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Numerical and experimental analysis of heat and moisture content transfer in a lean-to greenhouse

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Abstract

In this paper, heat transfer and moisture content in a lean-to passive solar greenhouse has been studied. A mathematical model based on energy equilibrium and a one-dimensional mathematical model for the unsaturated porous medium have been founded and developed to predict the temperature and moisture content in soil and the enclosed air temperature in the greenhouse. On the condition that plant and massive wall is neglected, the air is mainly heated by the soil surface in the greenhouse, which absorbs the incident solar radiation. With increase in depth, the variation of the temperature and moisture content in soil decreases on account of ambient, and the appearance of the peak temperature in soil postpones. All results should be taken into account for a better design and run of a greenhouse.

Keywords: Greenhouse; Heat transfer; Moisture content

1. Introduction

Passive solar greenhouses are often applicable to grow plants of high quality in the cold climates. There are great interactive effects among the soil temperature and air temperature in greenhouse, which are the main environment factors affecting plant growth and development. The energy balance has been conducted and the air temperature have been measured and predicted in greenhouse under various conditions by Sharma et al. [1], Gabriel et al. [2], Kurklu and Bilgin [3]. A lean-to greenhouse, in which the incident solar irradiation can be fully absorbed, has been widely used by Xing et al. [4], Jorge R.Barral et al. [5]. During the period that plant seed exists in soil or plant is small, and so the ground is mainly covered with bare soil in greenhouse, plant can be neglected and the ground of greenhouse may be nearly taken as bare soil. As a kind of unsaturated porous media, soil is consisted of soil particles, liquid water, gaseous mixture of vapor and air and other chemical and biological substances. Some typical theories of heat and mass transfer in moisture porous were established by Philip and DeVries [6], Luikov [7], Slattery [8], Whitker [9] and the researches in the soil area were also reported by Milly [10]. However, the effects between the temperature of soil surface and the air temperature in greenhouse are also signification and there still exist some theoretical aspect of moisture movement in porous materials to be improved.

In the present work, a lean-to greenhouse shown schematically in Fig. 1 has been investigated. The mathematical model based on energy equilibrium and a one-dimensional mathematical model for the unsaturated porous media has been founded. Major objectives of the present study focuses on selecting efficient strategies for a better design and run of a greenhouse.

2. System description and mathematical analysis

2.1. System description

A lean-to passive solar greenhouse with a south inclining roof under investigation is shown schematically in Fig. 1. The roof and wall except the north wall consists of plate glass. A 60 cm wide massive wall is built at the north side of the greenhouse, which has two functions, one as a solar

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Nomenclature

A	area, m^2
c	specific heat, J/kg K
D_l	diffusivity of water in porous medium, m^2/s
g	gravitational acceleration vector, m/s^2
G_{ssun}	rate of solar flux absorbed by soil surface in the greenhouse, W/m^2
G_{wsun}	rate of solar flux absorbed by the north wall inside the greenhouse, W/m^2
G_{gsun}	rate of solar flux absorbed by the glass enclosure of the greenhouse, W/m^2
h_m	convective mass transfer coefficient, m/s
k_l	liquid water thermal conductivity, W/(m k)
k_{lw}	unsaturated permeability of liquid water, m^2
k_{gw}	equivalent permeability of gas-mixture, m^2
k_m	apparent thermal conductivity, W/(m k)
k_s	solid thermal conductivity, W/(m k)
k_g	gaseous thermal conductivity, W/(m k)
k_w	thermal conductivity for surface of the north wall absorber, W/(m k)
k_g	hydraulic conductivity of gas m/s
k_l	hydraulic conductivity of liquid, m/s
$\dot{m}$	mass rate of phase change, kg/(m^3 s)
p	pressure, Pa
Pr	Prandtl number
Q_{as}	convective heat exchange between the air and the surface of soil in greenhouse, J
Q_{aw}	convective heat exchange between the air of the greenhouse and the inside surface of the north wall, J
Q_{awo}	convective heat exchange between the ambient and the outside surface of the north wall, J
Q_{cai}	convective heat exchange between the air of the greenhouse and the glass enclosure of greenhouse, J
Q_{cao}	convective heat exchange between the ambient and the glass enclosure of greenhouse, J
Q_{rg}	thermal radiation exchange of the glass enclosure with the soil surface and the north wall surface in the greenhouse, J
Q_{rs}	thermal radiation exchange of the soil surface with the glass enclosure and the north wall surface in the greenhouse, J
Q_{rw}	thermal radiation exchange of the inside surface of the north wall with the soil surface and the glass enclosure in the greenhouse, J
Q_{sky}	thermal radiation exchange between the glass enclosure of greenhouse and sky, J
Q_{skyw}	thermal radiation exchange between the outside surface of the north wall and sky, J
r	latent heat, J/kg
T	temperature, K (°C)
T_{ao}	ambient temperature, °C
u	velocity component in x-direction, m/s
v	velocity component in y-direction, m/s
x	horizontal coordinate, m
y	vertical coordinate, m

Greek symbols

β	thermal expansion coefficient, 1/K
τ	time, s
μ	dynamic viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ρ^o	density of saturated water, kg/m^3
θ	phase content
θ_{ls}	moisture content of the soil surface

Subscripts

c	cold wall
g	gaseous
l	liquid water
m	apparent mean
s	solid, soil
w	north wall

Superscripts

-	average

absorber, the other as a heat storage and insulator. Plant is neglected in the greenhouse, so the ground of greenhouse can be nearly taken as bare soil.

2.2. Theoretical modeling

In discussing the physical mechanisms of heat and mass transfer in the soil by the conservational differential equations, some basic assumptions should be made as follows:

(1) homogeneous and isotropic medium with no distension or contraction;
(2) subject to local thermal equilibrium throughout the analysis domain;
(3) liquid phase and gas phase in funicular (continuous) states respectively;
(4) valid for Boussinesq's approximation in gaseous natural convection;
(5) ideal-gas treatment for gaseous mixture in pore space of porous matrix.

As the viscosity dissipation effects and the accelerated pressure drop of the liquid water are neglected, the liquid water in soil is drawn by the gravitation and the capillary attraction caused by moisture content gradient of the soil; As the viscosity dissipation effects of gas are neglected, the gas in soil is drawn by buoyancy, Darcy's resistance and pressure drop of gas flow, so the three kinds of above force keep

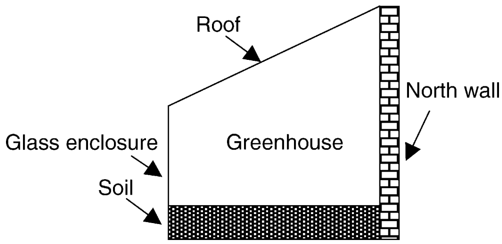

Fig. 1. Schematic of a lean-to type passive solar.

equilibrium. Therefore, a one-dimensional mathematical model for the unsaturated porous soil has been founded by Zhang and Liu. [11]

Continuity:
For water liquid:

$$\frac{\partial\rho_l\theta_l}{\tau} + \frac{\partial\rho_l\theta_l u_l}{y} = -\dot{m} \tag{1}$$

For gas:

$$\frac{\partial\rho_g\theta_g}{\tau} + \frac{\partial\rho_g\theta_g u_g}{y} = \dot{m}; \tag{2}$$

$$\theta_l + \theta_g + \theta_s = 1 \tag{3}$$

Momentum:
For water liquid:

$$u_l = -\frac{D_l}{\theta_l}\frac{d\theta_l}{dy} - \frac{K_l}{\theta_l} \tag{4}$$

For gas:

$$u_g = \frac{K_g\beta(T_s - T_c)}{\theta_g} + \frac{dp}{dy}\frac{K_g}{\rho_g\theta_g g} + \frac{\theta_l}{\theta_g}u_l \tag{5}$$

Energy:

$$(cp)_m\frac{dT_s}{dt} + (\theta_l\rho_l c_l u_l + \theta_g\rho_g c_g u_g)\frac{dT_s}{dy} = \frac{d}{dy}\left(k_m\frac{dT_s}{dy}\right) - r\dot{m} \tag{6}$$

The apparent physical properties of unsaturated porous soil are simply set to the mean ones, say

$$(cp)_m = \theta_l\rho_l c_l + \theta_g\rho_g c_g + \theta_s\rho_s c_s,$$
$$k_m = \theta_l k_l + \theta_g k_g + \theta_s k_s,$$

The hydraulic conductivityK_l, K_ν was defined from the previous work by Liu and Peng [12], $K_l = k_{lw}g/\nu_l$ $K_g = k_{gw}g/\nu_g$.

2.3. Boundary conditions and Initial conditions

Numerical simulations were performed under the ambient and operative conditions. A typical cold and sunny day of November in Wuhan, China was considered, and the outdoor temperature [13] and the solar radiative variation [14] were given by Eqs. (7) and (8).

$$T_{ao}(\tau) = \bar{T}_{ao} + T_{ar}\cos\left(\frac{\pi}{12}(\tau - 14)\right) \tag{7}$$

$$G_{sun}(\tau) = \hat{G}_{sun}\sin\left(\frac{\tau - a}{b - a}\pi\right), \quad a < \tau < b \tag{8}$$

where $\bar{T}_{ao}$ is for average outside temperature of 10 °C; T_{ar} for amplitude temperature of 5 °C; $\hat{G}_{sun}$ for maximum solar radiation of 350 W/m^2; a for sunrise hour at 6:00 in the morning; b for sunset hour at 18:00 in the afternoon; and τ for time hours.

The assumptions for the energy equilibrium equations of the proposed passive solar greenhouse have been written with the following assumptions:

(1) There was no stratification in the air temperature of the greenhouse.
(2) No temperature gradient exists along the glass enclosure surface of greenhouse, on the surface of the soil and on the north wall surface inside the greenhouse.
(3) The surface of the soil, enclosure and covers in greenhouse are considered as gray body.
(4) The air radiation absorbency in the greenhouse is neglected.

The initial and boundary conditions from the energy balance equations are given below:

For the glass enclosure and roof of the greenhouse

$$G_{gsun} + Q_{cai} + Q_{cao} + Q_{rg} = 0$$
$$T = T_{gb}, \quad u = 0, \quad v = 0 \tag{9}$$

For the inside surface of the north wall

$$A_w k_w\frac{dT_w}{dx} = G_{wsun}A_w + Q_{aw} + Q_{rw}$$
$$u = 0, \quad v = 0 \tag{10}$$

For the soil surface in the greenhouse

$$A_s k_m\frac{dT_s}{dy} = G_{ssun}A_s + Q_{rs} + Q_{as}$$
$$u = 0, \quad v = 0 \tag{11}$$

Moisture content, $\dot{m} = A_s h_m(\theta_{ls}\rho_s^o - \theta_a\rho_a^o)$,
$$(\theta_l\rho_l u_l + \theta_g\rho_g u_g) = \dot{m} \tag{12}$$

At depth of 1 m in the soil : $T = \text{constant};$

moisture content, $\frac{\partial\theta_l}{\partial y} = 0$ (13)

Initial conditions τ=0 T = constant, $\theta_l = \theta_l(y)$, θ_s = constant

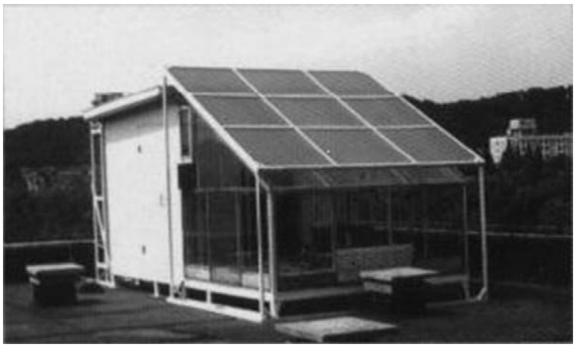

Fig. 2. Photograph of an experimental setup of passive solar greenhouse.

3. Numerical procedure

To investigate the interactive effects between the soil temperature and air temperature in the greenhouse, and the temperature and moisture content in the soil, the plane is neglected, the Eqs. (1)–(6) together with the boundary conditions, Eqs. (7)–(13), were solved by a finite difference method. The time step was of much concern and several values of $\Delta\tau$ had been examined for the grid chosen. It had been found that the maximum deviation between the results using $\Delta\tau = 10$ s and $\Delta\tau = 20$ s was only 1.5%. Hence, the time steps of $\Delta\tau = 20$ s together with the grid size of 80 for the depth of the soil were used for the unsteady-state numerical calculations performed in this study.

4. Experiments

Measurement of the temperatures were made with thermocouples connected with numerical voltage setting, which were placed on the soil surface and at the depth of 8 and 15 cm within soil, in the middle of the greenhouse. The ambient temperatures were measured with a mercurial thermometer. The measurement of the airflow speed was conducted with an anemometer. Solar radian was measured with an actinography. The type of MP-406 moisture probes (made in ICT corporation in Australia) were placed at the depth of 4 and 16 cm within sand soil. The type of CYH-3605A humidity instrument was placed in the air space of the greenhouse. A photograph of the experimental setup of the passive heating system is shown in Fig. 2.

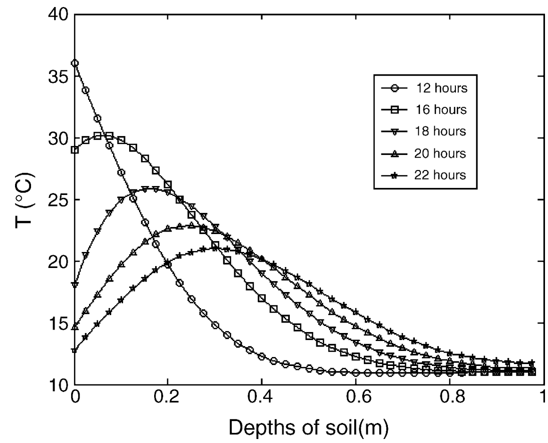

Fig. 4. Predicted soil temperature distribution of a day.

5. Results and discussion

5.1. The performance of the air temperature and soil temperature in the greenhouse

Observing Fig. 3, we can find that due to the variation of solar irradiation, the temperature difference among the ambient, the soil surface and air in the greenhouse changes. At 14:00 h in the afternoon, there exists more than 15 °C between the temperature of the soil surface and the ambient temperature, and the air of the greenhouse is also 10 °C higher than the outdoor. In contrast, while no solar radiation

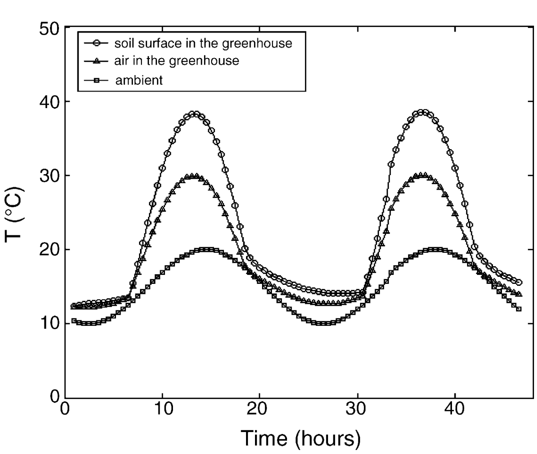

Fig. 3. Comparison of predicted temperature among ambient, soil surface and air in greenhouse.

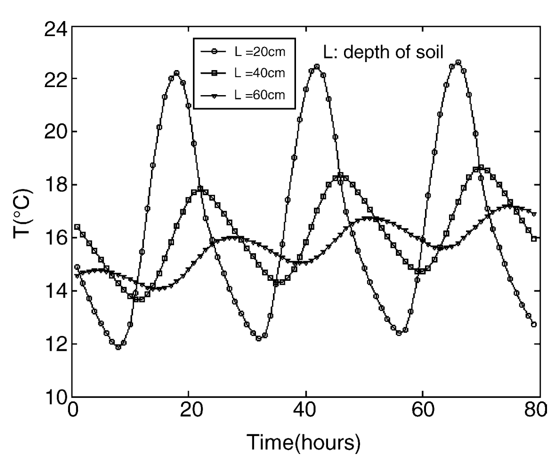

Fig. 5. Predicted hourly values of soil temperature at depth of 20, 40 and 60 cm in greenhouse.

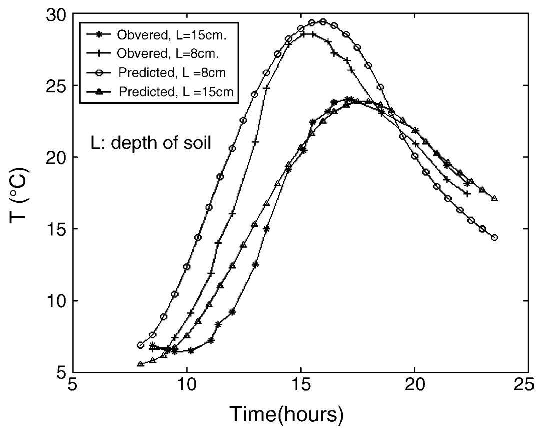

Fig. 6. Comparison of measured temperature among ambient, soil surface and air in greenhouse.

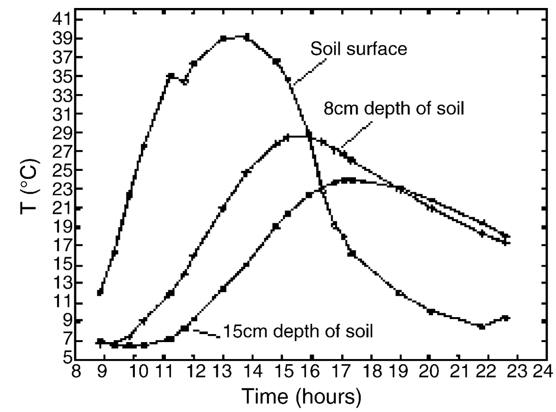

Fig. 8. Comparison between measured and predicted values of soil temperature in greenhouse.

was available and no heat-insulated method was taken for the glass enclosure, the temperature in the greenhouse drops quickly, the soil surface temperature is slightly higher than the air temperature in the greenhouse and there is a bit of temperature difference between the air of the greenhouse and the ambient temperature. The soil surface temperature is above the air temperature all the time. Thus, the incident solar radiation absorbed by the soil surface has been divided into two parts, one heat the air in the greenhouse, the other transfers into the inside of soil.

As shown in Figs. 4 and 5, with increase in depth, the variation range of temperature reduces and the peak temperature of the soil moves to the inside, and the appearance of that postpones, accordingly, the influence of environment on soil temperature decreases. At a certain depth, for instance, at 0.8–1 m, the soil temperature keeps constant. When there is no solar irradiation available, the heat stored in the soil bed transfers to the surface and releases to the outside of soil. So, there is thermal inertia in soil bed. The predicted values of temperature are corresponding to the measures, as shown in Figs. 6–8.

5.2. The performance of moisture content in the soil

From Figs. 9–11, It can be seen that due to the periodic variation of the solar radiation, the temperature and relative humidity of ambient, the moisture content of the soil bed upside changes regularly, which was vaporized more in the daytime than in the nighttime. As the amount of water from the bottom of the soil bed was less than that of water lost to the air space in the daytime, the moisture content in the upside of soil bed decreased greatly, In contrast, owing to the reduction of the air temperature, the increase of the air relative humidity and no solar irradiation in the night, the water from the bottom of the soil bed was more than the water vaporized, and so the moisture content in the upside of the soil bed increased. Without irrigation**,** the moisture content in soil decline in whole. The wavy variation of the moisture content went to disappear and the effects of the outside on the moisture content reduced with increase in depth of the soil. The predicated moisture content profile in soil was corresponding to the observed one in experiment field plots.

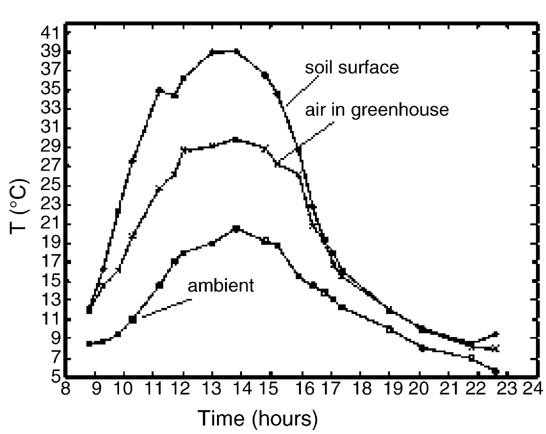

Fig. 7. Hourly values of temperature measured on soil surface, at 8 cm and at 15 cm of soil bed in the greenhouse.

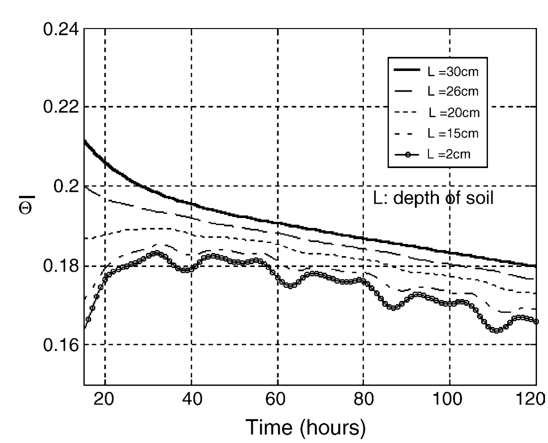

Fig. 9. Predicted hourly values of moisture content at 2, 15, 20, 25 and 30 cm depth of soil in greenhouse.

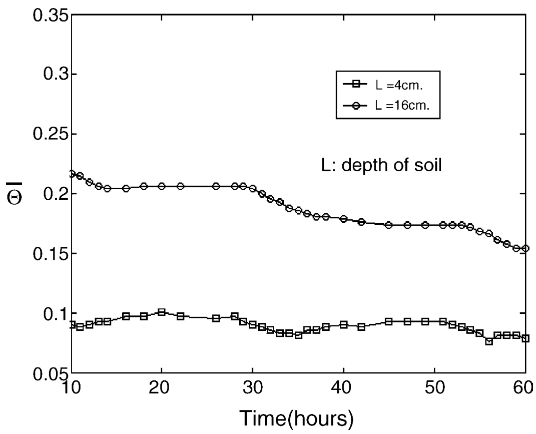

Fig. 10. Measured hourly values of moisture content at 4 and 16 cm depth of soil in greenhouse.

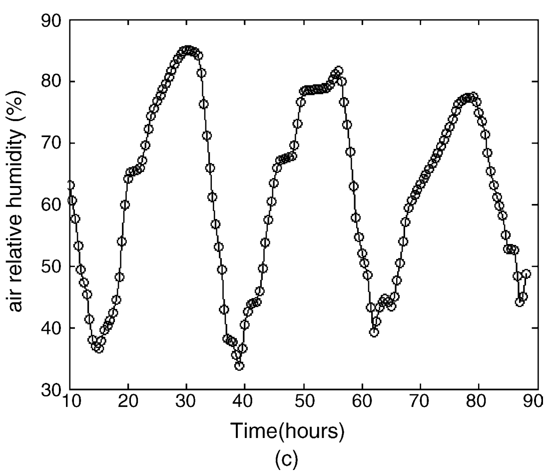

Fig. 11. Measured values of air relative humidity in greenhouse.

6. Conclusion

From the above discussion, we can conclude that the temperature of the air, the soil and the wall in greenhouse is mainly influenced by solar irradiation. With increase in depth, the periodic variation range of the soil temperature and the moisture content in soil decreases, and the appearance of the peak temperature of soil postpones. During night, the moisture content in the upside of soil bed increases. Heat absorption, storage and insulation are the main factors in greenhouse. So, the results should be taken into account for a better design and run of a greenhouse.

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