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Modeling and experimental validation of heat transfer and energy consumption in an innovative greenhouse structure

Morteza Taki [a,*], *Yahya Ajabshirchi* [a], *Seyed Faramarz Ranjbar* [b], *Abbas Rohani* [c], *Mansour Matloobi* [d]

[a] *Department of Biosystems Engineering, Faculty of Agriculture, University of Tabriz, Iran*
[b] *Department of Mechanical Engineering, Mechanical Engineering Faculty, University of Tabriz, Iran*
[c] *Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Iran*
[d] *Department of Horticultural Science, Faculty of Agriculture, University of Tabriz, Tabriz, Iran*

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ABSTRACT

The commercial greenhouse is one of the most effective cultivation methods with a yield per cultivated area up to 10 times more than free land cultivation but the use of fossil fuels in this production field is very high. The objectives of this paper are to modeling and experimental evaluation of heat and mass transfer functions in an innovative solar greenhouse with thermal screen. For this propose, a semi-solar greenhouse was designed and constructed at the North-West of Iran in Azerbaijan Province (38°10′N and 46°18′E with elevation of 1364 m above the sea level). The inside environment factors include inside air temperature below screen (T_a), inside air temperature above screen (T_{as}), crop temperature (T_c), inside soil temperature (T_s), cover temperature (T_{ri}) and thermal screen temperature (T_{sc}) were collected as the experimental data samples. The dynamic heat and mass transfer model used to estimate the temperature in six different points of the semi-solar greenhouse with initial values and consider the crop evapotranspiration. The results showed that dynamic model can predict the inside temperatures in four different points (T_a, T_c, T_{ri}, T_s) with MAPE, RMSE and EF about 5–7%, 1–2 °C and 80–91% for greenhouse without thermal screen and about 3–7%, 0.6–1.8 °C and 89–96% for six different points of greenhouse with thermal screen (T_a, T_c, T_{ri}, T_s, T_{as}, T_{sc}), respectively. The results of using thermal screen at night (12 h) in autumn showed that this method can decrease the use of fossil fuels up to 58% and so decrease the final cost and air pollution. This movable insulation caused about 15 °C difference between outside and inside air temperature and also made about 6 °C difference between T_a and T_{as}. The experimental results showed that inside thermal screen can decrease the crop temperature fluctuation at night.

* Corresponding author. Fax: +98 4113356007.
E-mail addresses: mortezataaki@gmail.com, Mtaki88@ms.tabrizu.ac.ir (M. Taki).
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Nomenclature

Q	heat load (W)
α	heat load coefficient (W/m^2 K)
v	outdoor wind speed (m/s)
I	solar radiation (W/m^2)
T	temperature (K)
F	view factor (–)
E	emission coefficient (–)
A	surface area (m^2)
c_p	specific heat capacity (J/kg K)
d	thickness (m)
V	volume (m^3)
$\Phi_{m-c-a-H_2O}$	mass flow rate of water vapor from crop to indoor air (kgH$_2$O/s)
k_{c-a-H_2O}	mass transfer coefficient of water vapor from the crop to the indoor air ($\frac{m}{s}$)
C_{c-H_2Os}	saturation concentration of water vapor at the temperature of the crop (kgH$_2$O/m^3)
C_{a-H_2O}	concentration water vapor at the temperature of the indoor air (kgH$_2$O/m^3)
R_{cut}	leaf cuticular resistance (s/m)
R_{s-H_2O}	stomata resistance (s/m)
R_{b-H_2O}	boundary layer resistance (s/m)
$R_{\min}$	minimum internal crop resistance (s/m)
f_I	radiation dependency effect (–)
f_{Tc}	temperature dependency effect (°C)
f_{CO_2}	CO_2 dependency effect (–)
f_{H_2O}	H_2O dependency effect (–)
LAI	leaf area index (–)
I_{c-s}	heat absorbed by canopy (W/m^2)
Q_{c-a-H_2O}	heat load from canopy to indoor air below screen (W)
Q_{a-sc-H_2O}	heat load from indoor air below screen to screen (W)

Greek symbols

η_{ri-Is}	absorption coefficient shortwave radiation by roof (–)
η_{s-Is}	absorption coefficient of shortwave radiation by soil (–)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
λ_s	soil thermal conductivity (W/m K)
λ_{nw}	north wall thermal conductivity (W/m K)
$\overline{\rho}$	average density of air below and above screen (kg/m^3)
η_{c-Is}	absorption coefficient shortwave radiation by crop (–)

Subscripts

a	inside air below screen
s	inside soil
ri	inside roof
o	outside
c	crop
nwi	inside north wall
nwo	outside north wall
$a–s$	inside air to soil
$sc–a$	screen to inside air below screen
$sc–as$	screen to inside air above screen
$sc–ri$	screen to inside roof
Cl_{sc}	thermal screen closure
ss	lower layer of soil
$a–as$	below screen to above screen
$s–c$	soil to crop
$s–sc$	soil to screen
$as–sc$	inside air above screen to screen
as	inside air above screen
$rd–ri$	radiation absorption by roof
$s–ri$	soil to inside roof
$ro–o$	roof to outside
sk	sky
in	inside room of greenhouse
$a–sc$	inside air below screen to screen
$ro–sk$	roof to sky
$rd–s$	radiation absorption by soil
$s–ss$	upper to lower soil
$rd–c$	radiation absorption by crop
$a–c$	inside air to crop
$as–ri$	above screen to roof
$ri–c$	inside roof to crop
$sc–ri$	screen to inside roof
$c–sc$	crop to screen
l_f	mean leaf width
R_{b-heat}	leaf boundary layer resistance (s/m)

1. Introduction

Greenhouse cultivation is the popular intensive kind of crop production with a yield per cultivated unit area more than 10 times higher than a field crops. Vegetables, ornamental and fruits crops are cultivated under greenhouse conditions. Greenhouse structure, covering and inside instruments provide a very suitable environment needs to grow all kinds of the crops and resulting in higher yield, quality and in the lengthening of the market availability of the products. Greenhouse production requires the use of large amounts of energy, water, pesticides and it usually generates huge quantities of wastes to be disposed of it. Investment, labor and energy costs per unit area are much higher in a greenhouse industry than in any other agricultural sectors [1]. Sustainable greenhouse systems, socially supportive, commercially competitive and environmentally sound, depend on cultivation techniques, equipment management and constructive materials aim to reduce agrochemicals, energy and water consumption as well as waste