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Original Research Paper

Modelling Greenhouse Thermal Environment in North China Based on Simulink

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ABSTRACT

This paper deals with the problem of modelling greenhouse indoor thermal environment in China. In order to achieve this goal, six main factors were taken into account in describing the greenhouse heat exchange with the outside, including solar radiation, artificial heating, long wave radiation, convection, ventilation and crop transpiration. According to the thermal balance principle of greenhouse, by quantizing vent opening, based on a design idea of Simulink platform, a non-linear differential mathematical model for simulating the greenhouse indoor air temperature was built. An experiment was taken to testify the validity of the simulation model in a Venlo type greenhouse in North China during spring. By using two groups of typical measured data in different weather conditions, the simulated value agreed well with the measured data. The results show that the standard errors in sunny and cloudy days are 0.6738°C and 0.3051°C respectively, as well as the index of simulation effectiveness is 81.17% and 82.12%. The results provide a basis of a model for the environmental regulation research on North China greenhouse.

INTRODUCTION

Modelling and numerical simulation of greenhouse microclimate (Bennis et al. 2008) not only contribute to the accurate prediction of greenhouse environment, but also can provide theoretical basis and practical guidance for the study on environmental control technology and greenhouse structural design. As one of the most sensitive environmental factors, temperature has a significant influence to the crop's various physiological phenomena and growth, so the research on greenhouse environment can start from the indoor thermal environment firstly.

In recent years, the domestic research on the greenhouse thermal environment is increasing gradually. But most research is aimed at the sunlight plastic greenhouse (Li et al. 2005, Meng et al. 2009), while the study of modern greenhouse is relatively less. Many studies abroad on the intelligent greenhouse have made a lot of progress (Fatnassi et al. 2009, Lamnatou et al. 2013, Chandra et al. 1981), however these researches cannot be used directly in China, due to the big regional differences, such as the structural characteristics and the management way (Wang et al. 2010, Xu et al. 2005).

To solve this problem, an experiment in a Venlo type greenhouse was carried out in North China during spring. Through the analysis of indoor and outdoor heat exchange, this research built a mechanical model of greenhouse indoor temperature. The study would provide a certain reference value and guiding significance to the development of Chinese modern intelligent greenhouse in the future.

MATERIALS AND METHODS

The Heat Balance Analysis of Greenhouse

(a) Heat source: 1. Solar radiation is the main heat source for greenhouse, which can be calculated as:

$$Q_{rad} = A_c R_a \tau_a \quad ...(1)$$

Where,

R_a- Total solar radiation reaching at the greenhouse surface, w/m^2

A_c- The covering surface area, m^2

τ_a- The total light transmittance of cover material, related to the material types, degree of cleaning and aging

2. The heating pipe energy exchange belongs to the convective heat transfer, follows the Newton's law of cooling (Lamrani et al. 2001):

$$Q_{heater} = 1.95 A_p (T_p - T_i)^{4/3} \quad ...(2)$$

Where,

A_p- The surface area of hot water pipes, m^2

T_p- The temperature of hot water pipes, K

T_i- The indoor air temperature, K

(b) Heat expenditure: According to the heat transfer analysis, greenhouse heat expenditure mainly includes the following aspects:

1. The long-wave thermal radiation from greenhouse covering to the sky, which follows Stefan - Boltzman's law

(Wu et al. 2007):

$$Q_{crad} = \varepsilon_{12} A_c \sigma (T_i^4 - T_o^4) \quad ...(3)$$

Where, σ-Stefan-Boltzmann constant, w/m²/K⁴; T_o-The outdoor temperature, K; ε_{12} - United emissivity between greenhouse surface with outside air emission rates, calculated by $\varepsilon_{12} = (\varepsilon_1^{-1} + \varepsilon_2^{-1} - 1)^{-1}$, ε_1 ε_2 - the emissivity of sky and greenhouse covering respectively.

2. According to the Newton's law of cooling, convection exchange between greenhouse covering and outside air is:

$$Q_{cac} = K_v A_c (T_i - T_o) \quad ...(4)$$

Where, K_v - cover material heat transfer coefficient of wind speed, w/m²/K. In Venlo type greenhouse, K_v = 2.8+1.2v (Roy et al. 2002), v - the average wind speed of outdoor, m/s.

3. Natural ventilation is the main way to regulate indoor environment. According to the related theory and method (Li et al. 2005), the greenhouse ventilation heat can be calculated as:

$$Q_{vent} = \frac{G_v (c_p \rho)(T_i - T_o)}{3.6} \quad ...(5)$$

Where, G_v - greenhouse ventilation quantity, m³ / hr, related to the wind speed v, the vent area of A_v, the open degree of vents U, and the wind correction coefficient K_d (when the wind direction is perpendicular to the greenhouse vents K_d =1), so under the condition of natural ventilation, there is $G_v = K_d U A_v v$.

4. Evapotranspiration energy consumption:

$$Q_{tran} = \lambda E A_s \quad ...(6)$$

Where, λ - latent heat of evaporation, MJ/kg; E - the measured crop evapotranspiration, kg/m²/s; A_s - crop planting area, m²

Besides, there were some other energy exchanges, such as underground heat transfer, crop photosynthesis, respiration, condensation and evaporation of water vapour, which are negligible relative to the above forms, thus they were all omitted in this research.

(c) Heat balance equation: According to the principle of greenhouse thermal equilibrium, the greenhouse dynamic mathematical model was built (Ding et al. 2009):

$$\Delta Q = V \rho c_p \frac{dT_i}{dt} = Q_{rad} + Q_{heater} - Q_{crad} - Q_{cac} - Q_{vent} - Q_{tran} \quad ...(7)$$

Where, dT_i / dt means the change rate of indoor temperature.

Test situation: The experiment was carried out in a Venlo type greenhouse (Model: V96) in North China Institute of Water Conservancy and Hydroelectric Power, Henan Province, in May 2014. The test greenhouse is equipped with heating, ventilation, fertigation, sunshade and computer centralized control system, which has a total area of 537.6 m² (19.2×28), a span of 9.6 m, roof height of 4.73 m, roof angle of 22°, top ventilation of 27%, and domestic cover material of 4 mm float glass.

The greenhouse model specific parameters are given in Table 1.

Test method: This experiment took greenhouse eggplant in North China as the research object. The measured data include: outside total radiation, indoor and outdoor air temperature and humidity, soil humidity, wind speed and direction outside, and the open degree of vents, u=[0, 1, 2], where 0-no ventilation, 1-open skylights only, 2-open skylights and side windows at the same time. All the above data were collected automatically by indoor all-weather test measurement system and outdoor weather instrument, setting the acquisition time step for 30 min.

This paper chose the data for April 27th (sunny) and April 30th (cloudy) as the typical research, which contained the two kinds of typical climate characteristics and have certain representativeness.

Simulink model: As shown in function (7), the mathematical model of greenhouse temperature is a nonlinear differential equation. And there are complex correlativity among the various parameters and variables, which cause a certain difficulty for the direct calculation (Bennis et al. 2008). In this paper, based on the idea of sub-modular design, the function (7) is represented as a Simulink block diagram to be calculated, using the Simulink toolbox (Fig. 1).

As shown in Fig. 1, this block diagram has three inputs (Ra, Gv, To) and one output (Ti). The sub modules (Q_{rad}, Q_{heater}, Q_{crad}, Q_{cac}, Q_{vent}, Q_{tran}, *detaQ*) are respectively established according to the functions (1)-(7).

Table 1: Table of model parameters.

Parameters	Symbol	Value	Units
Greenhouse volume	V	2150.6	m³
Indoor air density	ρ	1.2	kg/m³
Indoor air specific heat	c_p	1006	J/kg/K
The covering surface area	A_c	927.6	m²
The surface area of hot water pipes	A_p	73.9	m²
Crop planting area	A_s	510	m²
Vent area	A_v	145.2	m²
Light transmittance of glass	τ_a	0.89	1
Emissivity of glass	ε_1	0.9	1
Emissivity of air	ε_2	0.9	1
Stefan-Boltzmann constant	σ	5.67×10^{-8}	w/m²/K⁴

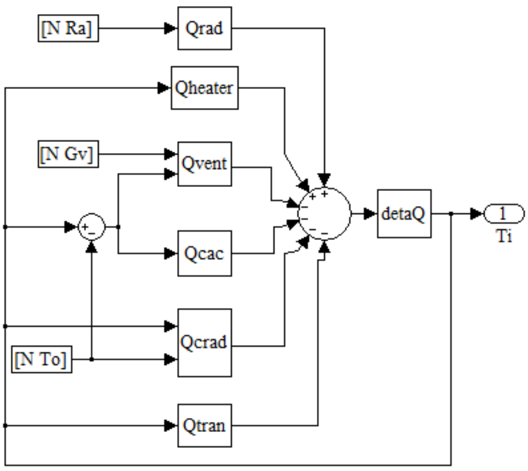


Fig.1: The simulink simulation model of temperature in greenhouse.

RESULTS

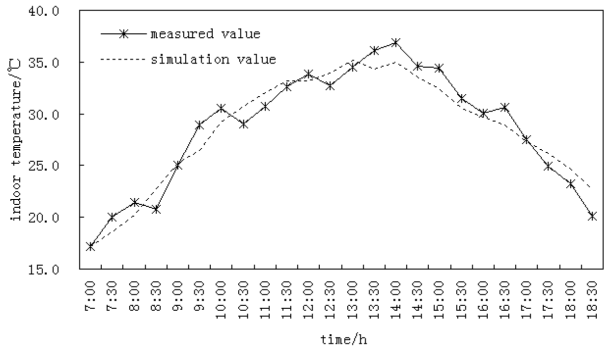
Using the two typical days data respectively for April 27th (sunny) and April 30th (cloudy) to verify the indoor temperature simulation model, results are shown as follows.

The fitting curves of the model are shown in Fig. 2, where the solid line and dotted line represent the measured value and the simulation value of the indoor temperature respectively. The simulation results indicate that, regardless of sunny or cloudy weather, the simulation curve fits the measured curve well, it is a consistent trend. On a sunny day, the maximum relative error between the simulation value and the measured value (RE_1) was 11.34%, root mean square error ($RMSE_1$) was 0.6738°C. On cloudy day, the indoor heat changed relatively smoothly, the maximum relative error (RE_2) was 5.63%, and the root mean square error ($RMSE_2$) was only 0.3051°C.

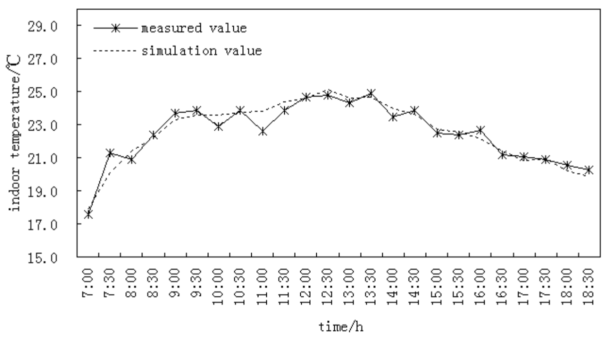
The correlation analysis of the simulation value and the measured value are shown in Fig. 3. Both were positively related, the related equations were respectively y1 = 0.9008 + 2.6705x and y2 = 0.8992 + 2.2614x, and the correlation coefficients were $R_1^2 = 0.9404$, $R_2^2 = 0.933$. The results show that there was no significant difference.

In order to test the degree of effectiveness of this model, the effectiveness index (Kumar et al. 2002) was calculated by the formula as follows:

$$EF = \left[1.0 - \frac{\sqrt{\sum_{i=1}^{N}(y(i) - y_m(i))^2}}{\sqrt{\sum_{i=1}^{N}(y(i) - \bar{y})^2}} \right] \times 100\% \quad ...(8)$$

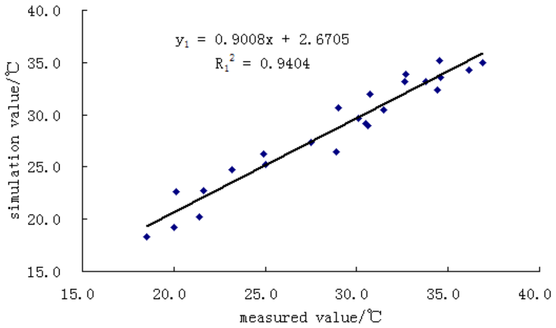


(a) 4.27 (sunny)

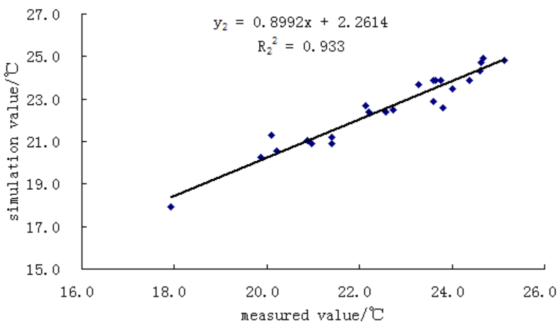


(b) 4.30 (cloudy)

Fig.2: Simulation results of the Simulink model.



(a) 4.27 (sunny)



(b) 4.30 (cloudy)

Fis. 3: Correlation analysis between the simulation and measured values.

Where, N - the number of samples, $y(i)$ - the system actual measured value, $\bar{y}$ - the average of measured value, $y_m(i)$ - the simulation value of the model.

Through calculating, the model simulation effectiveness index was 81.17% on sunny day and 82.12% on cloudy day respectively, which illustrated that the greenhouse thermal dynamic model built in this paper was effective.

DISCUSSION

According to the characteristics of Venlo type greenhouse in North China, the dynamic simulation model of greenhouse thermal environment was built, in the way of modular, based on Simulink toolbox. The simulation results show that no matter how the weather is outside, this model can effectively forecast the indoor temperature, and the simulation error of the model was within the permitted scope, which indicated the model was effective.

In addition, this paper has studied only on the thermal environment of greenhouse. However, some other environmental parameters, such as humidity, sunlight and CO_2, are also important to greenhouse production. Thus, how to build a comprehensive greenhouse environment model needs further research.

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