Simple greenhouse climate model as a design tool for greenhouses in tropical lowland

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Received 22 March 2006;

accepted 30 March 2007.

Available online 5 July 2007.

Abstract

Six prototypes plastic greenhouses were built in the tropical lowlands of Indonesia. The geometrical dimensions were designed using computational fluid dynamics (CFD) by taking local climate parameters as static reference boundary conditions. It is necessary to evaluate the climate dynamics inside the greenhouse during varying climatological conditions. A greenhouse climate model was developed to optimise cover properties and ventilation rate as main parameters, calculating only three state variables: average greenhouse air temperature T_{Air}, average greenhouse air water vapour pressure (expressed as air water vapour pressure deficit D_{Air}), and average canopy temperature T_{Can}. Solar radiation distribution, air exchange by ventilation, and crop transpiration constituted the backbones of the model. The climate outdoor and inside the test greenhouses with crops having leaf area index from 0.02 to 4.10 were measured for one growing season. Measurements and calculations of T_{Air} and D_{Air} agreed satisfactorily, with less than 5% errors. It is concluded that the model is robust and could be used as a design tool for the tropical lowland greenhouses.

Nomenclature

A

area, m^2

C

coefficient

c

concentration, kg m^{-3}

c_p

specific heat of air, J kg^{-1} K^{-1}

D

water vapour pressure deficit, Pa

d

diagonal length of greenhouse floor, m

E

transpiration, kg m^{-2} s^{-1}

e

actual air water vapour pressure, Pa

e^*

saturation air water vapour pressure, Pa

F

aspect ratio

G

heat conductance, W m^{-2} Pa^{-1} (for the latent) or W m^{-2} K^{-1} (for others)

g

gravitational acceleration, m s^{-2}

H

heat exchange, W m^{-2}

h

average greenhouse height, m

I

transmitted radiation, W m^{-2}

K

sky clearness index

k

conductance of heat or mass, m s^{-1}

L

leaf area index, m^2 m^{-2}

l

length, m

M

molar weight, kg $kmol^{-1}$

O

light obstruction factor

P

absorbed solar radiation, W m^{-2}

R

universal gas constant, J $kmol^{-1}$ K^{-1}

r

resistance for heat transfer, s m^{-1}

S

outdoor global radiation, W m^{-2}

T

temperature, K

U

external wind speed, m s^{-1}

u

average wind speed inside greenhouse, m s^{-1}

w

width, m

κ

extinction coefficient

ϕ

airflow per unit ground area, m^3 s^{-1} m^{-2}

Φ

airflow, m^3 s^{-1}

Λ

calibration factor for indirect absorbed solar radiation

ς

ventilation reduction of the insect-proof screen

α

absorption coefficient

χ

characteristic width dimension of a leaf, m

δ

slope of the saturation air water vapour pressure function (Pa K^{-1})

ε

emission coefficient

γ

thermodynamic psychometric constant, Pa K^{-1}

λ

latent heat of water vaporization, J kg^{-1}

ρ

density of air, kg m^{-3}

σ

Stefan–Boltzmann constant, W m^{-2} K^{-4}

τ

transmission coefficient

ϒ

reflection coefficient

Subscripts

Air

greenhouse air

Can

canopy

CO_2

CO_2

CON

convection

Cov

greenhouse cover

d

discharge

dif

diffuse

dir

direct

e

boundary layer (external)

E

extraterrestrial

G

global

g

greenhouse ground

i

big leaf (internal)

LAT

latent

n

net

NIR

near-infrared radiation

o

ventilation opening

Out

outdoor

PAR

photosynthetically active radiation

r

roof opening

s

side opening

Scr

insect screen

Sky

sky

Str

greenhouse structural elements

LWR

long-wave radiation

UVR

ultra-violet radiation

VEN

ventilation

w

wind pressure

Article Outline

1. Introduction

Crop cultivation in tropical lowlands is subject to various stresses: heavy rainfall during the rainy season; water shortage during the dry season (Von Zabeltitz, 1999); and insect infestations. Cultivation in a greenhouse protects crops from these extremes. Protection against insect infestation requires the application of screens in the ventilating openings; however, these screens restrict natural ventilation needed to prevent high indoor air temperatures at the prevailing high levels of solar irradiation. Recently, with the adaptation of the optical properties of covering materials, it has become possible to reduce the thermal load of the greenhouse (Hoffmann & Waaijenberg, 2002; Hemming *et al.*, 2006). The problem is to find the optimal combination of restricted natural ventilation and adapted optical cover properties.

The objectives of this study are: (i) to evaluate the adaptation of the covering optical properties to lower the heat load in the greenhouse; (ii) to evaluate the effectiveness of natural ventilation, restricted by insect screens to remove excess heat from the greenhouse compartment; (iii) to evaluate the dynamic behaviours of the climate in the greenhouse during varying climatologic conditions; and (iv) to evaluate the growth of crop grown in the greenhouse with this dynamic behaviour.

This paper focuses on the development of a simple dynamic model for the greenhouse climate enabling the optimisation of the cover properties and ventilation rate. The model is required to quantify the effects of cover properties and ventilation on the greenhouse climate. The effect of crop transpiration is also considered because this is crucial in the cooling process.

The model was calibrated and validated in a field experiment in six prototype greenhouses in the tropical lowlands of Indonesia applying a reference cover. Effect of cover properties and ventilation will be presented in another paper. The geometry for optimal natural ventilation for the prototype greenhouses was previously designed applying computational fluid dynamics (CFD) with reference to local static climate conditions (Campen, 2005).

2. Model development

2.1. Basis of the model

Extensive greenhouse climate models with many state variables including heating and energy storage have been reported previously (Bot, 1983; De Zwart, 1996). The current model proposed is aimed at quantifying the effects of cover properties and ventilation on greenhouse air temperature, including the cooling effect of crop transpiration in unheated greenhouses. Therefore, the model was restricted to only the three state variables needed to evaluate the system: average greenhouse air temperature; average greenhouse air water vapour pressure; and average canopy temperature. Because the model is aimed at design at static conditions short term dynamics are not crucial so the model can be static, thereby following the dynamics of the outdoor weather.

The following assumptions are made: (i) the greenhouse is considered as a well-mixed compartment Roy et al. (2002); (ii) boundary conditions are outdoor solar radiation, outdoor air temperature and sky temperature; (iii) solar radiation imposes fluxes to the greenhouse cover, the greenhouse structural elements, the crop canopy, and the soil surface; (iv) the mentioned absorbed solar radiation fluxes are released (with some delay) for a determined part to the greenhouse air; and (v) the greenhouse cover is one thin plastic layer. Its optical properties are defined in the relevant spectral regions.

Then canopy and greenhouse air temperature follow from the steady state energy balances over the canopy and the greenhouse air respectively, as indicated in Fig. 1:

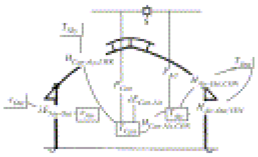
(1a)

$$0=P_{Can}-H_{Can\text{-}Sky,LWR}-H_{Can\text{-}Air,CON}-\lambda E_{Can\text{-}Air},$$

(1b)

$$0=P_{Air}+H_{Can\text{-}Air,CON}-H_{Air\text{-}Out,CON}-H_{Air\text{-}Out,VEN},$$

where: P_{Can} is the absorption of solar radiation by the canopy; $H_{Can–Sky,LWR}$ is the heat exchange between canopy and sky by long-wave radiation; $H_{Can–Air,CON}$ is the sensible heat exchange between canopy and greenhouse air by convection; $\lambda E_{Can-Air}$ is the latent heat flux by canopy transpiration; P_{Air} is the imposed indirect solar radiation flux to the greenhouse air (solar radiation absorbed by greenhouse opaque elements and released to the greenhouse air), $H_{Air-Out,CON}$ is the overall heat exchange between greenhouse and outdoor air through the plastic cover by convection; and $H_{Air-Out,VEN}$ is the sensible heat exchange between greenhouse and outdoor air by ventilation. All fluxes are in W m^{-2} greenhouse area.



Full-size image (20K)

Fig. 1. Representation of the state variables, fluxes, and boundary conditions: e_{Air} and e_{Out}, water vapour pressure of the greenhouse and outdoor air; T_{Can}, T_{Air}, T_{Out} and T_{Sky}, temperatures of the canopy, greenhouse air, outdoor air and sky; S, outdoor global radiation; P_{Can}, absorption of solar radiation by canopy; P_{Air}, imposed indirect solar radiation flux to the greenhouse air; $\lambda E_{Air-Out}$, latent heat exchange between greenhouse and outdoor air by ventilation; $\lambda E_{Can-Air}$, latent heat flux by canopy transpiration; $H_{Can-Sky,LWR}$, long-wave radiation exchange between canopy and sky; $H_{Air-Out,CON}$, overall heat exchange between greenhouse and outdoor air through the plastic cover; $H_{Can-Air,CON}$, sensible heat exchange between canopy and greenhouse air by convection; and $H_{Air-Out,VEN}$, sensible heat exchange between greenhouse and outdoor air by ventilation.

The heat transfer terms in the steady state balances are a function of the acting temperature differences, so the basic equation for canopy temperature is derived from Eq. (1a) as

(2a)

$$0=P_{Can}-G_{Can-Sky,LWR}(T_{Can}-T_{Sky})-G_{Can-Air,CON}(T_{Can}-T_{Air})-\lambda E_{Can-Air},$$

where: $G_{Can-Sky,LWR}$ is the heat conductance (transfer coefficient) between canopy and sky by long-wave radiation in W m^{-2} K^{-1}; $G_{Can-Air,CON}$ is the heat conductance between crop and greenhouse air by convection in W m^{-2} K^{-1}; T_{Can}, T_{Sky}, and T_{Air} are the temperatures of the crop, the sky, and the greenhouse air, respectively, in K.

The basic equation for greenhouse air temperature is derived from Eqn (1b):

(2b)

$$0=P_{Air}+G_{Can-Air,CON}(T_{Can}-T_{Air})-G_{Air-Out,CON}(T_{Air}-T_{Out})-G_{air-Out,VEN}(T_{Air}-T_{Out}),$$

where: $G_{Ai\text{–}Out,CON}$ is the overall sensible heat conductance between the greenhouse and outdoor air via the plastic cover by convection in W m^{-2} K^{-1}; $G_{Air\text{–}Out,VEN}$ is the sensible heat conductance between greenhouse and outdoor air by ventilation in W m^{-2} K^{-1}; and T_{Out} is the outdoor air temperature in K.

The state variable actual greenhouse air water vapour pressure e_{Air} in Pa, needed for the sub-model on crop transpiration, can be calculated from the latent heat balance over the greenhouse air:

(2c)

$$0=G_{Air\text{-}Out,LAT}(e_{Air}-e_{Out})-\lambda E_{Can\text{-}Air}(S,T_{Air},T_{Can},e_{Air}),$$

where: $G_{Air-Out,LAT}$ is the latent heat conductance by ventilation in W m^{-2} Pa^{-1}; e_{Out} is the actual outdoor air water vapour pressure in Pa; and S is the outdoor global radiation in W m^{-2}.

2.1.1. Solar radiation distribution

Distribution of solar radiation determines the first terms in the model Eqs. (2a) and (2b). Direct *dir* and diffuse *dif* components of the S distribute differently. According to Spitters *et al*. (1986), they are calculated as a function of the ratio between S and extraterrestrial radiation S_E with S_E, being calculated according to Allen *et al*. (1998). All radiation is in W m^{-2}.

Another important item is the spectral distribution. According to the Global Spectral Irradiance ASTM G173-03 (2003), the reference total global energy is partitioned into ultra violet radiation (UVR) (4.6%), photosynthetically active radiation (PAR) (43.4%), and near infrared radiation (NIR) (52.0%). The partition would vary slightly with meteorological conditions but a fixed ratio is chosen as given in brackets.

To allow evaluation of the effect of the radiometric properties of the reference cover used in the prototype greenhouse, they are defined in terms of transmission τ, absorption α, and reflection Υcoefficients for the spectral regions of UVR, PAR, and NIR; and for the radiation components of diffuse and direct (Table 1). The greenhouse transmission coefficient for the direct PAR spectrum $\tau_{PAR,dir}$ is calculated by ray-tracing (Swinkels *et al*., 2000) as a function of solar position (elevation and azimuth) as given in Table 2. The factor $\tau_{PAR,dir}$ is used to determine the greenhouse transmission for the whole spectrum of global radiation.

Table 1.

Transmission τ absorption α, and reflection Υcoefficients for the reference plastic cover, ASTM G173–03 weighted

	Diffuse			Direct ⊥		
	UVR	**PAR**	**NIR**	**UVR**	**PAR**	**NIR**
τ	**0.136**	0.765	0.758	**0.159**	**0.896**	**0.888**
α	**0.681**	0.052	0.052	0.658	0.052	0.052
γ	**0.183**	0.183	0.190	0.183	0.052	0.060

Bold values were measured, the others estimated.

UVR, ultra-violet radiation; PAR photosynthetically active radiation; NIR near-infrared radiation.

Table 2.

Photosynthetically active radiation transmission coefficient of the greenhouse covering structure as a function of azimuth and elevation calculated with MatLight model (Swinkels *et al*., 2000)

Azimuth, degree	**Elevation, degree**										
	0	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0	0.000	2.542	1.586	1.068	0.844	0.747	0.696	0.648	0.624	0.607	0.601
10	0.000	2.583	1.595	1.060	0.840	0.745	0.693	0.646	0.623	0.606	0.601
20	0.000	2.578	1.585	1.056	0.839	0.747	0.692	0.646	0.623	0.605	0.602

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Azimuth, degree	Elevation, degree										
	0	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
30	0.000	2.521	1.554	1.024	0.825	0.742	0.687	0.646	0.624	0.606	0.602
40	0.000	2.398	1.479	0.982	0.805	0.735	0.679	0.645	0.625	0.604	0.601
50	0.000	2.205	1.373	0.923	0.780	0.716	0.670	0.642	0.622	0.606	0.602
60	0.000	1.967	1.249	0.862	0.750	0.695	0.662	0.639	0.621	0.604	0.602
70	0.000	1.698	1.112	0.808	0.717	0.678	0.652	0.634	0.618	0.605	0.601
80	0.000	1.415	0.993	0.767	0.692	0.659	0.645	0.631	0.617	0.605	0.601
90	0.000	1.277	0.952	0.763	0.688	0.659	0.645	0.632	0.619	0.607	0.602

The absorbed solar radiation by the greenhouse cover P_{Cov} and by the greenhouse structural elements P_{Str} (both in W m^{-2} as all fluxes given below) are defined as

(3)

$$P_{Cov}=\alpha_{Cov,UVR,dif}S_{UVR,dif}+\alpha_{Cov,UVR,dir}S_{UVR,dir}+\alpha_{Cov,PAR,dif}S_{PAR,dif}+\alpha_{Cov,PAR,dir}S_{PAR,dir}+\alpha_{Cov,NIR,dif}S_{NIR,dif}+\alpha_{Cov,NIR,dir}S_{NIR,dir},$$

$$P_{Str}=\alpha_{Str}(\tau_{UVR,dif}S_{UVR,dif}+\tau_{UVR,dir}S_{UVR,dir}+\tau_{PAR,dif}S_{PAR,dif}+\tau_{PAR,dir}S_{PAR,dir}+\tau_{NIR,dif}S_{NIR,dif}+\tau_{NIR,dir}S_{NIR,dir}),$$

where for example: $\alpha_{Cov,PAR,dir}$ is the absorption coefficient of greenhouse cover in the direct PAR spectrum; $S_{PAR,dir}$ is the direct component of global radiation in the PAR spectrum; α_{Str} is the absorption coefficient of the greenhouse structural elements, not being spectral selective and assumed equal for diffuse and direct solar radiation; and $\tau_{UVR,dif}$ is the greenhouse transmission coefficient for the diffuse UVR spectrum.

The transmitted radiation by the greenhouse is given with an example for the PAR I_{PAR}:

(4)

$I_{PAR,dif}=(1-a_{Str})\{(1-O_{Scr})(\tau_{PAR,dif}S_{PAR,dir})+O_{Scr}S_{PAR,dif}\tau_{PAR,dif}\tau_{Scr,dif}\}, I_{PAR,dir}=(1-a_{Str})(\tau_{PAR,dif}S_{PAR,dir}), I_{PAR}=I_{PAR,dif}+I_{PAR,dir},$

where: $I_{PAR,dif}$ and $I_{PAR,dir}$ are the transmitted radiation by the greenhouse for diffuse and direct PAR, respectively; O_{Scr} is the light obstruction factor of the insect screen; and $\tau_{Scr,dif}$ is the diffuse radiation transmission coefficient of the insect screen.

The greenhouse transmissions for the UVR I_{UVR} and for the NIR I_{NIR} are calculated in a similar way as done for the I_{PAR}. The transmission of the global radiation by the greenhouse I_G is then calculated as

(5)

$I_G=I_{UVR}+I_{PAR}+I_{NIR}.$

Absorption of diffuse solar radiation by the canopy is calculated according to Goudriaan and Van Laar (1994):

(6)

$$P_{PAR,Can} = (1-0.057)\{1-\exp(-0.715L)\}I_{PAR},$$
$$P_{NIR,Can} = (1-0.389)\{1-\exp(-0.358L)\}I_{NIR},$$
$$P_{Can} = P_{PAR,Can} + P_{NIR,Can},$$

where: $P_{PAR,Can}$ and $P_{NIR,Can}$ are the absorption of PAR and NIR by the canopy, respectively; and L is the leaf area index in $m^2\ m^{-2}$.

Following the notations in the model, P_{Air} is determined as:

(7)

$P_{Air}=\Lambda\{P_{Cov}+P_{Str}+(I_G-P_{Can})\},$

where: Λ is the calibration factor for indirect absorbed solar radiation indicating the part of the radiation absorbed by the greenhouse cover (P_{Cov}), structural elements (P_{Str}) and soil surface ($I_G - P_{Can}$) released to the air.

2.1.2. Ventilation process

For the tropical lowland greenhouse, the ventilation process is crucial in realising an acceptable indoor climate. CFD modelling (Campen, 2005) for the design of the test prototype greenhouse indicated that both continuous sidewall and roof top ventilation were needed for sufficient ventilation efficiency with insect screens in the openings. For such greenhouse, the general ventilation principles can be applied (Bot, 1983; De Jong, 1990; Boulard & Baille, 1995), keeping in mind the greenhouse-specific aspects.

The geometry of a single rectangular opening is defined by its length l_o and width w_o, both in m (Bot, 1983). For the total greenhouse, half of the openings are for inflow and half are for outflow so the effective opening area equals 0.5 A_o with A_o being the total ventilation opening in the greenhouse in m^2 (Bot, 1983; Boulard & Baille, 1995). The flow resistance can be expressed in the aspect ratio F_o (Bot, 1983) or the discharge coefficient C_d (Boulard & Baille, 1995; Roy *et al.*, 2002) with $C_d=F_o^{-0.5}$. Bot (1983) experimentally determined the aspect ratio for a rectangular opening without flaps as

(8)

$$F_o = 1.75 + 0.7\exp\{-(l_o/w_o)/32.5\}.$$

The combined pressure difference over the opening due to the wind and temperature effect drives the airflow through the opening Φ_{VEN} in m^3 s^{-1} as extensively reported in literature (Bot, 1983; De Jong, 1990; Boulard & Baille, 1995; Roy *et al.*, 2002). Therefore, for greenhouses with both side and roof openings and applying C_d for the flow resistance of the opening it was derived that (Roy *et al.*, 2002)

(9)

$$\Phi_{VEN} = C_d\{((2g((A_s A_r)^2/(A_s^2 + A_r^2))(T_{Air} - T_{Out})/T_{Out}) + ((A_s + A_r)/2)^2(C_w U^2)\}^{0.5},$$

where: g is the gravitational acceleration in m s^{-2}; A_s is the area of side opening in m^2; A_r is the area of roof opening in m^2; C_w is the wind pressure coefficient; and U is the external wind speed at 10 m reference height in m s^{-1}.

If greenhouse air temperature is lower than outdoor air temperature, the air is stagnant so the temperature effect can be neglected:

(10)

$$\Phi_{VEN} = 0.5(A_s + A_r)\, C_d\, C_w 0.5\, U.$$

The coefficient C_w is greenhouse dependent while it relates the reference wind speed to the ventilation driving pressure difference over the opening. Therefore the geometry of the greenhouse, the obstacles near the greenhouse and wind direction play a role. A number of investigations provide a wide range of C_w values (Boulard & Baille, 1995; Fatnassi *et al*., 2004).

When the ventilation reduction ς of the insect-proof screen is known, the airflow through the opening with screen $\Phi_{Scr,VEN}$ in m^3 s^{-1} is estimated as:

(11)

$$\Phi_{Scr,VEN}=\Phi_{VEN}(1-\zeta).$$

The airflow per unit ground area from the greenhouse air to the outdoor air φ_{VEN} in m^3 s^{-1} m^{-2} and the average wind speed inside the greenhouse u in m s^{-1} are defined as:

(12a)

$$\phi_{VEN}=\Phi_{Scr,VEN}/A_g,$$

(12b)

$$u=\Phi_{Scr,VEN}/(h\,d),$$

where: A_g is the greenhouse ground area in m^2; h is the average greenhouse height in m; and d is the diagonal length of greenhouse floor in m.

2.1.3. Crop transpiration

Crop transpiration is calculated according to the Penman–Monteith (P–M) evaporation model. The P–M model, sometimes referred to as 'big leaf' model, is based on the overall energy balance over the crop with large leaf area index:

(13)

$$\lambda_{ECan-Air}=(\delta_{Air}I_n+\rho c_p D_{Air}k_e)/\{\delta_{Air}+\gamma(1+k_e/k_i)\},$$

where: δ_{Air} is the slope of the saturated air water vapour pressure function at greenhouse air temperature in Pa K^{-1}; I_n is the net radiation at the canopy in W m^{-2}; $\rho\ c_p$ is the volumetric specific heat of air in J m^{-3} K^{-1}; D_{Air} is the water vapour pressure deficit of the greenhouse air in Pa; γ is the thermodynamic psychometric constant in Pa K^{-1}; k_e and k_i are the boundary layer (external) conductance and the big leaf (internal) conductance in m s^{-1}. Note that $I_n=P_{Can}-H_{Can-Sky,LWR}$.

Value of k_e is approximated according to Stanghellini (1987):

(14a)

$$k_e=2L/r_e,$$

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(14b)

$$r_e = 1174\,\chi^{0.5}/\{(c|T_{Can} - T_{Air}| + 207\,u^2)^{0.25}\},$$

where: L is the leaf area index in $m^2\ m^{-2}$; r_e is the leaf boundary layer resistance for the heat transfer in $s\ m^{-1}$; and χ is the characteristic dimension of a leaf in m. Stanghellini included factor of 2 L to make the k_e suitable for the P–M model.

Value of k_i is approximated according to Nederhoff (1994):

(15)

$$k_i = 0.0203\,\{1 - 0.44\exp(-2.5 \times 10^{-3}\,I_{PAR})\}\\ \exp(-3.1 \times 10^{-4}\,c_{CO_2}),$$

where: c_{CO2} is the ambient CO_2 concentration, expressed here in ppm. Here, I_{PAR} is expressed in μ mol $s^{-1}\ m^{-2}$. The conversion for PAR is 1 W m^{-2}=4.5 μmol $s^{-1}\ m^{-2}$.

2.2. Parameter estimations

Most model parameters can be estimated from literature. The long-wave radiative heat conductance between canopy and sky is calculated as function of crop development according to De Zwart (1996):

(16)

$$G_{Can-Sky,LWR} = 4\{(T_{Can} + T_{Sky})/2\}^3\,\varepsilon_{Can,LWR}\sigma\\ \times \{1 - \exp(-\kappa_{Can,LWR}L)\}\tau_{Cov,LWR},$$

where: $\varepsilon_{Can,LWR}$ is the long-wave radiation emission coefficient of the canopy; σ is the Stefan–Boltzmann constant; $\kappa_{Can,LWR}$ is the long-wave radiation extinction coefficient of the canopy; and $\tau_{Cov,LWR}$ is the long-wave radiation transmission coefficient of the cover.

The sensible heat conductance between the canopy and the air is related to the boundary layer conductance for water vapour transport according to (De Zwart, 1996):

(17)

$$G_{Can-Air,CON} = 2L\rho c_p/r_e.$$

Leaves exchange sensible heat at both sides of the leaf so the exchange area equals 2 L.

The overall sensible heat conductance between the greenhouse and outdoor air via the cover for a single span plastic greenhouse can be considered as dependent on external wind speed due to the external convection (Boulard & Baille, 1993; Boulard & Wang, 2000) as:

(18)

$$G_{Air-Out,CON} = 6 + 0.5\,u.$$

The sensible and latent heat conductance between the greenhouse and outdoor air via ventilation openings are given as

(19)

$$G_{Air-Out,VEN} = \rho c_p \phi_{VEN},$$

(20)

$$G_{Air-Out,LAT} = \lambda M \varphi^{VEN} / RT,$$

where: M is the molar weight of water in kg kmol^{-1}; R is the universal gas constant in J kmol^{-1} K^{-1}; and T is the air temperature in K.

Temperature of the sky for all sky conditions is according to Aubinet (1994)

(21)

$$T_{Sky} = 94 + 12.6\ln(e_{Out}) - 13K + 0.341\,T_{Out},$$

where: K is the sky clearness index and is the average value of the ratio between S and S_E for the given day.

The saturation air water vapour pressure e^* in Pa as a function of air temperature (NASA, 2005) and slope of the saturation air water vapour pressure function δ in Pa K^{-1} are given as:

(22a)

$$e^* = 2.229 \times 10^{11} \exp(-5385/T),$$

(22b)

$$\delta = (5385/T^2) 2.229 \times 10^{11} \exp(-5385/T).$$

3. Experimental details

3.1. Experimental site and test greenhouse dimensions

Six greenhouses having the same dimensions (Fig. 2) according to Campen (2005) were built in Purwakarta (107°30′E, 630′S, altitude 25 m), West Java, Indonesia for field experimentation. The greenhouses were covered with three types of 200 µm thick low-density polyethylenes, UVR absorbing and diffusing, differing in NIR reflection. Two rows of three greenhouses were arranged, the distance between the greenhouses within the rows was 9.6 m and the distance between the rows was 10 m.

 Full-size image (30K)

Fig. 2. Photograph of the greenhouses in the field.

Ventilation openings were available in the sidewalls with width of 2.75 m. In the roof, the width of the horizontal ventilation opening below the lifted cover was 2 m. The ground area of the greenhouse was 144 m^2, the volume was estimated to be 823 m^3, average height was 5.72 m and average roof angle was 27.5°. All ventilation openings were covered with Mononet 600 insect screens.

3.2. Crop, cultural procedures, leaf area index and transpiration measurements

Tomato of a determinant growing type (variety ‘Permata’) was grown in the six test greenhouses. Five beddings, all covered with plastic mulch (silver colour upside, black downside), were prepared in each greenhouse allowing excess irrigation water to drip via a 0.076 m gutter made of half-polyvinyl chloride (PVC) pipe to the drainage collector placed outdoor each greenhouse. Each tomato plant was grown on a black polybag. The crops were transplanted at a leaf area index of 0.02 and cultivated according to the high-wire system. The crops were arranged in a double-row system with a plant density of 2.94 m^{-2}.

Destructive samples were taken regularly with a 2 week interval. Specific leaf area was determined from measurement of leaf area and its corresponding dry weight, and thus the leaf area index was deduced. Crop transpiration during daytime (06:30–17:15) at a leaf area index of 1.39 was measured for 2 successive days at day of year (DOY) 322 and 323 by manually weighing and solving the water balance between irrigation and drainage from a total of 18 plants.

3.3. Measurement of climate

Global radiation and PAR were measured at a height of 4 m inside three greenhouses and outdoors using 4 pyranomters (CM11, Kipp and Zonen, Delft, The Netherlands) and 4 PAR sensors (TFDL, Wageningen, The Netherlands). Indoor sensors were mounted at a position meant not to be constantly shaded by the insect screens in the roof opening. Air temperature, and air relative humidity were measured by dry and wet bulb ventilated hygrometers (Priva Hortimation, De Lier, The Netherlands) inside all greenhouses at a height of 1.5 m at the start of the experiment and with growing crop at 25 cm above the crop, and outdoors at a height of 1.5 m. Outdoor wind velocity was measured at a height of 10 and 2 m by cup anemometers.

All sensors were connected to two data loggers (Datataker 500, Data Electronics, Rowville, Australia). These data loggers scanned all signals every 1 s and computed 15 min averages for logging. Daily rainfall was measured manually using a rainfall gauge.

4. Results and discussion

All reported results are based on data collected in the greenhouse with reference cover during one growing season, from 23 October 2003 to 27 January 2004 with outdoor climate as summarised in Table 3. Two sets of data were discriminated (Table 4). Each data set represented seven individual days with various conditions of crop growth and weather so that the model was calibrated and validated on independent extensive boundary conditions. In the model, Eqs. (2a), (2b) and (2c) were iteratively solved to calculate the state variables T_{Air}, e_{Air} and T_{Can}. Moreover, I_G and I_{PAR} were calculated from the radiation data. The variables, except T_{Can}, were also measured. Accuracy of model results was evaluated using percent error of the mean values and root-mean-square error (RMSE).

Table 3.

Summary of climatic condition during the experiment, for months of October, November, December 2003 and January 2004

	Average or instantaneous value			
	October	**November**	**December**	**January**
Rainfall, mm month^{-1}	23	117	156	235
Sum S, MJm^{-2} d^{-1}	18.7	17.5	15.3	16.9

	Average or instantaneous value			
	October	**November**	**December**	**January**
Maximum sum S, MJ m^{-2} d^{-1}	24.6	22.7	22.6	23.3
Maximum S, W m^{-2}	1134	1070	1084	1188
Clearness of sky, %	48	44	40	44
Sum PAR, MJ m^{-2} d^{-1}	8.4	7.6	6.8	7.2
Wind speed, m s^{-1}	1.6	1.4	1.7	1.4
Maximum wind speed, m s^{-1}	8.33	6.45	5.73	5.41
Temperature maximum, °C	34.2	33.1	32.2	32.1
Temperature minimum, °C	23.4	24.0	23.7	23.6
RH maximum, %	95.1	97.0	96.3	98.0
RH minimum, %	46.1	40.7	34.5	35.2
D_{Out} maximum, kPA	2.75	2.23	1.86	1.78
D_{Out} minimum, kPA	0.98	0.77	0.69	0.58

S, outdoor global radiation; PAR, photosynthetically active radiation; RH, outdoor air relative humidity; D_{Out}, outdoor air water vapour pressure deficit.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6WXV-4P481W4-2&_user=6763742&_coverDate=09%2F30%2F2007&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1366521828&_rerunOrigin=scholar.google&_acct=C000070526&_version=1&_urlVersion=0&_userid=6763742&md5=63e1e038d8e8c0ee0c7a3295c290673e

Table 4.

List of the data used for model calibration and model validation

	2003					2004	
Model Calibration	**1**	**2**	**3**	**4**	**5**	**6**	**7**
DOY	296	322	336	350	364	13	27
Measured L	0.02	1.39	2.42	2.60	2.89	3.45	4.10
Model validation	1	2	3	4	5	6	7
DOY	302	316	330	344	358	7	21
Estimated L	0.07	0.81	2.15	2.53	2.75	3.18	3.84

DOY, day of year; *L*, leaf area index.

The ventilation submodel was parameterised with the CFD results (Campen, 2005) applying Econet SF insect screen. This screen has a ventilation reduction of 0.44 (Ajwang & Tantau, 2005). Meanwhile the ventilation reduction of the Mononet 600 used in the experimental prototype greenhouse was determined to be 0.40. Accordingly, values for C_w of 0.04 and average u of 0.10 m s^{-1} were derived. With values for χ of 0.05 m, and T_{Can}–T_{Air} of 2 K (Stanghellini, 1987), the calculated value for $G_{Can-Air,CON}$ is 11.2 L W m^{-2} K^{-1} in the crop transpiration model. The other parameters for the model are given in Table 5.

Table 5.

Values of parameters used in the model

Parameter	Value	Description
Plastic cover		
Thermal transmission $\tau_{cov,LWR}$	0.3845	Measured
Insect screens		
Transmission for diffuse $\tau_{Scr,dif}$	0.765	Deduced from comparable screens
Transmission for direct $\tau_{\mathrm{Scr,dir}}$	0.882	Deduced from comparable screens
Ventilation reduction ζ	0.40	Measured
Greenhouse		
Width, side ventilation $w_{o,s}$, m	2× 2.75	By design
Length, side ventilation $l_{o,s}$, m	2×24.6	By design
Width, roof ventilation $w_{o,r}$, m	2	By design
Length, roof ventilation $l_{o,r}$, m	15	By design
Volume, m^3	823	By design
Floor area, m^2	144	By design
Average height h, m	5.7	By design
Diagonal length d, m	17.8	By design
Structural absorption α_{Str}	0.03	De Zwart (1996), modified

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Parameter	Value	Description
Screen absorption α_{Scr}	0.04	De Zwart (1996)
Screen light obstruction O_{Scr}	0.21	By design
Wind pressure coefficient C_w	0.04	Campen (2005), CFD calibrated
Discharge coefficients		
Side ventilation $C_{d,s}$	0.662	Bot (1983); calculated
Roof ventilation $C_{d,r}$	0.676	Bot (1983); calculated
Crop canopy coefficients		
Thermal extinction $\kappa_{Can,LWR}$	0.64	Stanghellini (1987)
PAR extinction $\kappa_{Can,PAR}$	0.715	Goudriaan and Van Laar (1994)
PAR reflection$\kappa_{Can,PAR}$	0.057	Goudriaan and Van Laar (1994)
NIR extinction $\kappa_{Can,NIR}$	0.358	Goudriaan and Van Laar (1994)
NIR reflection $\kappa_{Can,NIR}$	0.389	Goudriaan and Van Laar (1994)
Thermal emission $\varepsilon_{Can,LWR}$	0.987	Sugita *et al.* (1996)

PAR, photosynthetically active radiation; NIR, near-infrared radiation; CFD, computational fluid dynamics.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6WXV-4P481W4-2&_user=6763742&_coverDate=09%2F30%2F2007&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1366521828&_rerunOrigin=scholar.google&_acct=C000070526&_version=1&_urlVersion=0&_userid=6763742&md5=63e1e038d8e8c0ee0c7a3295c290673e

4.1. Calibration of the model

Measured and computed radiation data were in close agreement (Fig. 3). However, at midday during clear days with high direct radiation level a difference was observed. Interaction between direct radiation and greenhouse construction elements (structure, plastics, and screens) produces unevenness in the shadow patterns inside the greenhouse. One stationary radiation instrument placed inside the greenhouse then deviates from the average.

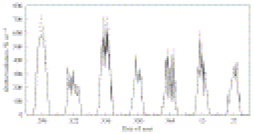 Full-size image (29K)

Fig. 3. Model calibration for 7 non-successive days. Time courses of the global radiation transmission through the greenhouse: ——, measured; - - - - - -, calculated.

Several tests revealed that only a small part of the solar radiation absorbed by the opaque elements of the greenhouse, as expressed in Eq. (2b), was released to the greenhouse air. Therefore, a value of 0.1 for the calibration factor Λ, as applied in Eq. (7), fitted best for the data set with leaf area index ranging from 0.02 to 4.1. The use of a value for Λ of 0.1 for an extensive range of leaf area index is helpful, because it allows the simple model to be suitable for various climatic conditions independently from growth stages. The value for Λ of 0.1 was related to the naturally ventilated plastic greenhouse with a high coupling between the greenhouse and the outdoor climatic conditions.

The agreement between the measured and calculated state variables T_{Air}, and e_{Air} (expressed as vapour pressure deficit D_{Air}) was evident during 5 out of the 7 days used for the model calibration (Fig. 4). The error observed at DOY 350 could be related to an error on the measured T_{Out}, whilst the errors observed at DOY 364 could be related to an error on the measured e_{Air}. The behaviour of the computed T_{Can} (Fig. 4) was comparable to the T_{Can} reported by other researchers (Yang *et al*., 1990; Boulard & Baille, 1993; Papadakis *et al*., 1994).

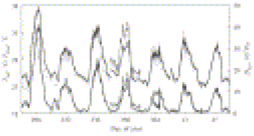 Full-size image (39K)

Fig. 4. Model calibration for 7 non-successive days. (Upper graph) Time courses of the greenhouse air temperature T_{Air}: , measured; ——, calculated; canopy temperature T_{Can}: - - - - - -, calculated; (Lower graph) time courses of the greenhouse air water vapour pressure deficit D_{Air}: , measured; ——, calculated.

The measured and calculated cumulative daytime transpiration fluxes on the two successive days they were measured, were comparable (measured 1.57 and 1.59 mm; calculated 1.78 and 1.58 mm, respectively). This indicates that applying k_e of Stanghellini (1987) and k_i of Nederhoff (1994) in the P–M model was justified.

4.2. Validation of the model

For the validation data set (Table 4) the model calculated I_G and I_{PAR} and the state variables T_{Air}, D_{Air} (Fig. 5) satisfactorily. The errors were less then 5% with RMSE of 42 W m^{-2} for I_G, 17 W m^{-2} for I_{PAR}, 0.39 °C for T_{Air}, and 0.10 kPa for D_{Air} (Table 6). Scatter plot of the measured and computed T_{Air} and D_{Air} (Fig. 6) shows that the calculated and measured data were well represented around the 1:1 line. Therefore, we can conclude that the simple model is capable of representing the greenhouse behaviour satisfactorily.

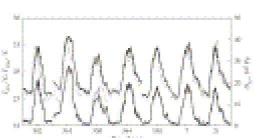 Full-size image (38K)

Fig. 5. Model validation for 7 non-successive days. (Upper graph) Time courses of the greenhouse air temperature T_{Air}: , measured; ——, calculated; canopy temperature T_{Can}: - - - - - -, calculated; (Lower graph) time courses of the greenhouse air water vapour pressure deficit D_{Air}: , measured; ——, calculated.

Table 6.

Mean values of the measured and computed transmission of global and photosynthetically active radiation by the greenhouse I_G and I_{PAR}, and the air temperature and water vapour deficit in the greenhouse T_{Air}, and D_{Air} and their corresponding values for the per cent error and root-mean-square error (RMSE)

	Measured	Calculated	Percent error	RMSE
I_G, W m^{-2}	150	142	5	42
I_{PAR}, W m^{-2}	67	64	4	17
T_{Air}, °C	27.28	27.17	0.4	0.36
D_{Air}, kPa	0.73	0.72	2.4	0.10

Number of data −762.

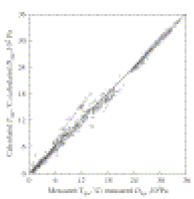
Full-size image (23K)

Fig. 6. Model validation for 7 non-successive days. Calculated versus measured: □, greenhouse air water vapour pressure deficit D_{Air}; ○, greenhouse air temperature T_{Air}.

4.3. Application of the model

The radiation distribution submodel is capable to calculate radiation transmission by the greenhouse including reduction of NIR transmission through the cover. Variation in greenhouse dimension and ventilation openings closely corresponds to variation in airflow through the openings, which can be quantified in the ventilation submodel. The effect of the crop is evaluated in the transpiration submodel. Each submodel is uniquely simulating effects of variation of their corresponding parameters on the state variables. With these features, the model is applicable for: (i) evaluating the effects of ventilation, cover properties, and crop transpiration on the inside greenhouse climate; and (ii) designing an optimal tropical lowland greenhouse based on the selection of the greenhouse dimensions (floor area, volume, ventilation area) and the covering material properties.

5. Conclusions

A simple dynamic climate model was developed enabling the calculation of three state variables: average greenhouse air temperature; average greenhouse air water vapour pressure and average canopy temperature. The model was parameterised, calibrated, and validated thoroughly. A consistent performance of the model was observed, both in the calibration and validation stage. All calculation errors were less than 5% of the measured mean values. It is concluded that the model is robust and could be used as a design tool for the tropical lowland greenhouse, optimising especially cover properties and ventilation. However, the size and geometry of the ventilation openings realising the designed ventilation has to be determined subsequently by, e.g. CFD modelling.

Acknowledgements

The Dutch Ministry of Economic Affairs provided financial support for the project. The greenhouses were built and financed by Rovero Systems B.V., The Netherlands. The plastic films were developed by Oerlemans Plastic B.V./Plasthill B.V., The Netherlands. PT East West Seed Indonesia provided the experimental site, the crop and cultivation materials and skilled technical assistance for the maintenances and samplings throughout the field experimentation.

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