A Model for the Greenhouse Environment as Affected by the Mass and Energy Exchange of a Crop

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Abstract

A mathematical model to compute hourly change of the greenhouse environment was designed. The system considered comprises the soil, crop, air and glass or vinyl cover. The feed-back effect of the crop on the greenhouse environment is built in, and the temperature and humidity fields are simultaneously solved. Boundary conditions are the incident short-wave irradiance, the downward long-wave radiant flux density, the air temperature, the air humidity, the wind speed, all measured outside the greenhouse, and the water potential of soil in the greenhouse. The system is characterized by its scale, its properties regarding the heat transfer, the ventilation rate, and physiological characteristics of the crop about the water exchange. With these system parameters and boundary conditions, the model calculates not only the air temperature and humidity inside the greenhouse, but also the radiation balance, sensible and latent heat flux densities on the cover, the heat flux density through the cover, the latent and sensible heat exchange by ventilation, the radiation balance on the crop surface, the surface temperature of crop, and transpiration rate from the crop. The model was used to simulate the air temperature and humidity inside the greenhouse as affected by the ventilation rate. The results accorded qualitatively with experimental results so far reported.

1. Introduction

The purpose to study the environment in a “house” (here it refers to any constructions for growing plants, such as growth chambers, glass-houses, and vinyl houses) is to predict and to control it for favorable growing conditions on the basis of the understanding of its built-up mechanism. Theoretical approach based on the energy balance is one of the most effective method to achieve such purpose. Though many models along

this line have been presented, essential progress beyond Businger (1963) seems not to be attained.

For models to be effective, they must meet certain general criteria. First, they should predict in experimentally verifiable ways the physical and physiological processes that are known to occur in the system with reasonable accuracy. Second, they should be general and flexible enough to be applicable to any specific systems under various environmental conditions. To meet these criteria, the environmental parameters as inputs should be the primary boundary conditions that are easily measured and unaffected by existence of the

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system. Also, the system should be defined unambiguously in terms of the physical and physiological properties that can be readily determined with available methods.

Seginer and Levav (1971) reviewed all greenhouse models based on the energy balance method since Businger (1963). They pointed out that boundary conditions used in these models except the one by Takakura et al. (1969) are not completely primary. Businger (1963), for instance, determined the inside air temperature as a function of the outside air temperature, the net radiation on the outer surface of cover and on the house floor, the soil heat flux and the evaporation rate from the floor. Obviously, the net radiations, the soil heat flux and the evaporation rate are not primary boundary conditions, but dependent on the inside air temperature and other state variables themselves. Essentially the same treatment can be found in almost all other models so far reported.

Another point to be noted in the previous models including Seginer and Levav (1971) is that the feed-back effect exercised by the mass and energy exchange of crop on the house environment is not adequately taken into account. The surface evaporation or crop transpiration, for example, is given as a boundary condition (e.g., Businger, 1963). Or, it is determined from state variables, but the crop resistance which regulates the transpiration rate and the sensible heat exchange is fixed (Seginer and Levav, 1971).

In this investigation a model to meet the following conditions is developed: (i) all boundary conditions are primary and the system is characterized by the system parameters that can be measured or estimated; and (ii) the feed-back effect by crop on the greenhouse environment, that is, the control of mass and energy exchanges exercised by the variable crop resistance, is linked with other physical processes in the house.

To achieve this objective, we must solve a number of nonlinear equations simultaneously. Thus, fundamental relations are simplified as much as possible to avoid unnecessary complexity and the emphasis is placed on deriving the behavior

of the system as a whole.

2. Theoretical analysis

2.1. Basic assumptions of the model

The system is vertically layered; soil, crop, air, and cover (or wall), from the bottom to the top (Fig. 1). Further assumptions for this system are as follows.

- (i) The upper boundary of the system is at a distance from the cover, where the house has no influence upon the environmental parameters. This boundary is specified in terms of the air temperature (T_0 , °C), the humidity (e_0 , g m⁻³), the wind speed (U_0 , m s⁻¹), the short-wave irradiance (S_0 , W m⁻²), and the downward long-wave radiant flux density (L_0 , W m⁻²). The lower boundary is the soil layer inside the house, specified in terms of soil water potential (ϕ_s , bar).
- (ii) The system is horizontally uniform. Each layer is also vertically uniform.
- (iii) Horizontal transfer of the radiation in the system is negligible.
- (iv) There is no artificial heat source in the system.
- (v) The air flow in the house is uni-directional and horizontal. Also, it is uniform throughout the house.

Fig. 1. Vertical structure of the system specified by boundary conditions, system parameters, state variables and flux densities.

Under these constraints the model calculates the state variables and flux densities that are shown in the right-hand side of Fig. 1. The definitions of these quantities are to be given in the following sections.

2.2. Modeling of each sub-system

2.2.1. Cover

Heat balance for the cover as a whole is;

$$\{(S_o - S_d - S_e + S_u) + (L_o - L_d - L_e + L_u)\} A_f + (H_b - H_t + \lambda E_b - \lambda E_t) A_w = 0 \quad (1)$$

where

S = short-wave radiant flux density, W m^{-2}

L = long-wave radiant flux density, W m^{-2}

H = sensible heat flux density, W m^{-2}

E = water vapor flux density, $\text{g m}^{-2} \text{s}^{-1}$

A_f = floor area of the house, m^2

λ = latent heat of vaporization, J g^{-1}

A_w = wall area of the house, m^2

and the suffixes d, e, u, b and t refer to the direction and the reference surface of each flux as indicated in Fig. 1. To be simple, we disregard the evaporative flux density at the outer surface of the cover (E_t) in the following analysis.

Considering up to the secondary scattering, we obtain the following relations between each flux density of short-wave radiation:

$$S_d = \tau_c S_o + \alpha_c S_u \quad (2)$$

$$S_u = \alpha_s S_d \quad (3)$$

$$S_e = \alpha_c S_o + \tau_c S_u \quad (4)$$

Where τ is the transmittance, and α the reflectance. Suffixes c and s refer to the cover and to the crop surface, respectively.

Assuming that the radiation emitted from the cover or the crop depends on its mean temperature and the transmittance of the cover is negligible, we have the following relations for each flux density of long-wave radiation:

$$L_d = (1 - \epsilon_c) L_o + \epsilon_c \sigma T_c^4 \quad (5)$$

$$L_u = (1 - \epsilon_s) L_d + \epsilon_s \sigma T_s^4 \quad (6)$$

$$L_e = (1 - \epsilon_c) L_u + \epsilon_c \sigma T_c^4 \quad (7)$$

where ϵ 's is emissivities, T 's mean temperatures

in $^\circ\text{K}$, and σ the Stefan-Boltzman constant in $\text{W m}^{-2} \text{K}^{-4}$

The convective heat flux densities on both surfaces of the cover can be expressed as

$$H_t = h_t (T_t - T_o) \quad (8)$$

$$H_b = h_b (T_a - T_b) \quad (9)$$

$$\lambda E_b = \lambda (h_b / C_v) (e_a - e(T_b)) p \quad (10)$$

where

h_t = heat transfer coefficient of air on the outer surface of the cover, $\text{J m}^{-2} \text{s}^{-1} \text{C}^{-1}$

h_b = heat transfer coefficient of air on the inner surface of the cover, $\text{J m}^{-2} \text{s}^{-1} \text{C}^{-1}$

T_t = temperature of the outer surface of the cover, $^\circ\text{C}$

T_b = temperature of the inner surface of the cover, $^\circ\text{C}$

T_a = air temperature inside the house, $^\circ\text{C}$

C_v = volumetric heat capacity of the air, $\text{J m}^{-3} \text{C}^{-1}$

e_a = water vapor density inside the house, g m^{-3}

$e(T_b)$ = saturation water vapor density at T_b , g m^{-3}

Furthermore, p is a parameter that specifies either the wetness of the cover or the efficiency of the condensation to the cover, varying between 0 and 1.0. It corresponds to the wetness parameter or to the capture efficiency used by Seginer and Levav (1971). But, in this study it has a new feature – not completely an input parameter, but a ‘semi-state’ variable. Whether water evaporates from or condenses to the cover cannot be predetermined, but it should be determined according to the state of the greenhouse. Thus a value of p is first given as 1.0, and the equations are solved simultaneously. If the solution for E_b thus obtained assumes negative value (evaporation), a predetermined value of wetness parameter is assigned to p . If E_b is positive (condensation), a value for capture efficiency is assigned to p . With this correction, the calculation is repeated to obtain E_b as well as other state variables.

Saturation water vapor density at given temperature is specified by the Goff-Gratch equation

(e.g., List, 1966). Instead, however, we use a numerically simpler formula proposed by Murray (1967):

$$e(T_b) = 1323.0 \exp \{ 17.269 T_b / (237.3 + T_b) \} / (273.16 + T_b) \quad (11)$$

The heat flux density through the cover (A_c , $J m^{-2} s^{-1}$) can be calculated from

$$H_c = (T_b - T_t) k_c / b_c, \quad (12)$$

where k_c is the thermal conductivity in $J m^{-1} s^{-1} ^\circ C^{-1}$ and b_c the thickness in m of the cover. On introducing the overall heat transfer coefficient (U , $J m^{-1} s^{-1} ^\circ C^{-1}$) defined as

$$U = 1 / (1/h_t + b_c/k_c + 1/h_b)$$

we can also determine H_c from

$$H_c = U(T_a - T_o), \quad (13)$$

on the assumption that the balance of radiation fluxes can be neglected.

The mean temperature of the cover (T_c , $^\circ C$) can be approximated by the relation:

$$T_c = (T_t + T_b) / 2 \quad (14)$$

Three variables, H_b , E_b and T_s , are the secondary boundary conditions to be obtained from the following sub-models. Then, we can determine fourteen unknowns in the above equations (S_d , S_e , S_u , L_d , L_e , L_u , H_t , H_c , T_t , T_c , T_b , T_a , e_a , $e(T_b)$), by solving eqs. (1) through (14) simultaneously.

2.2.2. Air inside the greenhouse

Under the steady state conditions the following heat and water vapor balances hold for the inside air:

$$(H_s + \lambda E_s) A_f + \{ (H_{vo} + \lambda E_{vo}) - (H_v + \lambda E_v) \} A_{we} - (H_b + \lambda E_b) A_w = 0 \quad (15)$$

$$E_s A_f + (E_{vo} - E_v) A_{we} - E_b A_w = 0 \quad (16)$$

in which

A_{we} = the wall area in m^2 across which the air is exchanged between the house and its surrounding.

H_{vo} = sensible heat flux density due to the

inflow air, $W m^{-2}$

H_v = sensible heat flux density due to the outflow air, $W m^{-2}$

E_{vo} = water vapor flux density due to the inflow air, $g m^{-2} s^{-1}$

E_v = water vapor flux density due to the outflow air, $g m^{-2} s^{-1}$

The last four quantities can be expressed in terms of temperature and humidity as

$$H_{vo} = C_v T_o U_a \quad (17)$$

$$H_v = C_v T_a U_a \quad (18)$$

$$E_{vo} = e_o U_a \quad (19)$$

$$E_v = e_a U_a \quad (20)$$

Auxiliary variable, U_a ($m s^{-1}$), introduced in the above relations, is defined as

$$U_a = R V / (A_{we} \times 3600)$$

where V is the volume of the house in m^3 and R is the air ventilation rate in hr^{-1}

Variables e_a and T_a can be obtained from the aforementioned submodel (2.2.1), and H_s and E_s are determined by the submodel for canopy (2.2.3). Then, the unique solutions for H_b , E_b , E_v , E_{vo} , H_v , and H_{vo} can be obtained from eq. (15) through eq. (20) with primary boundary conditions and system parameters. Although A_{we} may not necessarily be the same as A_w , it is assumed to be equal to A_w in this study, a common assumption made in the greenhouse modeling.

The basic equations so far described are essentially the same as those used in Seginer and Levav (1971).

2.2.3. Crop

According to the whole canopy concept given by Monteith (1964), the crop grown in the house is assumed to exchange water vapor and heat at a certain level within the crop layer (acting surface). Then, the energy balance for this layer is

$$NR_s - H_s - E_s - H_p = 0, \quad (21)$$

in which NR_s is the net radiant flux density at the acting surface, and H_p the heat flux density transferred below this surface. Let us further

assume that the net radiation at the acting surface is identical to that at the crop surface. NR_s is then given by

$$NR_s = S_d - S_u + L_d - L_u$$

Sensible and latent heat exchanges between the crop and the air can be calculated from

$$H_s = C_v(T_s - T_a)/R_a \quad (22)$$

$$E_s = \{e(T_s) - e_a\}/(R_a + R_c) \quad (23)$$

where R_a is the aerodynamic resistance and R_c the canopy resistance both in $s\ m^{-1}$. Also, $e(T_s)$ is the saturation water vapor density at T_s , a function of T_s , $f(T_s)$, as given in eq. (11):

$$e(T_s) = f(T_s). \quad (24)$$

If we assume the storage heat by the crop is negligible, we may obtain that

$$H_p = H_g \quad (25)$$

where H_g is the soil heat flux density in $W\ m^{-2}$

The canopy resistance, R_c , is the overall leaf resistance of the whole crop and can be approximated as (Szeicz et al., 1973)

$$R_c = R_L/(2 \cdot LAI) \quad (26)$$

The resistance of the individual leaf, R_L , is defined as

$$1/R_L = 1/R_{cu} + 1/R_s \quad (27)$$

where R_{cu} is the cuticular resistance, and R_s the stomatal resistance, both expressed in $s\ m^{-1}$. The stomatal resistance, R_s , is in turn a dependent variable of the leaf water potential (ϕ_L , bar) as (Van Bavel, personal communication)

$$R_s = R_{sm} (1 + |\phi_L| S |\phi_L| E_1) \quad (28)$$

in which R_{sm} is the minimum stomatal resistance in $s\ m^{-1}$, E_1 the threshold value in bar^{-1} and S the sensitivity of the stomata in bar^{-1} , all being obtained from experimental relation between R_s and ϕ_L .

The water vapor flux density at the leaf surface (E_s , $g\ m^{-2}\ s^{-1}$) can be expressed as

$$E_s = (\phi_s - \phi_L)/R_{plc} \quad (29)$$

where ϕ_s is the soil water potential in bar, R_{plc} the overall plant resistance to the water flow in $bar\ g^{-1}\ m^2\ s$.

Aforementioned subsystem cover (2.2.1) provides NR_s , T_a , and e_a , while the subsystem soil in the following section determines H_g . With these values as inputs, eq. (21) through eq. (29) can be solved to determine nine unknowns (H_s , E_s , H_p , T_s , $e(T_s)$, R_c , R_L , R_s and ϕ_L) uniquely. By relating R_c (or R_L) to the leaf and soil water status, as expressed by eqs. (27), (28) and (29), we have incorporated the feed-back effect of crop on the house environment in our model.

2.2.4. Soil

The variable to be determined by this subsystem is the soil heat flux density, H_g , as indicated previously in 2.2.3. Ideally, we should determine the value of H_g by solving the energy balance equation at the soil surface and the heat conduction equation simultaneously, with constant temperature at a certain depth in soil as a boundary condition. To be simple, however, we determine H_g from an empirical relation in this study.

It is known empirically that H_g can be related to the net radiant flux density at the soil surface (NR_g , $W\ m^{-2}$) as

$$H_g = C_1 \cdot NR_g \quad (30)$$

Constant C_1 is called storage ratio and a function of time in general. But, in this study it is fixed at 0.10. Similar empiricism is introduced to determine NR_g , again for the simplicity. NR_g is related to NR_s as (e.g., Uchijima, 1976)

$$NR_g = NR_s \cdot \exp(-C_2 \cdot LAI) \quad (31)$$

The value of extinction coefficient C_2 is assumed to be 0.66.

H_g and NR_g can be calculated from eqs. (30) and (31), using the value of NR_s determined from the subsystem cover (2.2.1).

2.3. Method of solution

Fig. 2 summarises the relations among the submodels so far described. Parameters in parallelogram are outputs from one submodel, being

Fig. 2. Components of the system (COVER, INAIR, CANOPY, and SOIL) and their relations in terms of input and output variables. Parameters in card symbols are primary boundary conditions.

Fig. 3. Relation between two subroutines, COVAIR and CANOPY with respect to common unknown variables (H_s , E_s , T_s , T_a , T_c and e_a) and boundary conditions (S_o , L_o , T_o , U_o and e_o).

carried over to another submodel as inputs (thus secondary boundary conditions for a latter sub-model), as each arrow indicates. Primary boundary conditions are given in card symbols.

In our program, submodels 'cover' and 'in-air' were combined into one subroutine COVAIR, and 'canopy' and 'soil' into another subroutine CANOPY. Thus COVAIR can be solved for T_a , e_a , and T_c if H_s , E_s and T_s that are obtained from the CANOPY are given along with primary

boundary conditions (Fig. 3). With T_a , e_a and T_c thus computed from the COVAIR as inputs, the CANOPY then calculates H_s , E_s , and T_s . Starting with appropriate initial guesses for H_s , E_s , and T_s , the above procedure is repeated till the changes in these quantities become sufficiently small. The values for 31 variables at this stage should satisfy eqs. (1) through (31) simultaneously. In each sub-routine, the Newton-Raphson method was used to solve a set of equations. More details about the numerical methods used here are given by Takami (1977).

2.4. Input data for sample calculations

Table 1 shows the system parameters used in sample calculations. A plastic house with an area ratio $A_r (=A_f/A_w)$ of 0.5 was considered. The leaf area index (LAI) of the crop grown in the house was 2.5, and crop properties regarding water vapor and heat exchanges were assumed to take somewhat arbitrary average values obtained from several crops (Van Bavel, personal communication). The heat transfer coefficient of air on the upper surface of the cover (h_t , $J m^{-2} s^{-1} ^\circ C^{-1}$) was calculated as a function of wind speed of the ambient air (U_o , $m s^{-1}$):

$$h_t = (8.3 + 2.9 U_o)(4.2 \times 10^3 / 3600)$$

Environmental conditions given in Table 2 represented a typical clear day in spring with relatively dry air. Under such conditions we simulated the changes of energy balance, temperature and humidity in the house as the ventilation rate was increased from 0 to $80 hr^{-1}$ in $5 hr^{-1}$ step.

3. Results and discussion

3.1. Energy balance, temperature and humidity in the house

Fig. 4 schematically illustrates the vertical temperature profile of the system for various ventilation rates. Though T_a is assumed to represent the temperature of vertically uniform air inside the house, it is plotted in the middle height of the air layer in this figure to make the figure more illustrative.

Table 1. Input data for system parameters.

Symbol	Definition	Value	Unit
τ_c	Cover transmittance	0.80	—
α_c	Cover reflectance	0.10	—
α_s	Canopy reflectance	0.20	—
ε_c	Cover emissivity	0.98	—
ε_s	Canopy emissivity	1.00	—
k_c	Thermal conductivity of the cover	0.14	$\text{J m}^{-1}\text{s}^{-1}\text{°C}^{-1}$
b_c	Thickness of the cover	0.0002	m
h_b	Heat transfer coefficient on inner surface of cover	11.1	$\text{J m}^{-2}\text{s}^{-1}\text{°C}^{-1}$
A_r	Area ratio	0.5	—
R_a	Leaf boundary layer resistance	50.0	s m^{-1}
R_{sm}	Minimum stomatal resistance	400.0	„
R_{cu}	Cuticula resistance	5000.0	„
R_{plc}	Plant resistance	20.0	$\text{bar s m}^2\text{g}^{-1}$
E_1	Threshold value	0.25	bar^{-1}
S	Stomatal sensitivity	0.1	„
LAI	Leaf area index	2.5	—
C_1	Storage ratio	0.1	—
C_2	Attenuation coefficient of net radiation in the canopy	0.66	—

Table 2. Input data for boundary conditions.

Symbol	Definition	Value	Unit
T_o	Outside air temperature	20.0	°C
H_o	Outside humidity	10.0	g m^{-3}
U_o	Outside air speed	1.5	m s^{-1}
S_o	Outside short-wave irradiance	700.0	W m^{-2}
L_o	Outside long-wave irradiance	300.0	„
ϕ_s	Soil water potential	-2.0	bar

Temperature decreased monotonically with height in this system with a particular set of environmental parameters used in the calculation. The rate of temperature decrease with R decreased as R increased. The temperature of the acting crop surface, for instance, was 40.6°C in a completely closed house ($R=0.0\text{ hr}^{-1}$), and it decreased to 28.4°C as the house was strongly ventilated ($R=80.0\text{ hr}^{-1}$). The corresponding decrease in the inner-wall surface temperature was smaller, being about 10°C. The difference in temperature

between two surfaces of the cover decreased exponentially as R increased. This difference in temperature was 0.14°C in its maximum at $R=0\text{ hr}^{-1}$, and 0.02°C when R was 80.0 hr^{-1} .

Such changes in temperature with ventilation rate agreed qualitatively with results of Iwakiri and Uchijima (1971), though process of the latent heat transfer is disregarded in their model. Furthermore, the air temperature in the house (T_a) was slightly lower than the average of inner surface temperature of cover (T_b) and the tem-

Fig. 4. Vertical profiles of temperature for various ventilation rates; 0, 5, 20, and 80 hr^{-1} .

perature of the acting crop surface (T_s). Although the deviation increased as R increased, the relative magnitude was 11% at $R = 80 \text{ hr}^{-1}$. Thus, T_a may be approximated as

$$T_a \approx (T_s + T_b)/2,$$

as Iwakiri and Uchijima (1971) assumed.

Fig. 5 gives $\Delta T (= T_a - T_0)$ as well as $\Delta e (= e_a - e_0)$, as a function of R . Temperature difference between inside and outside the house, ΔT , decreased exponentially from 15.6°C at $R = 0 \text{ hr}^{-1}$ to 2.2°C at $R = 80 \text{ hr}^{-1}$. Humidity difference, Δe ,

Fig. 5. Temperature and humidity differences, $\Delta T (= T_a - T_0)$ and $\Delta e (= e_a - e_0)$, as functions of ventilation rate (R , hr^{-1}).

exhibited similar change with R . But the relation appeared to shift from one to other at the ventilation rate of around 15 hr^{-1} where condensation onto the cover wall occurred, as Fig. 6 indicates.

Iwakiri and Uchijima (1971) examined numerically the effects of R , the area ratio (A_r) and the heat transfer coefficient on the outer surface of cover (h_t) on ΔT . According to their result for the same A_r , h_t and NR_s as we used here, ΔT decreased from about 20°C to 7°C as R increased from 0 hr^{-1} to 80 hr^{-1} . In their result, ΔT is about 5°C higher at each ventilation rate than that in this study. This difference is significant and may be primarily due to the influence of the

Fig. 6. Flux densities of heat (a) and water vapor (b) as functions of ventilation rate. E_b is the condensation rate onto the inner surface of the cover, E_s the evaporation rate and E_v the water vapor flux density in the ventilation. H_b is the heat flux density at the inner surface of the cover, H_s the sensible heat flux density from the crop, and H_v the heat flux density in the ventilation.

latent heat transfer on ΔT which we have taken into account in the present model, since the difference in the heat transfer coefficient of the inner surface of the wall (h_b) is small, their h_b being $2.0 \times 10^{-4} \text{ ly s}^{-1} \text{ } ^\circ\text{C}^{-1}$, while ours was $2.6 \times 10^{-4} \text{ ly s}^{-1} \text{ } ^\circ\text{C}^{-1}$.

In Fig. 6, water vapor flux densities (a) as well as sensible heat flux densities (b) are given as functions of R . Condensation on the inner surface of the cover occurred at the ventilation rates below 15 hr^{-1} and increased with the decreasing ventilation rate up to $0.52 \text{ g m}^{-2} \text{ s}^{-1}$ at $R = 0 \text{ hr}^{-1}$. Condensation rate of $0.52 \text{ g m}^{-2} \text{ s}^{-1}$ amounted to about half of the transpiration rate (E_s , $\text{g m}^{-2} \text{ s}^{-1}$) under these conditions.

The sensible heat flux density (H_v) and the water vapor flux density (E_v) due to ventilation of the air first increased rapidly, then at a lower rate, as the ventilation rate was increased. It should be noted that the rate at which H_v increases with R was greater than that for E_v , thus the Bowen ratio for the heat exchange due to ventilation ($H_v/(\lambda E_v)$) increased from 0.40 to 0.74 when R increased from 0 to 80.

Evaporative flux density (E_s) showed a slight decrease with R up to $R = 15 \text{ hr}^{-1}$. E_s began to increase above $R = 15 \text{ hr}^{-1}$, then approached to a constant asymptotically. The change in H_s with R was also small, exhibiting a reverse trend of E_s . Thus the Bowen ratio of the crop surface (acting surface) remained almost constant at 0.49 above $R = 15 \text{ hr}^{-1}$. Crop resistance (R_c) was about 100 s m^{-1} , which was little affected by the ventilation rate.

Though the results described above appear to be reasonable, definite verification of the model should be provided by experiments. Partial test of the model is given in Takami and Uchijima (1977).

3.2. Evaluation of the calculation method

The accuracy of the calculations can be evaluated from three energy balance equations (1), (15), and (21), and the water vapor balance equation (16). The degree of accuracy is determined by the convergence decision in the iteration

loop. There are three convergence decisions in the computational procedure of this model, two of three in the Newton-Raphson iteration loop in both the sub-routines COVAIR and CANOPY, and one in the iteration loop between these sub-routines. The condition of convergence was set as follows. In the COVAIR the calculation was stopped when the change in T_b with iteration became less than 0.001°C , and in the CANOPY when the change in T_s was less than 0.001°C . In the last loop, iteration was terminated when the change in E_s , H_s , and T_s were $0.0001 \text{ g m}^{-2} \text{ s}^{-1}$, 0.1 W m^{-2} and 0.005°C , respectively. Balance equations with the solutions obtained under such conditions were of the order of magnitude as

$$\text{eq. (1)} \sim 10^{-3} \text{ W m}^{-2}$$

$$\text{eq. (15)} \sim 10^{-6} \quad "$$

$$\text{eq. (21)} \sim 10^{-4} \quad "$$

$$\text{eq. (16)} \sim 10^{-6} \text{ g m}^{-2} \text{ s}^{-1}$$

Note that the original balance equations except (21) are divided by A_w here. Thus the solution obtained sufficed all equations simultaneously with enough accuracy.

In numerical calculations, rapidness of convergence is also important. The Newton-Raphson method, used in each sub-routine, is known to yield solutions for such a system considered here quite rapidly (Takami, 1977). This is so, because a reasonable initial guess can be made easily. For instance, the temperature of the acting crop surface may be estimated at the air temperature inside the house. Another reason may be the stableness of the system in commonly occurring environments. The solutions noted above were obtained with three to four iterations.

On the other hand, the simple iteration method, used between sub-routines, may be slow in yielding solutions, since no correction is made in each iterative step. In fact, oscillations occurred in some cases by this method. Thus the method was modified to use the arithmetic mean of two previous values successively as improved solutions. The method with this modification converged in about twenty iterations in the cases used for sample calculations. Though the method does not

converge as rapidly as the Newton-Raphson method, it appears to be useful for computer usage, since the algorithm involved is most simple.

4. Conclusion

A steady state model for the greenhouse environment, based on the heat and water vapor balances, was designed. The model takes account of the feed-back regulation, exercised by the crop grown in the house, on the greenhouse environment. Given the primary boundary conditions (environmental parameters outside the house) and system parameters, the model determines the state of the house and of the crop with respect to temperature and humidity. Vertical flux densities of radiation, sensible and latent heats are also calculated along with the horizontal heat fluxes due to ventilation. A simple algorithm based on the iterative method was used to solve a set of algebraic equations, including several non-linear ones, simultaneously.

Some sample calculations were made to evaluate the effect of ventilation rate on the house environment. The dependence of temperature and humidity inside the house on ventilation rate appeared to be reasonable. Partial experimental test reported elsewhere (Takami and Uchijima, 1977) also suggests the validity of the model, though more complete experiments are certainly necessary.

The model, though a steady state one, can be used to simulate a time course of the state of a system for a day if the inputs averaged over a certain period of time (say, an hour or half an hour) are given successively.

Calculations were made with HITAC 5420 of the Computing Centre for Research in Agriculture, Forestry and Fishery, Ministry of Agriculture and Forestry.

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作物の物質とエネルギー変換を考えに入れた 温室環境モデル

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要 約

作物を栽培した温室の内部環境の時間変化を計算するために、作物の物質・エネルギー変換を考えに入れた数学モデルが作られた。問題を単純にするため、温室システムは土壌層、作物層、内部気層、ガラス壁またはビニール被膜、外部気層からなると考えた。温室環境に対する作物のフィードバック影響が組み込まれていて、内部の温度状態と湿度状態とが同時に計算できるようになっている。モデルの境界条件は、ハウス外の短波放射、下向きの長波放射、気温、湿度および風速で、すべて測定できる。このほかハウス内土層の水分ポテンシャルも用いられている。このシステムの特徴は、ハウスの大きさ、その熱的な性質、換気率および水分交換についての植物の生理的特徴によって表わされる。このような境界条件

およびシステム定数が与えられると、この温室モデルはハウス内の気温と湿度ばかりでなく、被覆面上の放射収支、顕・潜熱フラックス、熱貫流量および換気による顕・潜熱交換量も計算することができる。このほかに、植被面の放射収支、表面温度および作物の蒸散強度も計算できる。この温室モデルを用いて、温室内の気温と湿度に対するハウス換気回数の影響をしらべた。換気に伴う内部気温の変化は現在まで報告されている結果と定性的によく一致することがわかった。また、ハウスの熱収支特性の換気による変化がモデルを用いて研究された。換気によって、内壁面への水蒸気凝結量は急減するが、植被面の熱収支構造はほとんど変化しなかった。