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A study on thermal calculation method for a plastic greenhouse with solar energy storage and heating

Naijun Zhou [a,*], Yaxiong Yu [a], Jinping Yi [b], Rui Liu [c]

[a] School of Energy Science and Engineering, Central South University, Post Box: 410083, Changsha, Hunan, PR China
[b] Hunan Zhongda Design Institute Co., Ltd., Post Box: 410083, Changsha, Hunan, PR China
[c] Dakang Energy Development Co., Ltd., Post Box: 518057, Shenzhen, Guangdong, PR China

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ABSTRACT

Plastic greenhouse has been widely used in agriculture and horticulture due to its prolonging period for crops growth. In this work, an approach that stores solar energy in the daytime and provides heat by earth-tube at night was proposed, and then applied to a plastic greenhouse to elevate the inside air temperature. A one-dimensional dynamic model was established to assist the design of the solar energy storage and heating system and to evaluate the system performance. Using the model developed in Matlab, the date-hour change patterns of characteristic temperatures in the plastic greenhouse were obtained, through calculating the heat gains of various surfaces and heat storage by hour from solar radiation and solving the unsteady-state heat conduction equation in the structure components of the greenhouse. The calculated results show good agreement with the measured data, indicating that the method is valid and can be applied to the design of solar energy storage and heating system as well as the thermal performance analysis of greenhouses.

1. Introduction

As a major type of sunlight greenhouse, the plastic greenhouse has been widely used worldwide and has achieved great success in agriculture and horticulture, because it can prolong growth period and increase outputs of corps. A plastic greenhouse is usually structured with steel skeletons, walls and roof covered by transparent material, and its covering area is about 400–1200 m^2. In northern China, the plastic greenhouse is mostly single slope with rear walls. For a normal plastic greenhouse, energy inside mainly comes from solar radiation helping the crops to grow. In the daytime, the temperatures of soil, the structure components and the air inside greenhouse increase as the energy from solar radiation are accumulated and stored; at night, the greenhouse is able to maintain proper temperature condition with the help of thermal curtain.

In spring, summer and autumn, the greenhouse can keep favorable growing conditions through insulation, ventilation, etc. While in high temperature season, the temperature inside can reach over 50 °C during the day, and therefore, proper ventilation and shading devices are required. The ventilation is also needed to release the harmful gas in cold season. In winter, the temperature inside greenhouse is too low for corps to grow in normal condition. Heating measures, such as coal furnace, are usually used to maintain favorable growing conditions. In this work, a novel technology that can store solar energy in the daytime and provide heat by earth-tube at night was proposed and applied in a plastic greenhouse to replace the conditional heating by coal furnace.

In order to design the solar energy storage and heating system and evaluate its performance, a thermal calculation method was proposed. The thermal calculation method was studied to help predicting heat loss flux in the greenhouse and date-hour change patterns of inside air temperatures, improving greenhouse structure and control method based on the predicted results, as well as designing and optimizing the energy supply and control system to maintain proper inside air temperature. The overall objective is to derive a heat calculation method for the greenhouse and to develop a software program for the greenhouse design and control method optimization.

Many researchers have investigated the influence of irrigation scheduling, soil propriety and moisture conditions to crops in the greenhouse. The shape, construction and orientation of greenhouse were also studied (Bonachela et al. (2006), Li et al. (2005), Balghouthi et al. (2005), Sethi (2009), Al-Mahdouri et al. (2014)).

Some researches were conducted to develop greenhouse thermal models describing heat and mass transport processes. Kindelan (1980) developed a one-dimensional dynamic model to

* Corresponding author.
E-mail address: njzhou@csu.edu.cn (N. Zhou).

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Nomenclature

A	area, m^2
a	discharge coefficient
C_w	wind effect coefficient
C_p	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
d_i, d_o	internal and external diameter of the tube, m
E	solar radiation intensity, $W \cdot m^{-2}$
E_0	extraterrestrial solar radiation, $W \cdot m^{-2}$
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
H	solar altitude angle, degree
H_{ven}	vertical vent opening, m
ΔH	latent heat, $kJ \cdot kg^{-1}$
m	air mass ratio, dimensionless
N	node number on surface, dimensionless
N_{lea}, N_{ven}	the number of air changes between inside air and ambient due to leakage and ventilation, h^{-1}
q	heat loss flux of inside air, $W \cdot m^{-2}$
Q	total heat rate, $J \cdot s^{-1}$
R_b	geometric factor, the ratio of beam radiation on tilted surface to that on horizontal surface, dimensionless
t_r, t_s	sunrise and sunset time on collector surface, hour
$T(n, t)$	temperature of nodal point n at t min, K
T_{sky}	equivalent sky temperature, K
T_m	melting temperature, K
v_{am}	wind speed, $m \cdot s^{-1}$
V_g	total volume of greenhouse, m^3

Greek letters

α_V	thermal expansion coefficient, K^{-1}
β	mounting angle, the angle between the plane of the surface in question and the horizontal, degree
γ	surface azimuth angle, east negative, and west positive, degree
δ	solar declination, degree
ε	absorb coefficient, dimensionless
θ	solar incident angle, degree
θ_z	zenith angle, the solar incident angle for horizontal surface, degree
λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
ν	kinematic viscosity, $m^2 \cdot s^{-1}$
ξ	weather factor, dimensionless
ρ	density, $kg \cdot m^{-3}$
τ	atmospheric transmissivity on clear day, dimensionless
τ_c	transmissivity coefficient of film, dimensionless
ψ	local longitude, degree
φ	latitude, degree
ω	hour angle, degree

Subscripts

a, am	inside air and ambient air
b, d	beam radiation and diffuse radiation
c	thermal curtain or film
Ew	east wall
f	fluid (water)
g	greenhouse
Fc, Rc	front slop and rear slop
h	horizontal surface
i, o	inside and outside
k	is Ew, Lw, Uw and Ww, respectively
Lw	lower part of rear wall
p	pipe in the heat storage box
Rw	rear wall
s	soil or solar collector
t	title surface or earth tube on the soil surface
Uw	upper part of rear wall
ven	ventilation
Ww	west wall

predict the internal environment, and divided the greenhouse into four elements including soil, plant, internal air and cover (i.e. film), of which the boundary conditions must be specified as a function of time, as exterior temperature, wind speed, solar radiation and so on.

Tiwari and Gupta (2002) found that the shape of the greenhouse affects the inside air temperature in both winter and summer, also the north wall increases both the inside air temperature and storage water temperature significantly in both seasons. Tiwari et al. (2003), Gupta and Tiwari (2004) found that the solar fraction mainly depends on latitude and declination angle, and the solar fraction on north wall is higher during winter mouths and lower during summer months by using Auto-CAD to determine the distribution of solar radiation intensity on north wall. Gupta and Tiwari (2005) found that the reflection surface on the transparent north wall in greenhouse can maximize the solar radiation on the soil surface.

Bartaznas et al. (2005) compared the influence of air heater and heating pipes, and their results indicated that the use of mixed system is favorable in greenhouse.

Kumari et al. (2006) modeled the greenhouse integrated with a solar collector. Modeling results show that the plant temperature and inside air temperature increase significantly with the increase in collector area and decrease with an increase of plant mass.

Abdel-Ghany and Kozai (2006) analyzed the radiation and convection heat transfer in a naturally ventilated greenhouse, the test results showed that the overall heat transmission coefficient is in the range 3.0–6.0 $W \cdot m^{-2} \cdot K^{-1}$ and energy absorbed by water vapor should be considered.

Sethi and Sharma (2008) found that the night curtain or a thermal screen drawn inside or outside the greenhouse cover during nighttime in winter months reduces the heat loss to the ambient. In the paper, the performances of two solar heating systems used in greenhouse were studied and compared.

Berroug et al. (2011) used a dynamic model to study the thermal performance of greenhouse with a north wall made of phase-change materials.

Du et al. (2012) developed a simulation model to predict the performance of greenhouse with a heat-pipe system, and this model can estimate the heating power required in cold weather and heat loss from the greenhouse.

Sethi and Sumathy (2013) made a comprehensive review of existing thermal models. They indicated that some issues from radiation conversion and thermal energy storage are yet to be solved, in order to use the solar energy for heating the greenhouse during the night.

Few works had been found to study the combination of solar collector, phase change material, earth tube heating and movable thermal curtain in greenhouse. In present work, greenhouse integrated with solar energy storage and heating system, and movable thermal curtain was studied for improving the greenhouse temperature in winter. We used storage box filled with phase change material to store energy absorbed by solar collector, and earth tube net to heating the greenhouse at night.