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Thermal analysis of a hybrid solar energy saving system inside a greenhouse

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ABSTRACT

The intensive greenhouse energy requirements are a major operational and economical problem for producers around the world. Energy conservation techniques and innovative applications of solar energy for heating are being employed in greenhouse operation to reduce heating costs during cold periods. The present study investigated the development of a mathematical model to predict the thermal efficiency of a novel hybrid solar energy saving system inside a heated greenhouse. The solar system consisted of a transparent water-filled polyethylene sleeve and two perforated air-filled polyethylene tubes on the top peripheral sides of it. Above the sleeve and between the two tubes, rockwool substrates were placed for hydroponic cultivation of tomato crop. In order to validate this model, experiments were carried out in two identical parts of a polyethylene arched-type greenhouse to obtain data during winter. By comparing the measured and the predicted values, a correlation of 95% was found, indicating that the model can simulate the water temperature inside the hybrid solar sleeves. Moreover, the additional energy provided by the hybrid solar system reached approximately 23% during the examined period, depending on solar radiation levels.

1. Introduction

Improved control of environmental conditions inside greenhouses by providing the required heating and artificial lighting, and the intensified production systems, led to increased energy consumption [1]. Utilization of solar energy is a factor that can contribute to the reduction of greenhouse production cost, especially since the greenhouse itself is a solar collector [2–4]. Research projects in utilization of solar energy for greenhouse heating resulted in the development of many passive solar systems with water filled plastics tubes or sleeves, but only few of them found practical application [5,6]. These systems had been designed for soil grown crops, which nowadays are replaced by hydroponic cultivation. Water filled polyethylene sleeves combined with perforated air tubes which serve also as hydroponic crop grow gutters reduce the heating cost in greenhouses by 7–36%, depending on the season, either with passive [7] or hybrid operation [8].

The greenhouse thermal environment is dependent on the heating system and can influence the greenhouse microclimate and production. Several numerical studies on greenhouse climate have been conducted to predict the greenhouse thermal environment based on energy and water vapour balance inside the greenhouse [9–11]. Dynamic simulation models of greenhouse microclimate were suggested to predict the microclimate inside a naturally ventilated greenhouse [12], based on several different scenarios [13] and also for a greenhouse with a heating system [14]. Time dependent simulations were conducted by several researchers to describe the energy balance of the greenhouse shape [15,16], the hydrothermal performance of a building [17] and the internal environment [18–20].

A reliable source of information to estimate heating costs in greenhouses could be provided by the use of mathematical models capable of simulating the performance of thermal systems with different designs. Many researchers designed mathematical models to study the performance of thermal systems that use water as a heat storage medium inside greenhouses with cultivation in soil. Mavrogiannopoulos and Kyritsis [21] developed a heat transfer model to calculate the thermal energy stored in passive solar polyethylene sleeves with water which were placed next to the crop. According to theoretical only calculations, energy saving with the use of the above system in a heated greenhouse with tomato crop reached 8% of the energy consumed. Thomas [22] studied the performance of passive solar polyethylene sleeves, where the heat medium was water, and analyzed the energy balance of the solar system. Also, the thermal performance of the system was

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Nomenclature

A_0	horizontal projection of the sleeve (m^2)
A_1	free surface area of the water-filled sleeve (m^2)
A_2	sleeve surface area in contact with airtubes (m^2)
A_3	sleeve surface area in contact with substrates (m^2)
A_4	sleeve surface area in contact with the black plastic sheet under the sleeves (m^2)
A_c	greenhouse covering surface area (m^2)
A_g	greenhouse total surface area (m^2)
b	diameter of PP-R tubes of the CHS (m)
C_e	canopy extinction coefficient
C_w	specific heat capacity of water ($J\ kg^{-1}\ °C^{-1}$)
c	coefficient depended to the air temperature and calculated based on the air thermal properties
D	horizontal diameter of sleeves (m)
D_c	greenhouse roof cover length which exchanges thermal radiation with the sleeves (m)
D_t	hydraulic diameter of the air-filled tubes (m)
F_{s-n}	view factor between the sleeve and the surface with which the sleeve exchanges thermal energy
F_{s-c}	view factor between the sleeve and the greenhouse cover
F_{s-p}	view factor between the sleeve and the plant canopy
F_{s-chs}	view factor between the sleeve and the PP-R tubes of the conventional heating system
F_{s-wh}	view factor between the sleeve and the white plastic ground cover
F_{s-s}	view factor between two sleeve surfaces
G_t	mass airflow rate in a tube per unit section of the tube ($kg\ s^{-1}\ m^{-2}$)
Gr	Grashof number
H	plants height (m)
h	length of the white plastic ground cover which exchanges thermal radiation with the sleeves (m)
h_{c1}	convective heat transfer coefficient between the sleeves and the greenhouse air ($W\ m^{-2}\ K^{-1}$)
h_{w2}	convective heat transfer coefficient between the black plastic sheet under the sleeves and the water in the sleeves ($W\ m^{-2}\ K^{-1}$)
I	solar radiation at sleeves upper surface ($W\ m^{-2}$)
I_o	solar radiation intensity entering the greenhouse ($W\ m^{-2}$)
K_w	thermal conductivity of the water ($W\ m^{-1}\ C^{-1}$)
LAI	cumulative leaf area index
m_w	mass of water (kg)
Nu	Nusselt number
Pr	Prandtl number
Q_{gr}	heat losses rate from the greenhouse (W)
Q_{ca}	heat exchange rate by convection between the sleeves and the greenhouse air (W)
Q_{cs}	heat exchange rate by convection between the sleeves water surface and the substrates (W)
Q_{ct}	heat exchange rate by convection between the sleeves and the air of the peripheral tubes (W)
Q_{cw}	heat exchange rate by convection between the sleeves water surface and the black plastic sheet under the sleeves (W)
Q_n	volumetric flow rate of the air pump ($m^3\ h^{-1}$)
Q_{sleeve}	thermal energy absorption rate by the water in the sleeves (W)
Q_{sR}	solar energy absorption rate by the water in the sleeves (W)
Q_{tR}	heat exchange rate by thermal radiation from the free surfaces of the sleeves (W)
q_d	daily amount of greenhouse heat losses ($kJ\ m^{-2}$)
q_{hs}	thermal energy provided by the conventional heating system (J)
q_{tot}	total daily thermal energy provided from the conventional heating system ($kJ\ m^{-2}$)
q_{ss}	released thermal energy from the water-filled sleeves (J)
q_{sleeve}	simulated released thermal energy from the HSESS ($kJ\ m^{-2}$)
Re	Reynolds number
r_c	solar radiation reflectivity coefficient of the sleeve (%)
SA_3	characteristic dimension of substrates (m)
SA_4	characteristic dimension of black plastic sheet under the sleeve (m)
T_α	temperature of the greenhouse air (°C)
T_b	temperature of the black plastic sheet (°C)
T_c	temperature of greenhouse cover (°C)
T_{chs}	temperature of the CHS tubes (°C)
T_i	desired air temperature in the greenhouse (°C)
T_n	temperature of surface n (°C)
T_o	external air temperature (°C)
T_p	temperature of plants (°C)
$T_{t\alpha v\alpha}$	average temperature in the air-filled tubes (°C)
T_{ts}	substrates temperature (°C)
T_w	temperature of water inside the sleeves (°C)
T_w^t	temperature of water inside the sleeves, previous time step (°C)
$T_w^{t-\Delta t}$	temperature of water inside the sleeves, current time step (°C)
T_{wh}	temperature of white plastic ground cover (°C)
T_{win}	inlet water temperature at the CHS (°C)
T_{wout}	outlet water temperature at the CHS (°C)
t_b	fraction of solar radiation transmitted through the bottom part of the sleeve (%)
t_{ws}	fraction of solar radiation passing through the sleeves to the white plastic ground cover (%)
U	overall heat transfer coefficient ($W\ m^2\ C^{-1}$)
u	air velocity ($m\ s^{-1}$)
V_w	water flow rate ($m^3\ s^{-1}$)
z	depth of water mass or sleeve height (m)

Greek letters

α_1	absortivity coefficient of black plastic sheet (%)
α_b	fraction of solar radiation absorbed by the black plastic sheet under the sleeves (%)
α_w	fraction of solar radiation absorbed by the water mass in the sleeves from above (%)
α_{w1}	fraction of solar radiation absorbed by the water mass in the sleeves from below (%)
β	fraction of energy absorbed near the upper surface of the water (%)
γ_1	reflectivity coefficient of the white plastic ground cover
ΔT	water temperature difference in the sleeves from day to night (°C)
Δt	time step (s)
ε	emissivity
κ	absorption coefficient for the water
ρ_α	density of air ($kg\ m^{-3}$)
ρ_w	density of water ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)

Abbreviations

HSESS	hybrid solar energy saving system
CHS	conventional heating system
PP-R	polypropylene tubes