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Effect of greenhouse orientation with respect to E-W axis on its required heating and cooling loads

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Abstract

The paper presents a comparison between two different orientations of a vegetable greenhouse with respect to East-West axis in Romania. The solar irradiance received by the greenhouse is estimated based on isotropic clear sky analysis model. Interior air temperature profiles are numerically simulated all along a day, in winter and in summer. In order to maintain a constant interior air temperature during vegetation, heating and respectively cooling required loads are computed. Different profiles are obtained for the considered orientations. Based on these profiles, the numerical simulation reveal energy savings for the E-W orientation with respect to N-S one, both in summer and winter periods. The results might be used for designing the cooling and heating equipment ensuring the optimum microclimate inside the greenhouse.

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Keywords: Solar energy; greenhouse; heating and cooling load

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1. Introduction

The importance of greenhouses in food production grew up constantly during the years. Accordingly, many papers targeting optimization of crops growth inside greenhouses were proposed in the open technical literature. Part of them treats physical phenomena of light absorption and nutrients required for productive crops. Others aim optimization of greenhouse shape, structure and orientation.

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Nomenclature

A	surface area, m^2
a_0, a_1	constants for standard atmosphere
$\dot{E}$	energy rate, W
G	radiation rate density, Wm^{-2}
h	heat transfer coefficient, $Wm^{-2}K^{-1}$
k	constant for standard atmosphere
n	number of a day in an year
p	pressure, Pa
T	temperature, K

Greek symbols

α	solar absorptance
β	slope of a tilted surface, deg
δ	solar declination
ε	cover emissivity
σ	Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ $Wm^{-1}K^{-4}$
φ	geographical latitude, deg
γ	surface azimuth angle, deg
γ_{psy}	psychrometric constant, $66PaK^{-1}$
λ	latent heat of vaporization of water, 2.540 MJ kg^{-1}
τ	atmospheric transmittance
$(\tau\alpha)(\tau\alpha)$	transmittance-absorptance product
θ	angle of incidence of beam radiation on a surface, deg
θ_z	zenith angle, deg
ω	hour angle, deg, $\omega = 15^0 \times (time - 12)$

Subscripts and superscripts

B	beam
D	diffuse
ET	extraterrestrial radiation
g	ground
sat,T	saturation, at temperature T
SC	solar constant, $1367W/m^2$
T, tot	total
vp,T	vapors, at temperature T
w	window

Among these, one may find the paper of Panwar et.al. [1], where an useful review of all thermal modeling, studied structures and shape optimization was performed. El-Maghlany et. al. [2] proposes an optimization procedure for five different elliptic shape greenhouses installed in Egypt; the considered optimization criterion being the total captured solar energy from November to May, in three different orientations of the greenhouse. Their recommendation is to align the greenhouse with respect to south direction for latitudes higher than 24ºN latitude. Dragicevic [3] also applied the same criterion for finding optimum orientation of an uneven-span single shape greenhouse and concluded that an E-W orientation should be preferred at latitudes of 44ºN and 54ºN as it receives less solar radiation in summer and provides higher air inside temperatures in winter. Sengar and Kothari [4] studied the thermal profile inside an E-W oriented arch shape greenhouse and compared the results to experimental data. They studied the increase in greenhouse temperature over ambient one as a function of solar radiation. Sethi [5] compared different shapes in E-W orientation during a typical summer day in India (31ºN) from the point of view of available solar energy and also inside air temperature. He concluded that maximum solar radiation is received by uneven-span shape greenhouse. Also, E-W orientation should be preferred for even-span or modified arch shape greenhouses.

To grow faster, usually crops require a constant air temperature inside the greenhouse. In these conditions, the cooling and heating greenhouse loads are important for determining the energy demands and for estimating annual operating costs. Joudi and Hasan [6] simulated the microclimate behavior based on a dynamic model and determined the hourly heating and cooling loads to maintain 20ºC inside an even span greenhouse in Baghdad (33.3 ºN latitude). They reported in January, a peak heating load of about 450W/m2 during night and a cooling rate of 450 W/m2 around noon.

The heating and cooling loads obviously depend on greenhouse shape and location. Thus, a local study is of great importance for simulating the greenhouse loads and availability for covering part of energy need from renewable sources. The aim of the present study is to simulate the heating and cooling loads required to maintain a desired air temperature level inside an even span shape greenhouse at 44.25ºN latitude (Bucharest, Romania). To achieve this goal, a simplified greenhouse thermal model was applied for simulating the temperature and solar heat gains profiles along a day, during winter and summer. Natural ventilated and non-ventilated greenhouse cases were analyzed in E-W and N-S orientations.

2. Greenhouse geometry and orientations

As presented by Panwar et.al.[1], different forms of vegetable greenhouses could be considered. For this study, a standard peak even span form was chosen. This structure is among the most studied in literature [1], [5]-[7]. The considered dimensions are: 4m wide, 45m long and 2m high. The roof has a triangular shape of 1m height. The cover is made of polyethylene whose transmittance-absorptance (τα) property is about 0.5. Two orientations of the greenhouse with respect to East-West axis are studied. The orientation is considered taking as reference the greenhouse length.

In the first case, the greenhouse is oriented on E-W direction, meaning that its length is parallel to E-W line. This is sketched in figure 1. As sun rises from East and climbs the sky by South, direct radiation is intercepted by two vertical wall surfaces as shown in figure 1-left side. At noon, direct radiation is intercepted by the two roof tilted surfaces and partially by the South oriented vertical side. After noon, sun is falling towards West, so that vertical surfaces intercept direct radiation.

The second case represents the N-S orientation of the greenhouse, i.e. its length is perpendicular on E-W axis, as shown in figure 2. In this case, length side walls intercept direct radiation during sunrise (S1, S2) and sunset (S3, S4), respectively. At noon, sunrays directly fall on the two tilted roof surfaces (S2, S3) and the vertical South oriented wall.

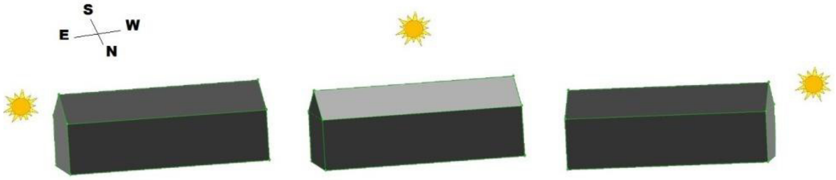

Fig. 1. Daily sunrays fall on a East-West oriented greenhouse: in the morning (left side), at noon (in center), in the evening (at right).

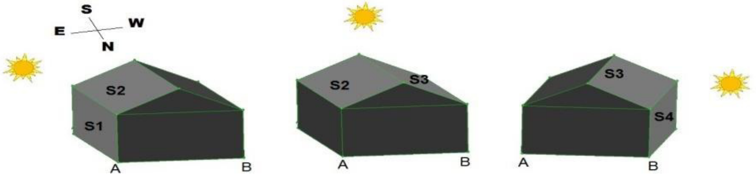

Fig. 2. Daily sunrays fall on a North-South oriented greenhouse.

As different surfaces are subjected to direct radiation for different periods of time, heat gain will differ between the two cases, as it follows.

3. Heat loads calculation

In order to determine the interior air temperature and the corresponding heating or cooling loads required to maintain a constant inside temperature, one needs to apply the energy balance equation on the greenhouse. The following assumptions are made: i) the air is uniformly mixed inside so that a uniformly distributed temperature, Ti is considered; ii) clear sky solar radiation model is applied; iii) steady state energy exchange processes is assumed. As a result, the energy balance equation for inside air is:

$$\dot{E}_{Ab}+\dot{E}_{Crop}+\dot{E}_{V}+\dot{E}_{L}+\dot{E}_{req}=0 \tag{1}$$

where the terms represent absorbed solar energy rate EAb, crop transpiration rate ECrop, energy rate associated to natural ventilation EV, loss energy rate between greenhouse air and environment EL and required heat rate for maintaining an imposed temperature Ti inside the greenhouse Ereq, respectively. When heating is required, $\dot{E}_{req}$ will be positive. In case of cooling necessity, $\dot{E}_{req}$ will be negative. If one imposes $\dot{E}_{req}$=0, eq. (1) is used to compute the equilibrium temperature of the inside greenhouse air.

Based on Hottel and Woertz model [8], direct GB, diffuse GD and total GT solar radiation densities intercepted by tilted surfaces are computed:

$$G_T=G_B+G_D \tag{2}$$

$$G_B=\tau_B G_{SC}\left(1+0.033\cos\left(360n/365\right)\right)\cos\theta \tag{3}$$

$$G_D=\left(0.271-0.294\tau_B\right)G_{SC}\left(1+0.033\cos\left(360n/365\right)\right)\cos\theta_z \tag{4}$$

Details may be found in [9] and [10]. The atmospheric transmittance for beam (direct) radiation, τ_B is computed according to ref. [11]. The angle of incidence of beam radiation on a surface is given by:

$$\begin{aligned}\cos\theta=&\sin\delta\sin\varphi\cos\beta-\sin\delta\cos\varphi\sin\beta\cos\gamma+\cos\delta\cos\varphi\cos\beta\cos\omega+\cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega+\\&+\cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{5}$$

where declination δ is estimated by Cooper equation for the nth day of the year [12]. The expression of $\cos\theta_z$ is obtained as particular case of eq. (5) for horizontal surface (β=0). The surface azimuth angle γ is -90° for East oriented walls, 0 for South ones, 90° if walls are facing West and 180° for North walls. The tilt β is either 90° for vertical walls, or 26.57° for the roof surfaces S2 and S3.

The solar radiation density absorbed inside the greenhouse is computed taking into account the transmittance-absorptance property of the cover material. In consequence, the total energy rate absorbed by the greenhouse is expressed by:

$$\dot{E}_{Ab}=\sum(\tau\alpha)G_T A \tag{6}$$

that counts when writing the energy balance equation on the greenhouse.

HORTITRANS model [13] is applied to determine the rate of crop transpiration that counts as heat rate in for the greenhouse energy balance equation:

$$\dot{E}_{Crop}=\lambda\left[aG_{Ab}/\lambda+h_t\left(p_{sat,Ti}-p_{vp,Ti}\right)/\left(\lambda\gamma_{psy}\right)\right]A_g \tag{7}$$

where $a=0.154LN\left(1+1.1LAI^{1.13}\right)$ and $h_t=1.65LAI\left[1-0.56\exp\left(-G_{Ab}/13\right)\right]$. The leaf area index (*LAI*) was considered 1 in this study, corresponding to young plants [13].

When considering a ventilation window of dimension Hw·Ww, the associated heat transfer rate is computed as:

$$\dot{E}_V = \dot{V}_V \rho c_p (T_a - T_i) \tag{8}$$

where the exchanged air volume flow rate is computed according to Roy [14]:

$$\dot{V}_V = 0.5 A_w C_D (0.5 g H_w \Delta T / T_a)^{0.5} \tag{9}$$

and the discharge coefficient depends on window width Ww and opening angle αw:

$$C_D = (1.75 + 0.7 \exp(-W_w / (32 \sin(\alpha_w))))^{-0.5} \tag{10}$$

In this study, a window of 1mx30m aperture was considered, opened at 90°.
Heat transfer between inside air and ambient is considered by convection and radiation:

$$\dot{E}_L = \dot{E}_{cv} + \dot{E}_{rad} = h_{cv}(T_a - T_i)A_{tot} + \varepsilon\sigma(T_a^4 - T_i^4)A_{tot} \tag{11}$$

where Atot is the total cover area of the greenhouse.

4. Results and discussions

The above described model was applied for simulating the greenhouse behavior during winter, on January the 15th, and summer, on June the 15th. The solar radiation was simulated using the Hottel and Woertz model, while the outside ambient temperature hourly profile was generated as a polynomial after the experimental monthly averaged data available on JRC website [15].

The energy balance equation (1), with $\dot{E}_{req}$=0, applied in the two situations provide the daily profile of the inside air equilibrium temperature, as shown in figures 3a-d, for a non-ventilated greenhouse (figure 3a in summer, 3c in winter) and for a natural ventilated one (figure 3b in summer, 3d in winter).

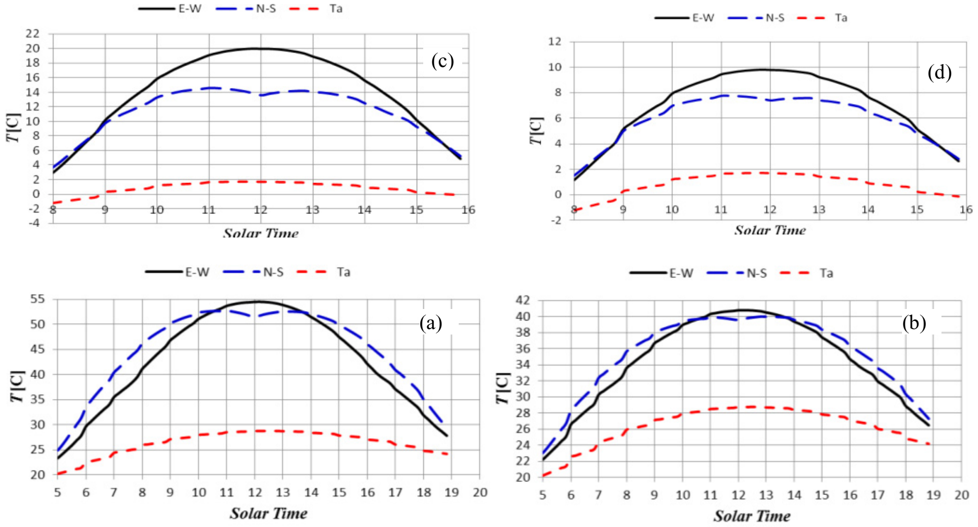

Fig. 3. Ambient and inside air temperatures for E-W and N-S orientated non-ventilated greenhouse (a) and natural ventilated greenhouse (b) in winter, at January 15th

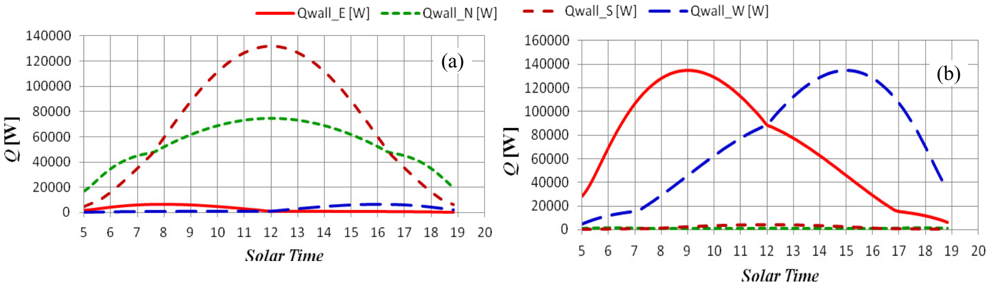

Fig. 4. Solar incident heat flux distributions for (a) E-W and (b) N-S orientations of greenhouse

One may notice that an E-W orientation of the greenhouse provides a smaller temperature inside the greenhouse during summer with about 3-5°C when comparing to N-S orientation. When natural ventilation is applied, the temperature does not exceed 42ºC in June in the given conditions. Figures 3c-d emphasize the behavior during winter periods. In case of a non-ventilated greenhouse (figure 3c), the maximum temperature is about 20ºC for a short period of time for E-W orientated greenhouse, while for a N-S orientation a temperature of about 14 ºC is maintained almost constant for a longer period of time during the day. When performing greenhouse ventilation (figure 3d), the temperature levels are lower with about 4-10ºC comparing to the non-ventilated case. A more important decrease appears for E-W orientation. One may conclude that from inside air temperature point of view, an E-W orientation of the greenhouse is preferred, since it offers lower values during summer and higher ones during winter.

Figures 4 show the heat fluxes daily distributions captured by the walls for the two considered greenhouse positions. In the case of E-W orientation, the main heating contribution belongs to the southern (S1 and S2) and northern (S3) oriented surfaces, the maximum heat flux intercepted occurring at noon. This behavior is due to the fact that these surfaces are almost all day long exposed to solar radiation and the variations of solar incidence angle have the same shape for all these walls. The eastern and western oriented surfaces intercept the solar irradiance only in the morning or in the afternoon respectively, but thanks to their relative position with respect to the sun path and to their lowers surfaces, their contribution to the greenhouse heating is almost negligible. In the case of N-S greenhouse orientation, the contribution is mainly shared between the eastern (S1 and S2) and western (S3 and S4) walls. In the morning, as the sun climbs on the sky, the eastern walls capture the most solar heat flux, that reaches the maximal value of about 138 kW around 9AM. As the time is passing, the solar incidence angle is diminishing on these walls but is growing on the western ones. As a result, the heat flux captured by the eastern walls decreases while the heat flux intercepted by the western ones increases, reaching the same maximal value of 138 kW at 3PM. After that, the heat flux captured by the western walls starts decreasing because both the solar irradiation and the incidence angle are diminishing. Practically, due to the symmetry of greenhouse geometry with respect to the N-S axis, the distributions of heat flux captured by the eastern and western walls are symmetric with respect to the noon. When comparing the two considered cases in June, the numerical results emphasize that the E-W orientated greenhouse intercepts up to 40kW lower total solar heat flux in the morning and afternoon and up to 20kW higher around the noon. They also show that in January, the total solar gain is all day higher for E-W orientation.

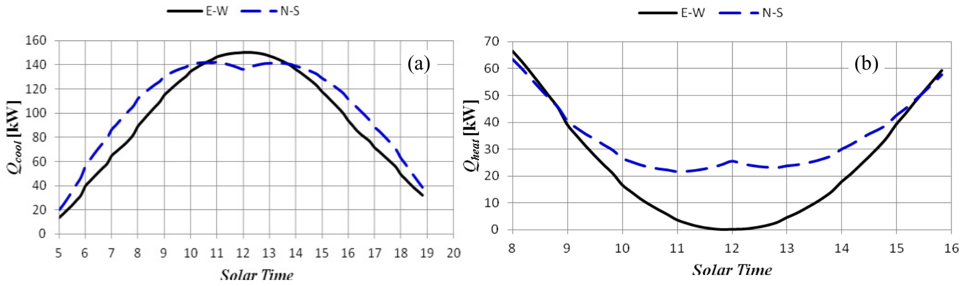

Fig. 5. Cooling (a) and heating (b) loads required for E-W and N-S orientations of a greenhouse in June and January, respectively

By imposing all day constant inside air temperature at Ti=20ºC, cooling and heating are required during June and January, respectively. Figures 5 emphasize the cooling and heating loads profiles for the two considered orientations. One may notice that in June, the cooling load is lower for the E-W oriented greenhouse, involving an energy saving of about 125 kWh/day. In January, the same E-W orientation provides heating energy load, with about 87 kWh/day lower.

5. Conclusions

Thermal and energy behavior of an even span shape greenhouse of dimensions 4m x 45m x 2m located at 44.25ºN latitude was performed. The computations reveal that an E-W orientation involves lower inside air temperatures and solar heat gain in summer and higher ones in winter, in comparison to a N-S orientation. As a result, the required cooling load during summer and heating load during winter, respectively, are also lower for an E-W orientation. The corresponding energy savings are about 125 kWh/day in June and 87 kWh/day in January.

One may conclude that at 44.25ºN latitude the E-W orientation of the considered even span shape greenhouse is preferred all along the year from the energy loads point of view.

Acknowledgements

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