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Simulation and optimization of solar greenhouses in Northern Jiangsu Province of China

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ABSTRACT

A simulating model was used to simulate and improve the thermal performance of solar greenhouses. Simulations with the weather conditions of Xuzhou, Jiangsu Province show that the greenhouse with clay brick wall (0.6 m thick) insulated with polystyrene boards (0.1 m) and the greenhouse with soil wall (3 m thick) perform better than the one with hollow concrete block wall (0.6 m thick). The lowest air temperature increases with thermal resistance and thermal inertia index of north wall. The thermal performance of the solar greenhouse with hollow concrete block wall can be improved by increasing the density and reducing the thermal conductivity of north wall. The soil wall can be conceptually divided into three layers from inside to outside: energy-storing layer, thermal stable layer, and thermal insulating layer. Thermal stable layer shrinks with the reduction of the size of north wall and it would disappear when the wall is reduced to a certain size. A trapezoidal soil wall with a top of 0.5 m and a base of 1.7 m appears to be a proper design if the air temperature is to be maintained above 10 °C under the weather conditions of Xuzhou, Jiangsu Province of China.

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1. Introduction

Solar greenhouses are mainly located in the northern region of China [1,2]. They are characterized by passive energy storage with no supplemental heating [3]. This gives them great advantage in term of energy efficiency over modern greenhouses where up to 75% of energy is used for heating in the countries in high latitudes [4].

Greenhouse passive heating has been studied by some researchers [5–7]. A solar greenhouse consists of south roof covered by a layer of plastic film, opaque north roof, a north wall, west and east end walls and a thermal blanket (Fig. 1). Passive heating is realized by north wall for storing solar energy [8,9]. Solar radiation transmits into the greenhouse through the south roof, and then is partially absorbed by the ground and walls. The temperatures of the interior surfaces rise as the absorbed solar radiation is converted to sensible heat. Then the heat transfers from the surfaces into the inside air via convection, and into the wall and ground via conduction. The solar radiation transmitted into greenhouse increases the temperature of both indoor air, and the walls and the ground. Meanwhile, part of the absorbed solar energy is transformed into latent heat by crop transpiration and evaporation from wet surfaces.

The north wall plays an important role in thermal insulation of solar greenhouse and it has been a pivotal topic in the optimization of solar greenhouse structure [10,11]. The materials and thickness of the north wall make differences on the microclimate inside solar greenhouse [12,13]. A number of studies have been done in an attempt to figure out proper north wall configurations that suit the local climate and economic conditions [14,15]. In recent years, greenhouse simulation models have been developed and used evaluate the thermal performance of north walls [16,17].

Greenhouse climate models play an important role in enhancing our understanding of the physics of greenhouse climate. They can be used to evaluate greenhouse designs or climate management strategies [18]. Many researchers have studied solar greenhouses by measuring the effects of various walls on indoor air temperatures [19–21]. However, long-term measurements are expensive and onerous. Hence, a generic model that predicts microclimate of solar greenhouses of any shape and size for any climatic conditions will be a valuable tool. Various models have been developed to predict solar greenhouse microclimate [4,22,23], but these models either lack the features we desire, or are not available for evaluation. A solar greenhouse thermal environment model,

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Notations

c	specific heat (J kg^{-1} °C^{-1})
D	thermal inertia index
d_i	thickness of the ith layer of wall (m)
T_L	lowest air temperature inside greenhouse (°C)
T_{fmax}	highest outdoor temperature of fine day (°C)
T_{fmin}	lowest outdoor temperature of fine day (°C)
T_{cmax}	highest outdoor temperature of cloudy day (°C)
T_{cmin}	lowest outdoor temperature of cloudy day (°C)
$\bar{T}_{max}$	average value of daily highest temperatures in January (°C)
$\bar{T}_{min}$	average value of daily lowest temperatures in January (°C)
T_{max}	extreme highest temperatures in January (°C)
T_{min}	extreme lowest temperatures in January (°C)
R_{ov}	total thermal resistance of north wall (m^2 °C W^{-1})
R_i	thermal resistance of the ith layer of wall (m^2 °C W^{-1})
R_{in}	heat resistance of inner surface (m^2 °C W^{-1})
R_{out}	heat resistance of outside surface (m^2 °C W^{-1})
S	thermal storage coefficient (W m^{-2} °C^{-1})
S_i	thermal storage coefficient of the ith layer of wall (W m^{-2} °C^{-1})
Z	temperature fluctuating period (s)

Greek letters

α_{in}	heat transfer coefficient of internal wall surface (W m^{-2} °C^{-1})
α_{out}	heat transfer coefficient of external wall surface (W m^{-2} °C^{-1})
λ_i	thermal conductivity of the ith layer (W m^{-1} °C^{-1})
λ	thermal conductivity (W m^{-1} °C^{-1})
ρ	density (kg m^{-3})

RGWSRHG, developed by the Key Laboratory of Agricultural Engineering in Structure and Environment, ministry of agriculture, China, has been extensively calibrated and validated [24,25]. The software based on the model is freely accessible.

In this study, we utilized the model to compare thermal performance of three solar greenhouses with different walls. Secondly, the effects of thermal resistance and thermal inertia index of north wall on the lowest air temperature inside greenhouse were studied using statistical analysis on the model simulation results. Thirdly, we examined how greenhouse thermal environment can be improved by manipulating the north wall materials and composition. Finally, we examined the temperature profile in the soil wall and investigated the effects of wall thickness on the temperature profile in the north wall and inside air temperature. The trapezoidal soil wall was optimized to minimize its cross section area.

2. Materials and methods

The model consists of modules for solar radiation, outdoor climatic conditions and five other modules that describe the components and processes exerting considerable effects on indoor thermal climate (wall, ground, covering material, air filtration and transpiration). Detailed model description can be found in Ma et al. [24]. Model inputs include greenhouse characteristics, crop, floor, geographic location and outdoor climatic conditions (Table 1). The tightness of greenhouse, crops density, and wetness of floor were treated in empirical ways in the model. We chose the common conditions in vegetable solar greenhouses as the inputs of the model. The outdoor climatic conditions consist of four temperature parameters: the highest and lowest temperatures during the fine day and those during cloudy days. The four temperature parameters are calculated by the following equations [24,26]:

$$T_{f\,max} = \bar{T}_{max} + 0.4 \times (T_{max} - \bar{T}_{max}) \quad (1)$$

$$T_{f\,min} = \bar{T}_{min} + 0.2 \times (\bar{T}_{min} - T_{min}) \quad (2)$$

$$T_{c\,max} = \bar{T}_{max} - 0.6 \times (T_{max} - \bar{T}_{max}) \quad (3)$$

$$T_{c\,min} = \bar{T}_{min} - 0.3 \times (\bar{T}_{min} - T_{min}) \quad (4)$$

where T_{fmax}, T_{fmin}, T_{cmax}, T_{cmin} are the highest and lowest outdoor air temperatures on sunny and cloudy days; $\bar{T}_{max}$ and $\bar{T}_{min}$ are the average values of the highest and lowest daily temperatures in January (the coldest month is January in China); T_{max} and T_{min} are the extreme high and low temperatures in January.

Three greenhouses (designated as greenhouse A, B, C) with the same geometric dimensions (length = 80 m; width = 9.8 m; height of ridge = 3.8 m) but with different north walls were simulated (Fig. 2). For greenhouse A, the north wall is constructed with clay bricks insulated with polystyrene boards in the middle; for greenhouse B, the north wall is constructed with hollow concrete blocks; for greenhouse C, the north wall is constructed with compact soil. The compositions and configurations of three types of wall are shown in Fig. 3. The material properties are given in Table 2. The height of north walls is 2.8 m. The thicknesses of three walls are 0.6 m, 0.6 m and 3.0 m (along the central median line), respectively. The width of top, base and central median line for the trapezoidal north wall of greenhouse C are 1.5 m, 4.5 m and 3.0 m, respectively.

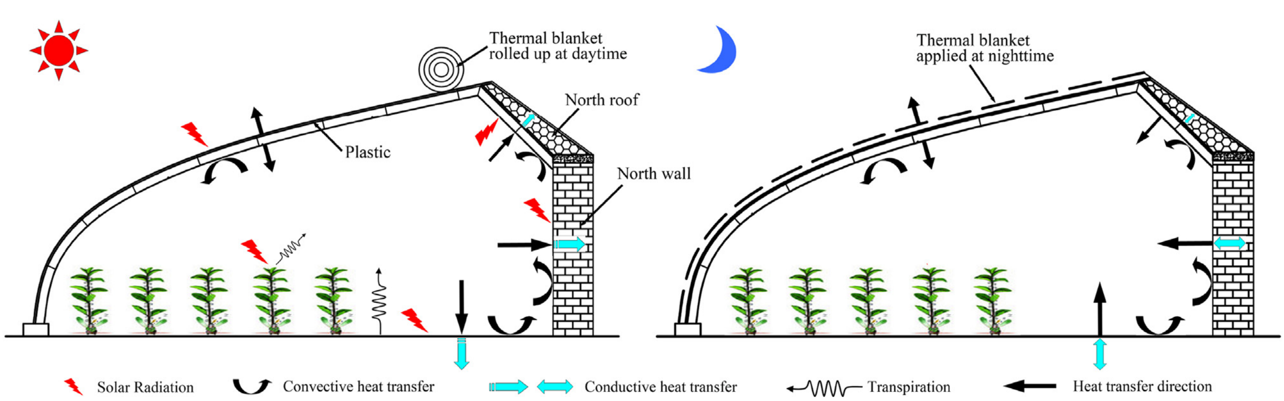

Fig. 1. Energy transfer modes in a solar greenhouse during the daytime and nighttime.

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