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Numerical modelling of temperature variations in a Chinese solar greenhouse

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ABSTRACT

The time-dependent temperature distributions inside a Chinese solar greenhouse are numerically predicted from external climatic conditions using a computational fluid dynamics (CFD) analysis. The boundary conditions are based on hourly measured data for the solar insolation and the sky, soil (1 m below the soil surface) and outside air temperatures, plus other parameters describing the external convection and radiation. The numerical model takes into account all of the heat transfer mechanisms including the variable solar insolation, the air infiltration, the heat capacities of the thick walls and the ground and the natural convection inside the greenhouse. The temperatures were measured experimentally in an enclosed solar greenhouse with a 12 m span and 5.5 m ridge height during the winter in northern China with the south roof covered with a thin plastic film during the daytime and with a thermal blanket added at night to reduce heat losses. The large temperature variations in the greenhouse were measured and predicted for the climatic conditions in northern China during three clear days followed by a cloudy day during the winter. The simulated air and soil temperatures have the same profile as the measured temperatures with the average temperature differences between the simulated and measured air temperatures during the nighttime less than 1.0 °C on the clear days and no more than 1.5 °C during the entire cloudy day.

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1. Introduction

During the day, northern China experiences sunshine more than 50% of the time but the temperatures are very low during the winter with monthly daily average temperatures in the colder three months falling below −10 °C in northeast China. Greenhouses enable the extension of the crop growing season in the cold climatic conditions of northern China, so flowers and vegetables can be produced year round. However, in large glass-covered heated greenhouses, the heating accounts for 30–50% of the total production cost (Wang et al., 1999). The fuel consumption then becomes an important economic factor for the greenhouse production, with the utilisation of renewable energy as the main measure for resolving the problem. The greenhouse industry is one field that can effectively use renewable solar energy. The average ratio of the solar energy input to the total energy (solar energy input plus the fuel energy input) inside a large greenhouse with a double polyethylene film covering the top from November to March in Iraq was about 0.41 (Hasson, 1991). Chinese solar greenhouses are relatively small, simple, energy-saving greenhouses that have a plastic film (usually about 0.0001 m thick) covering the slanted front roof during the day with a thermal blanket added at night to maintain the heat inside. A typical greenhouse structure is shown in Fig. 1. Chinese solar greenhouses are widely used in northern China and can produce vegetables and fruits in severe cold areas from 32 to 41°N latitude, and even beyond 43°N latitude with little or no auxiliary heating. Statistics for the year 2000 showed that more than 2600 million m^2 of solar greenhouses were in use (Pan et al., 2005). These greenhouses produce 90% of the vegetables eaten in northern China in the winter (Li, 2004). However, the greenhouses experience large air temperature and humidity variations inside the greenhouse with the microclimate inside largely dependent on the external climatic conditions when no auxiliary heating is supplied inside the greenhouse. Therefore, accurate models are needed to predict the temperature fluctuations inside the greenhouses as functions of the external conditions to improve the structural design and climate control.

In China, considerable attention has been given to the solar energy efficiency in solar greenhouses. Solar radiation absorption in solar greenhouses has been numerically simulated in various studies (Sun et al., 1993; Du et al., 2001; Li and Chen, 2004). The air temperatures inside solar greenhouses with various types of walls, spans and heights have been measured and analysed

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Nomenclature

A	area (m^2)
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	total layer thickness (m)
d	individual layer thicknesses (m)
E	canopy transpiration ($kg\,m^{-2}\,s^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	latent heat of vaporization ($J\,kg^{-1}$)
l	length (m)
N	air change rate (s^{-1})
q	heat flux ($W\,m^{-2}$)
R	ratio
RH	relative humidity
T	temperature (K)
t	temperature (°C)
V	volume (m^3)
v	wind speed ($m\,s^{-1}$)
α	reflection of the ground
β	angle between the south roof plane and the horizontal plane (°)
ε	emissivity
ρ	density ($kg\,m^{-3}$)
ω	humidity ratio
θ	incidence angle (°)
τ	time (s)
τ_b	cover transmittance for beam radiation
τ_d	cover transmittance for diffuse radiation
η	view factor

Subscripts

a	air
ao	air outside
ab, *bc*, *cd*, *bd*, *ac*, *ad*	lines
b	beam solar radiation
c	cover
cond	condensation
d	diffuse solar radiation
dp	dew point
g	ground
eff	effective
encl	enclosure
i	number of each layer
inf	infiltration
l	latent heat
o	outside
r	north roof
re	reflection
s	sensible heat
sf	south roof
sky	sky
solar	solar insolation
w	north wall
z	horizontal

(Chen et al., 1990; Kang et al., 1993; Tao et al., 2002; Tong et al., 2003).

However, these repeated measurements are too expensive in terms of both material and labour, and the results are only useful for the specified experimental conditions and the specified designs. Hence, a theoretical model is needed to accurately predict temperatures inside various types of solar greenhouse designs for various climatic conditions. Various theoretical models have been developed to predict the temperatures inside solar greenhouses (Li et al., 1994, 1997), but these models all assume uniform temperatures in each part of the system.

However, the temperature variations in each part of the greenhouse system are actually very dynamic processes both in time and in space that are not accurately modelled by these lumped capacitance models.

Computational fluids dynamics (CFD) techniques provide powerful methods for simulating the time- and space-dependent microclimatic conditions within the greenhouses, and have been increasingly used in analysing greenhouse structures. Bartzanas et al. (2002), Fath and Abdelrahman (2004), Boulard and Wang (2002), and Molina-Aiz et al. (2004) numerically predicted air temperatures, air flows and/or humidity distributions inside greenhouses. However, these simulations were conducted for large plastic or glass greenhouses with the simulations using steady or quasi steady-state CFD models. Chinese solar greenhouses are relatively small with a large thermal masses in the walls and in the ground which have important influences on the thermal conditions; therefore, the rapidly varying solar input and environmental conditions are much better simulated using fully time-dependent simulations. The model used in this research accounts for the solar energy absorbed by and stored in the walls and the soil including the temperature variations within these structures with the calculations based on actual measured hourly variations of the climatic conditions and of the soil temperatures 1.0 m below the soil surface. The time-dependent temperature distributions in a greenhouse are predicted using CFD simulations of the entire system during three successive clear days followed by a cloudy day.

2. Materials and methods

2.1. Simulated solar greenhouse

The simulations were performed for a Chinese solar greenhouse aligned lengthwise in the east–west direction in Shenyang, China (latitude: 41.8°N, longitude: 123.4°E, altitude: 42 m). The cross-section of the greenhouse structure shown in Fig. 1 includes a thick wall on the north side, a partial roof on the north side and the cover over the southern part of the top. The greenhouse was 60 m long and 12.6 m wide. The north wall was a layered structure 0.6 m thick constructed of brick, Styrofoam insulation and an air layer. The 0.2 m thick north roof was made of layers of wood, Styrofoam and other structural materials. The cover on the south roof was made of a 0.00012 m thick polyvinyl chloride (PVC) film during the daytime with a 0.02 m thick cotton blanket laid over the roof each night. Therefore, during the daytime the south roof of the greenhouse was covered with only a thin plastic film to allow sunlight in but was covered with the thick cover at night to insulate the greenhouse. Lettuce was planted on October 20, 2003 in the eastern part of the greenhouse with the soil under the plants covered by a plastic film. The soil and potted plants in the western section of the greenhouse were covered with plastic.

2.2. Experimental setup

The measurements were taken in the centre cross-section of the greenhouse. During the experiments, the data acquisition system recorded the solar insolation on horizontal surfaces inside and outside the greenhouse and temperatures and humidities inside and outside the greenhouse. The measurement positions inside the central section of the solar greenhouse are shown in Fig. 2.

Sensors numbered from 00 to 39 and from RH3 to RH7 were installed on November 25, 2003 while the sensors numbered from 40 to 51 were installed on February 11, 2004.

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