Solar Energy 165 (2018) 19–26

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A computational model to determine the optimal orientation for solar greenhouses located at different latitudes in China

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ARTICLE INFO

Keywords:
Solar greenhouse
Optimal orientation
Simulation
Field measurement

ABSTRACT

The orientation of solar greenhouses has a significant impact on the ability of the solar radiation energy received by the south pitched roof. In this study, based on the law of the solar trajectory and the theory of heat balance, the calculation model of the opening and closing time of the thermal insulation curtain for the south pitched roof of solar greenhouses in different latitudes is given. Using Extreme Value Theory, a method that can be used to determine the optimal orientation for solar greenhouses, i.e. to maximize the solar energy collection, has been proposed, with a consideration of impact from geographical latitude. To validate the proposed method, both simulation data (by EnergyPlus) and field measured data have been used and a good agreement has been observed. The model has been implemented to predict optimal orientations of solar greenhouse located at nine different regions, where solar greenhouses are mainly used in the northern China.

1. Introduction

Solar greenhouse is the local facilities agricultural architecture proposed by China, which can provide a suitable heat and humidity environment for vegetable crops by passive absorption of solar radiation (Ling et al., 2014, 2015; Wang et al., 2014). The orientation of solar greenhouse not only affects the sunshine time acceptable in solar greenhouse directly, but also affects the area of sunlight exposed to the walls and the ground of the solar greenhouse during the effective sunshine time (Dragicevic, 2011; Gupta and Chandra, 2002; Stanciu et al., 2016). Because of the dynamic change of solar trajectory and solar radiation intensity, it is important to determine the optimal orientation for solar greenhouses located at different latitudes, hence providing a balance between the indoor environment required by the vegetables or plants and greenhouse energy requirement.

However, the determination of the optimal orientation of greenhouse is not only directly related to the facility horticulture subject, but also closely related to the discipline of building physics and the discipline of building thermal environment. In the past, a lot of research of solar greenhouse orientation make the cultivation of vegetable crops as the center (Choi et al., 2008; Cao et al., 2009; Cheng et al., 2014). Because of the lack of support of the thermal theory of building, most of the solar greenhouse orientation is determined according to the field experience and lacks the scientific and quantitative guidance. The solar greenhouse orientation is just qualitative required by the Chinese standard of Structure and Properties Requirement for Sunlight Greenhouse and Plastic Tunnel (GB 19165-2003) CAAE (2003): *"solar greenhouses should be facing south, and the degree of movement from the true south to the west or east should be less than 10°"*.

In the study of greenhouse orientation, many scholars have carried out a large number of studies on the orientation of the glass greenhouse with double roofs. Dragicevic (2011) have tried to find the optimum orientation of an uneven-span single shape greenhouse and concluded that an east-west orientation should be preferred at latitudes of 44°N and 54°N as it receives less solar radiation in summer and provides higher air inside temperatures in winter. The amount of solar radiation received by five typical greenhouses has been estimated using a mathematical model developed by Sethi (2009) and the result recommended to use east-west orientation greenhouses at all latitudes on the northern hemisphere. Gupta et al. (2012) have used three-dimensional shadow analysis in AutoCAD to determine the best orientation for greenhouses and found that an orientation of 45° movement from the true south to the west resulted in highest solar collection during winter. El-Maghlany et al. (2015) analyzed the ability of receiving solar radiation by greenhouses at different locations and orientations and proposed that east-west orientation is most suitable for northern hemisphere applications, due to the maximum amount of heat captured. Both the architectural features and the construction forms of the double roofed glass greenhouse have great differences with the solar greenhouse discussed in this study, a calculation method suitable for

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https://doi.org/10.1016/j.solener.2018.02.022
Received 2 November 2016; Received in revised form 4 February 2018; Accepted 7 February 2018
0038-092X/

Nomenclature

Symbols

h	solar elevation angle, °
i	sunlight incidence angle, °
n	the typical winter time for off-season vegetable production
t_i	indoor air temperature, °C
t_o	outdoor air temperature, °C
t_1	opening time of thermal insulation curtain, h
t_2	closing time of thermal insulation curtain, h
q	daily cumulative solar irradiation, J
A	area of south pitched roof, m^2
I	solar radiation intensity, W/m^2
T_1	delay of the local sunrise time, min
T_2	ahead of the local sunset time, min
I_d	direct solar radiation, W/m^2
I_i	diffuse solar radiation, W/m^2
I_{ON}	solar radiation intensity at opening time of thermal insulation curtain, W/m^2
I_{OFF}	solar radiation intensity at opening time of thermal insulation curtain, W/m^2
I_0	solar radiation constant, W/m^2
K_f	heat transfer coefficient of plastic sheeting, W/(m^2 °C)
P	atmospheric transparency coefficient
Q_1	front roof radiant heat transfer, W/m^2
Q_2	front roof convection heat transfer, W/m^2
S	total solar radiation, J

Greek letters

α	solar azimuth angle, °
γ	solar greenhouse orientation, °
τ	plastic sheeting transparency, %
ϕ	latitude, °N
γ_{max}	optimal solar greenhouse orientation, °
δ	solar declination angle, °
ω	hour angle, °
θ	elevation of south pitched roof, °

solar greenhouse optimal orientation is urgently needed.

Chinese scholar Wei (1999) concluded that the orientation of solar greenhouse should be 5° movement from the true south to the west or to the east in the northern part of China, and the same solar energy can be obtained by the solar greenhouse when the degree of movement from the true south to the west or east is same. This conclusion is based on the theory that the cumulative sunshine time of the morning is the same as the afternoon, and it ignores the influence of the dynamic change characteristics of outdoor air temperature and atmospheric transparency. Zhang et al. (2010) analyzed the influence of solar greenhouse orientation to the opening and closing time of the thermal insulation curtain for the south pitched roof, and came to conclusion that the orientation should be 6–8° movement from the true south to the west for the overwintering planting pattern solar greenhouse, but the study did not take into account the impact of geographic latitudes. Li et al. (2003) analyzed the design principle of orientation and elevation angle of the front roof with the theory of the energy saving solar greenhouse in northwest China, and proposed that the best orientation of solar greenhouse in northwest China is true south or 5–8° movement from the true south to the west. At Shenyang, China (41.7°N), Bai et al. (2005) studied the influence of solar greenhouse orientation on the amount of entered sunlight, and the results showed that the optimal orientation of solar greenhouse at Shenyang was 5–6° movement from the true south to the west.

China has a vast territory, and the difference of climate and geographical features in different regions is great. What's more, the dynamic demand characteristics of the light and heat environment during the growth of vegetable crops are different. Therefore, it is important to form a calculation methods that can guide the optimization design of solar greenhouse orientation in different geographical latitude regions, so as to improve the efficient utilization of solar energy and improve production efficiency. In this study, a large number of theoretical analysis and experimental results about the thermal design of solar greenhouse of early research are combined. According to the heat transfer and the extreme value theory, this study regard the maximum solar radiation energy obtained from the south pitched roof of solar greenhouse as the research objective, and regard the sunshine time and sunshine quality available during the vegetable production as

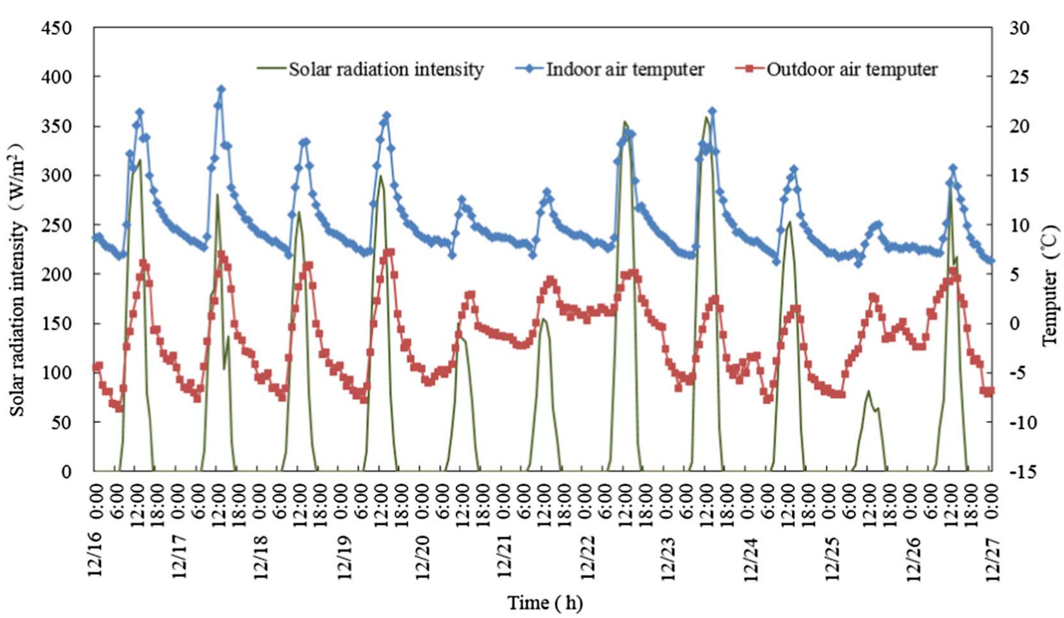

Fig. 1. Change rules of solar radiation intensity, indoor temperature and outdoor temperature of the solar greenhouse in Beijing.