Computers and Electronics in Agriculture 142 (2017) 9–28

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Development of a single energy balance model for prediction of temperatures inside a naturally ventilated greenhouse with polypropylene soil mulch

Audberto Reyes-Rosas, Francisco D. Molina-Aiz *, Diego L. Valera, Alejandro López, Sasirot Khamkure

Research Centre CIAIMBITAL, University of Almería, Ctra. Sacramento s/n, 04120 Almería, Spain

ARTICLE INFO

Article history:
Received 11 June 2017
Received in revised form 7 August 2017
Accepted 21 August 2017
Available online 1 September 2017

Keywords:
Greenhouse
Dynamic model
Natural ventilation
Thermal analysis
Plastic mulch

ABSTRACT

In this study, a semi-empirical dynamic model of energy balance was developed to predict temperatures (air, plants, greenhouse cover and soil) in a naturally ventilated greenhouse with a polypropylene mulch covering the soil in a Mediterranean climate. The model was validated using experimental data of 5 non-successive periods of 5 days throughout the crop season in the province of Almería (Spain). During the evaluation period, the transmissivity of the cover ranged between 0.44 and 0.80 depending on whitening, and the leaf area index of the tomato crops growing inside the greenhouse varied from L_{AI} = 0.74 to 1.30 $m^2\ m^{-2}$. The model mainly consists of a system of 6 non-linear differential equations of energy conservation at inside air, greenhouse plastic cover, polypropylene mulch and three layers of soil. We used multiple linear regressions to estimate the crop temperature in a simple way that allows a reduction in the number of parameters required as input. The main components of the energy balance in warm climate conditions are the solar radiation, the heat exchanged by natural ventilation and the heat stored in the soil. To improve the estimation of the heat exchanged by ventilation, different discharge coefficients were used for roof C_{dVR} and side openings C_{dVS}. Both coefficients changed throughout the time as a function of the height and opening angle of the windows and of the air velocity across the insect-proof screens. The model also used different wind effect coefficients C_w for Northeast or Southwest winds, to take into account the different obstacles (a neighbouring greenhouse at the south and a warehouse at the north). A linear regression of the wind direction angle θ_w was used as correction function for the volumetric ventilation flux *G*. The results showed that the accuracy of the model is affected mainly by errors in the cover transmissivity on cloudy days (when diffuse radiation prevails) and errors in the temperature of air exiting the greenhouse on windy days (when hot air stagnated near roof openings, that were closed by the climate controller to avoid wind damage). In general, the results of validation comparing calculated values with those measured on 25 days (with relative root mean square errors below 10%), show sufficient accuracy for the model to be used to estimate air, crop, plastic cover, polypropylene mulch and soil temperatures inside the greenhouse, and as a design tool to optimise the ventilation system characteristics and control settings.

1. Introduction

Greenhouses currently constitute the main system to produce high-yield and high-quality horticultural crops almost all year round in the Mediterranean region. Mild winter climatic conditions have allowed the development of more than 278,000 ha of low-plastic tunnel and greenhouses in the Mediterranean region (FranceAgriMer, 2013; Tüzel and Öztekin, 2015), making this the second largest zone in the world after Asia, which is come to more than 4.7 million ha of protected vegetable (Kang et al., 2013; Yang et al., 2014).

Spain had about 52,325 ha of greenhouses in 2014, 21,042 ha of which were occupied by tomato crops (MAGRAMA, 2014). The greatest concentration of greenhouses in the Mediterranean region is located in the province of Almería on the southeast coast of Spain, where a recent satellite imagery analysis put the greenhouse surface area at 30,007 ha (CAPDR, 2016).

Average tomato production in Almería's unheated greenhouses is around 17 kg m^{-2}, with some growers reaching yields of about 21 kg m^{-2} (Valera et al., 2016). These values are below the 55 kg m^{-2} obtained in the high-tech greenhouses of Northern Europe

* Corresponding author.
E-mail address: fmolina@ual.es (F.D. Molina-Aiz).

http://dx.doi.org/10.1016/j.compag.2017.08.020
0168-1699/

Nomenclature

Alphabetic symbols

C_{dVR}	roof vent discharge coefficients (–)
C_{dVS}	side vent discharge coefficients (–)
C_{dHLj}	discharge coefficient of the unscreened openings j (–)
$C_{d\varphi}$	discharge coefficient of the insect proof screens (–)
c_{pa}	specific heat of the air inside the greenhouse (J kg^{-1} K^{-1})
c_{pc}	specific heat of the greenhouse cover material (J kg^{-1} K^{-1})
c_{sjk}	specific heat of the soil between deeps z_j and z_k (J kg^{-1} K^{-1})
c_{spm}	specific heat of the polypropylene mulch (J kg^{-1} K^{-1})
C_w	wind effect coefficient (–)
D_r	thread density or number of thread per centimetre in each direction (threads cm^{-1} × threads cm^{-1})
e_c	cover thickness (m)
e_{sjk}	soil layer thickness between depth z_j and z_k (m)
e_{scr}	insect-proof screen thickness (m)
e_{spm}	polypropylene mulch sheet thickness (m)
E_{xy}	precision of measurement of the thickness (μm)
f_G	ventilation flux correction coefficient (–)
F_φ	pressure loss coefficient of the insect-proof screen (–)
g	gravitational constant (m s^{-2})
G	volumetric ventilation flow (m^3 s^{-1})
h_{ci}	convective heat transfer coefficient between interior air and greenhouse cover (W m^{-2} K^{-1})
h_{co}	outside air-cover convective coefficient (W m^{-2} K^{-1})
h_{si}	inside air-cover convective coefficient (W m^{-2} K^{-1})
H_{SR}	vertical distance between the midpoint of side and roof openings (m)
h_{vi}	convective heat transfer coefficient between interior air and plant leaves (W m^{-2} K^{-1})
k_L	extinction coefficient for conical leaves distribution (–)
K_p	insect-proof screen permeability (m^2)
k_s	extinction coefficient of plants for shortwave radiation (–)
k_{sjk}	thermal conductivity of soil layer between depth z_j and z_k (W m^{-1} K^{-1})
L_{AI}	leaf area index (m^2 m^{-2})
L_b	mean path length of solar beam radiation (m)
L_{cl}	characteristic leaf length (m)
L_{Vj}	length of the opening j (m)
n	number of measurements (–)
P_e	pressure outside the greenhouse (Pa)
P_v	proportion of area covered by plants (m^2 m^{-2})
q_{ac}	solar radiation absorbed by the greenhouse cover (W m^{-2})
q_{aspm}	solar radiation absorbed by the soil mulch (W m^{-2})
q_{rcNET}	net thermal radiation rate at the greenhouse cover (W m^{-2})
q_{rsNET}	net thermal radiation rate at the soil (W m^{-2})
q_{sc}	heat conducted beneath the polypropylene mulch (W m^{-2})
q_{sjk}	soil heat conducted in the soil layer between depth z_j and z_k (W m^{-2})
q_{sky}	downward longwave atmospheric irradiance (W m^{-2})
R	specific gas constant, 287 (J kg^{-1} K^{-1})
$\mathrm{Re_p}$	Reynold number (–)
R_g	outside global solar radiation flux density (W m^{-2})
$RMSE$	Root Mean Square Error (°C)
$RMSPE$	Root Mean Square Percentage Error (%)
R_{Si}	inside global solar radiation flux density (W m^{-2})
R_{Hi}	inside air relative humidity (%)
R_{sz0}	thermal resistance of the polypropylene mulch (m^2 K W^{-1})
S_c	surface area of greenhouse cover (m^2)
S_s	surface area of soil (m^2)
S_{VR}, S_{VS}	roof and the side openings' surface areas (m^2)
t	time (s)
T_i	interior air temperature (K)
T_e	exterior air temperature (K)
T_v	vegetation temperature (K)
T_c	average greenhouse cover temperature (K)
T_{sky}	temperature of sky (K)
T_{spm}	temperature of the polypropylene mulch (K)
T_{sk}	temperature of the soil at depth k (K)
u	air velocity inside the greenhouse (m s^{-1})
U_0	wind speed (m s^{-1})
V_g	greenhouse volume (m^3)
v_V	air velocity through the greenhouse vents (m s^{-1})
w_{Vj}	height of the opening j ($_R$ for roof and $_S$ for side openings) (m)
X_j	value predicted by the model at time j (K)
X_M	mean of values predicted by the model (K)
Y	insect-proof screen inertial factor (–)
Y_j	value measured at time j (K)
Y_M	mean of values measured (K)
z_k	depth in the soil (m)

Greek symbols

$\alpha_{ct}\alpha_{ct}$	cover absorptivity of thermal radiation (–)
α_{cw}	absorptivity of the whitened greenhouse cover to global solar radiation (–)
α_{Lpmt}	long wave radiation absorptivity of the polypropylene mulch covering the soil (–)
α_{Ls}	soil surface absorptivity of thermal radiation (–)
α_{pp}	polypropylene absorptivity of solar radiation (–)
α_{spm}	fraction of the incident solar radiation that is absorbed by the polypropylene mulch covering the soil (–)
α_{vj}	angle of opening (°)
δ_a	air density (kg m^{-3})
δ_c	greenhouse cover material density (kg m^{-3})
δ_{sik}	average density of the soil between depth z_i and z_k (kg m^{-3})
δ_{spm}	polypropylene density (kg m^{-3})
ε_c	emissivity of greenhouse cover (–)
ε_{spm}	emissivity of the polypropylene mulch covering the soil (–)
θ_G	angle of incidence of wind (°)
θ_w	wind direction (°)
μ_a	dynamic viscosity of the fluid (kg s^{-1} m^{-1})
ρ_∞	reflectance of a dense stand (–)
ρ_{cs}	downward effective reflectance of the covers (–)
ρ_{cw}	reflectance of the whitened cover to solar radiation (–)
ρ_L	reflectance of the tomato leaf tissue (–)
$\rho_p l$	effective reflectance of the plant layer to solar radiation (–)
ρ_{spm}	reflectance of the polypropylene mulch (–)
σ	Stefan–Boltsman constant (W m^{-1} K^{-4})
φ	insect-proof screen porosity (%)
τ_{cs}	downward effective transmittance between the greenhouse cover and the soil (–)
τ_{cw}	transmittance of the whitened cover to solar radiation (–)
τ_{cLW}	transmittance of the whitened cover to long wave radiation (–)
τ_{ha}	transmittance of the humid air due to absorption of water vapour to global solar radiation (–)
τ_L	transmittance of the leaf tissue (–)
τ_{Lpl}	tomato transmittance for diffuse longwave radiation (–)
τ_{pl}	transmittance of the plant layer to solar radiation (–)
τ_{Spl}	canopy transmittance for diffuse shortwave radiation (–)