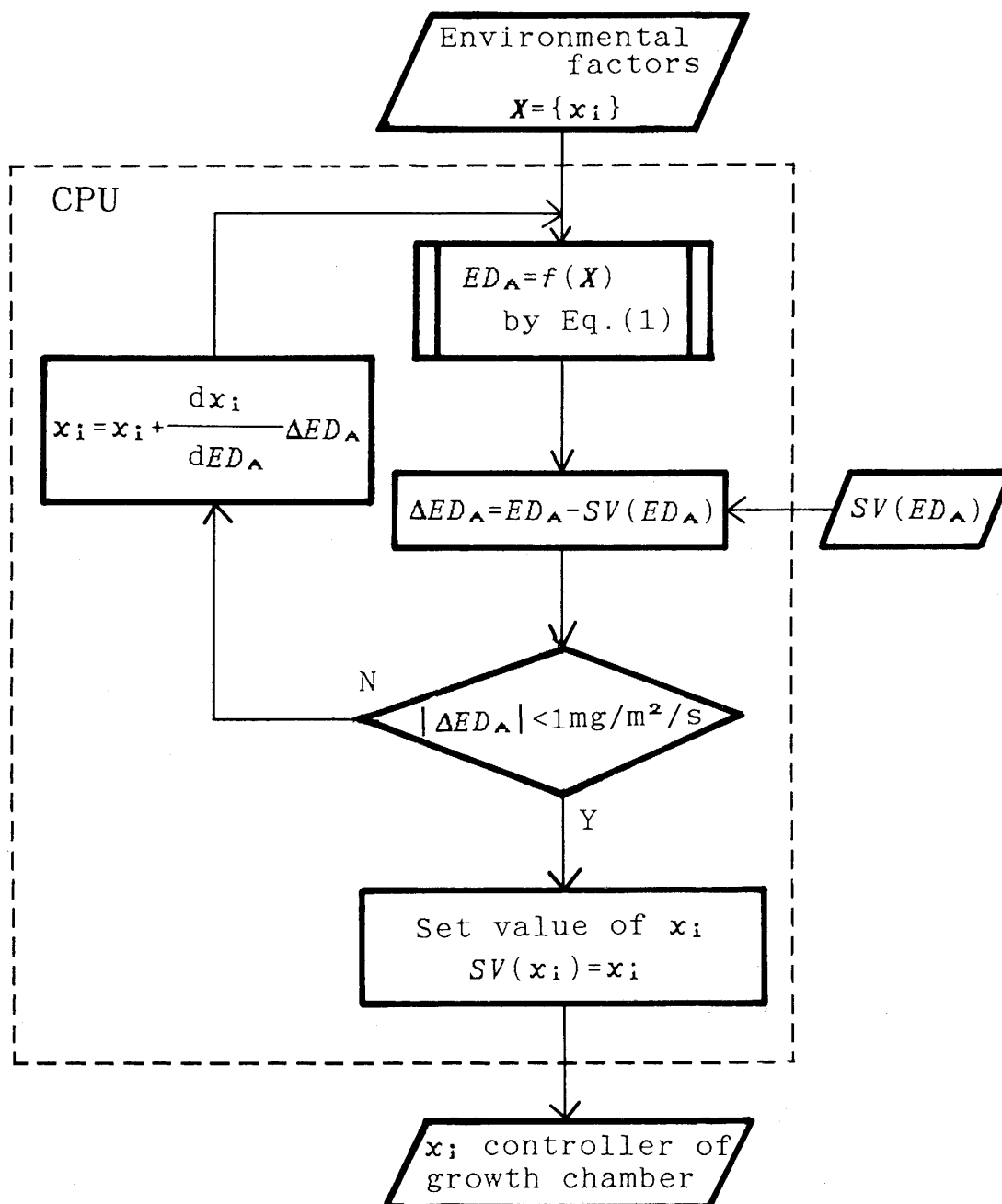


Fig. 1 A flow chart for the control of evaporative demand by manipulating one of the environmental factors responsible for evaporative demand: ED_A , evaporative demand by Eq. (1); X , environmental factors responsible for ED_A ; x_i , short wave irradiance or air temperature or humidity or wind velocity; $SV(ED_A)$, 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 manipulating RH was determined in consideration of the response characteristics 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°C, 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°C and 25 cm/s respectively, and ED_A was set at $SV (ED_A)$ of 73 mg/m²/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°C 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/m² 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/m²/s with an accuracy of ± 4 mg/m²/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/m²/s in the daytime according to increase in R_S : ED_{AU} was 30 mg/m²/s in the nighttime under $R_S=0$ W/m² and reached the maximum of 96 mg/m²/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 $40 \text{ mg/m}^2/\text{s}$ by the controlled ED_{AC} , while E_{AU} increased to $56 \text{ mg/m}^2/\text{s}$ 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

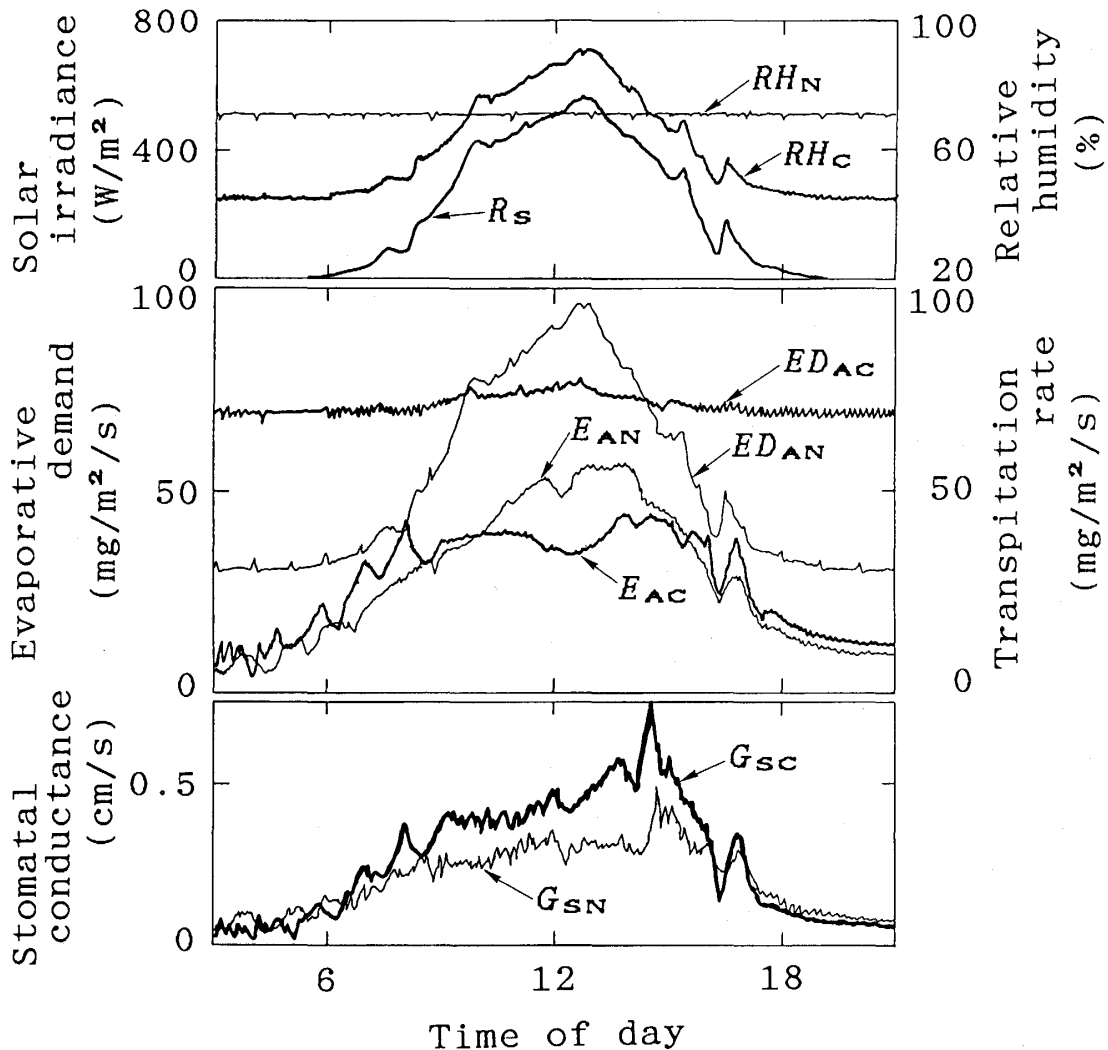


Fig. 2 Diurnal variations of short wave solar irradiance (R_s), relative humidity (RH), evaporative demand (ED_A), transpiration rate (E_A) and stomatal conductance (G_s) on a fair day in both of the ED_A -controlled and the ED_A -uncontrolled growth chambers: In the ED_A -controlled growth chamber, ED_A was controlled by manipulating RH at a constant desired value of $73 \text{ mg/m}^2/\text{s}$ 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.

transpiration 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 optimizing 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_{AU}	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 ($G_{AV} = G_{FO}/Le^{0.67} + G_{FR}/Le^{0.75}$).
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 ($4\epsilon_L \sigma T_E^3 / C_P \rho$).
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 $(1-RH/100) \times SA V$.
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 $(5.67 \times 10^{-8} \text{W/m}^2/\text{K}^4)$.

ACKNOWLEDGEMENT

The financial support by the Japanese Ministry of Education (No. 02454089) is gratefully acknowledged.

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