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The study on heat transfer model of covering layer of multi-span plastic greenhouse

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ABSTRACT

In order to study the heat transfer characteristics of covering layer of multi-span greenhouse, took the temperature condition as the main research object, the basic theory of heat transfer and mass transfer and the local climate condition as bases, established the thermal environmental model of plastic greenhouse covering layer. Used the mathematical software MATLAB, and the Runge - Kutta method to solve the thermal environment model, and the experimental data was used to test this model. The results showed that: the early winter, greenhouse production, the standard error of estimate RMSE was 0.82 between the covering layer simulation temperature and the measured temperature, the average absolute error within ±1.08 ℃; the winter, greenhouse idle stage, the standard error of estimate RMSE was 0.46 between the covering layer simulation temperature and the measured temperature, the average absolute error within ±0.38 ℃; the model had good simulation accuracy.

KEYWORDS

Multi-span greenhouse; Covering layer; Heat transfer model.

INTRODUCTION

The light-permeable covering surface is an important greenhouse structure. The nature of greenhouse covering material has a great influence on the quantity and quality of greenhouse light. The heat transfer characteristics of covering materials affect the heat preservation effect of the greenhouse. The outdoor climate and the thermal properties of covering material are the main determinant factors of the indoor micro-climate in greenhouse In addition to the artificial interference (ventilation, structural design and direction)[1]. Therefore, it is significant to explore the heat transfer characteristics of greenhouse covering materials for the greenhouse production. In recent years, foreign scholars have conducted many researched on the models and simulation of greenhouse covering materials. Poly-2 research team, USA, has developed a greenhouse environment model, by which the inner and outer surface temperatures are calculated for the covering materials through Euler integral method[2]. P. Feuilloley[3] and G. Issanchou[4] have created a theoretic model of heat transfer in covering materials comprehensively. Ling Jian, Li Yicui, Qiu Jianjun, et al have created a theoretic model of simulating the greenhouse heat transfer when they studied on the property of covering materials[5-7]. Li Shuhai, Ma Chengwei et al have constructed the heat environmental model for multilayer coverage and multi-span greenhouse[8]. The present paper uses the steady-state heat transfer theory and mass-energy balance principle; creates a heat energy equilibrium equation for the plastic coverage layer of multi-span greenhouses according to the characters of modern greenhouse; and verifies the model accuracy by comparing the simulative results through tests.

CREATION AND SOLUTION OF HEAT ENERGY BALANCE EQUATION OF COVERING LAYER

Creation of heat energy balance equation of covering layer

The sunlight penetrates through the covering layer and enters into the greenhouse during the daytime. Some of thermal radiation is absorbed by the light-permeable covering layer and the other penetrates the covering surface into the greenhouse. The light-permeable covering surface absorbs a part of direct sunlight, scattered light and indoor reflected light whilst it exchanges the heat with the ground and retaining layer in radiating way and exchanges the heat with the indoor and outdoor air in convective way. See Figure 1 for the heat transfer principle of the covering layer in greenhouse. We here omit the influence of condensation on the permeable lights by considering that the condensation occurs on the covering surface typically at night when the sunlight is weaker. It is assumed as below: ①the greenhouse covering layer is homogeneous and clean in the surface; ②neglecting the heat radiation; ③ it is deemed that there is no difference in the temperatures between inner and outer surfaces and the average temperature is T_c.

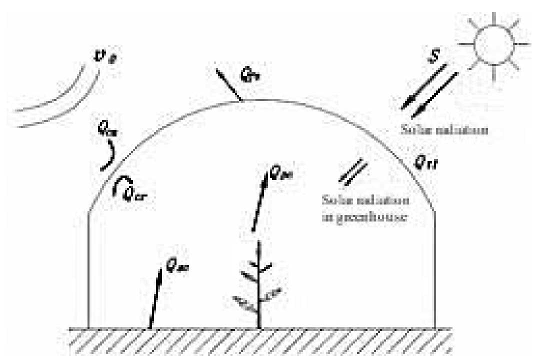

Figure 1 : Heat transfer theory of greenhouse covering layers

The heat transfer coefficient of greenhouse covering material is not associated to the characteristics of the covering material itself, but also to the actual use condition of the covering materials, namely, it is related to the outdoor solar radiation background, indoor and outdoor temperature difference and outdoor wind velocity.

The energy balance equation of greenhouse covering layer is calculated as per equation:

$$Q_c = Q_{cr} - Q_{ca} + Q_{t1} - Q_{f\alpha} + Q_{pc} + Q_{sc} \quad \textbf{(1)}$$

(1)Q_c is the energy provided by the covering layer (J/s):

$$Q_c = H_c\left(\frac{dT_c}{dt}\right) \quad \textbf{(2)}$$

Where, H_c is the heat capacity of covering layer, J/□; T_c is the temperature of the covering layer,□.

The heat capacity of a substance is the product of specific heat of a material and the quality of such material, so the formula for the heat capacity of covering layer is as below:

$$H_c = cm = c\rho V = c\rho A_c d \quad (3)$$

Where, c is the specific heat capacity of the covering material, KJ/(kg·℃); ρ is the density of the covering material, kg/m^3; A_c is the area of the covering area, m^2; *d is the thickness of the covering material*, m.
(2)Q_{cr} is the exchanged heat in convective way between covering layer and air inside the greenhouse (W); Q_{ca} is the exchanged heat in convective way between covering layer and air outside the greenhouse (W):

$$Q_{cr} = h_{cr} A_c (T_r - T_c) \quad (4)$$

$$Q_{ca} = h_{ca} A_c (T_c - T_a) \quad (5)$$

Where, T_r is the indoor air temperature, ℃;T_a the outdoor air temperature, ℃; h_{cr} is the coefficient of convective heat transfer between the covering layer and the indoor air, W/(m^2·℃); h_{ca} is the coefficient of convective heat transfer between the covering layer and the outdoor air, W/(m^2·℃);A_c is the area of covering layer, m^2.

Coefficient of convective heat transfer between inner side of covering material and indoor air is h_{cr}, Coefficient of convective heat transfer between outer side of covering material and indoor air is:

h_{ca}[9]: $$h_{cr} = 2.21(T_r - T_c)^{1/3} \quad (6)$$

$$h_{ca} = 7.2 + 3.84 v_o \quad (7)$$

Where, v_o is the outdoor wind velocity, m/s, measured by test.
(3) Q_{t1} is the solar energy absorbed in the covering layer (W):

$$Q_{t1} = \alpha_c s A_c \quad (8)$$

Where, α_c is the heat energy absorption rate of covering material.

(4)$Q_{f\alpha}$ is the reflective solar radiation in covering layer (W):

$$Q_{f\alpha} = f_c s A_c \quad (9)$$

Where, f_c is the reflective rate of solar radiation of the covering material.
(5)Q_{pc} is the reflective solar radiation of plants (W/m^2):

$$Q_{pc} = f_p \tau_c s A_c \quad (10)$$

Where, f_p is the reflective rate of solar radiation in plants.
(6)Q_{sc} is the reflective solar radiation of soil (W/m^2):

$$Q_{sc} = f_s (1-\alpha_p) \tau_c s A_c \quad (11)$$

Where, f_s is the reflective rate of solar radiation of soils.

The ratio of the radiation absorbed by an object to total radiation projected onto such object is called as an absorption rate of object to radiation. The ratio of radiation reflected by an object and the total radiation projected onto the surface of such object is called as the reflectivity of the object to radiation. The ratio of radiation permeated through an object and the total radiation projected onto the surface of such object is called as the transmissivity of the object to radiation[10]. Their relationship is absorption rate + reflectivity + transmissivity =1, namely: $\alpha_c+f_c+\tau_c=1$. The reflectance rate of ground is depended upon the ground nature and state. For the greenhouse soils, the reflectivity f_s of solar radiation is at about 10%~35%; typically, it is less in plant growth seasons and it is larger in the plant non-growth seasons.

Substituting the equation ② through ⑧ in equation ①, give the heat energy balance equation of the covering layer:

$$H_c\left(\frac{dT_c}{dt}\right) = h_{cr} A_c (T_r - T_c) - h_{ca} A_c (T_c - T_a) + \alpha_c s A_c - f_c s A_c + f_p \tau_c s A_c + f_s (1-\alpha_p) \tau_c s A_c \quad (12)$$

Solution method of model

In daytime, the temperature model of the covering layer is:

$$H_c\left(\frac{dT_c}{dt}\right)=h_{cr}A_c(T_r-T_c)-h_{ca}A_c(T_c-T_a)+\left[\alpha_c-f_c+f_p\tau_c+f_s(1-\alpha_p)\tau_c\right]sA_c \quad \textbf{(13)}$$

At night, the temperature model of the covering plate without solar radiation is:

$$H_c\left(\frac{dT_c}{dt}\right)=h_{cr}A_c(T_r-T_c)-h_{ca}A_c(T_c-T_a) \quad \textbf{(14)}$$

Divide by H_c on each side of equation ⑭, gives:

$$\frac{dT_c}{dt}=\frac{h_{cr}(T_r-T_c)A_c}{H_c}-\frac{h_{ca}(T_c-T_a)A_c}{H_c}+\frac{[\alpha_c-f_c+f_p\tau_c+f_s(1-\alpha_p)\tau_c]sA_c}{H_c} \quad \textbf{(15)}$$

From the above equation, the temperature of covering layer T_c is an ordinary differential equation about time t, where, T_r, T_a, v_o and s values appropriate to t time can be given by test. H_c, α_c, f_c, τ_c, α_p, f_p and f_s are determined by test conditions.

Providing $T_c=y$, $t=x$, $\frac{h_{cr}A_c}{H_c}=m$, $\frac{h_{ca}A_c}{H_c}=n$, $\frac{[\alpha_c-f_c+f_p\tau_c+f_s(1-\alpha_p)\tau_c]sA_c}{H_c}=w$, $T_r=a$, $T_a=b$, then, equation ⑮ is converted to

$$\frac{dy}{dx}=m(a-y)-n(y-b)+w=-(m+n)y+ma+nb+w \quad \textbf{(16)}$$

The general solution above equation is:

$$y=C_1e^{-(m+n)x}+\frac{ma+nb+w}{m+n} \text{ (C}_1\text{ is a constant)} \quad \textbf{(17)}$$

That is, the general solution of simulated temperature of covering layer in the daytime is:

$$T_c=C_1e^{-\frac{(h_{cr}+h_{ca})A_c}{H_c}t}+\frac{h_{cr}T_r+h_{ca}T_a+[\alpha_c-f_c+f_p\tau_c+f_s(1-\alpha_p)\tau_c]s}{h_{cr}+h_{ca}} \text{ (C}_1\text{ is a constant)} \quad \textbf{(18)}$$

Similar, the general solution of simulated temperature of covering layer at night is:

$$T_c=C_2e^{-\frac{(h_{cr}+h_{ca})A_c}{H_c}t}+\frac{h_{cr}T_r+h_{ca}T_a}{h_{cr}+h_{ca}} \text{ (C}_2\text{ is a constant)} \quad \textbf{(19)}$$

C_1 and C_2 are determined with the measured value of greenhouse environmental factors one day before the simulation day as the initial conditions. For the solution of above ordinary differential equation, it is a complicated and time-consuming process. We used the classical Runge-Kutta[11] (4-order Runge-Kutta) method to simulate numerically with the MATLAB software in order to reduce the artificial calculation load and give more accurate solution.

Simulation and verification of temperature model of covering layer

In test of model, the conformity is used for analysis between the estimated standard error (RMSE) and relative error (RE) in the common statistical regression. RMSE and RE can be calculated respectively using the following two formula[12]:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}(OBS_i-SIM_i)^2}{n}} \qquad RE=RMSE/\left[\left(\sum_{i=1}^{n}OBS_i\right)/n\right]\times 100\%$$

Where, BSi is the measured value, here referring to the temperature of covering layer in greenhouse; $SIMi$ is the simulative value, here referring to the simulative temperature of covering layer, n is the sample size. *The less the RMSE* is, the less the deviation between the simulative and measured values is and the higher the predicted accuracy is in the model[12].

TABLE 1 : Symbolic significance and relevant parameters values

Symbol	Symbolic significance	Parameter	Unit
H_c	The heat capacity of cover layer	$211.6 \times A_c$	J/℃
t	Time	3600	s
h_{cr}	The coefficient of convective heat transfer between cover layer and indoor air		$W/(m^2 \cdot ℃)$
h_{ca}	The coefficient of convective heat transfer between cover layer and outdoor		$W/(m^2 \cdot ℃)$
v_o	The outdoor wind speed		m/s
A_c	The effective coverage area of the greenhouse		m^2
T_c	The cover layer temperature		℃
T_r	Indoor air temperature		℃
T_a	The outdoor air temperature		℃
s	Outdoor solar total radiation		W/m^2
α_c	The heat absorption rate of covering materials		
f_c	The solar radiation reflectivity of cover material	$\alpha_c+f_c+\tau_c=1$	
τ_c	The solar radiation transmittance of cover material		0.8
f_p	The solar radiation reflectivity of cucumber	0.1	
f_s	The solar radiation reflectivity of soil	0.1	
τ_p	The solar radiation transmittance of cucumber	0.1	

TEST CONDITION AND METHOD

Test condition

The test was done in the multi-span plastic greenhouse of Shanxi Agricultural University in Nov.-Dec., 2012. The basic greenhouse structure is illustrated in Figure 2. The greenhouse is a 4-span steel structure framework arch in north-South direction. The covering material is 0.1mm-thick PE film with a coverage area 2640m^2, 34m width, 40m length, 3.5m height, 5.5m ridge height, 6620m^3 interior volume, and 8m span. It is double-layer plastic thermal insulation film with internal aluminum foil insulation curtain wall at 80% shading rate. The back, i.e. northern, wall is a masonry structure at 37cm thickness, 3.5m height, 34m length, 112m^2 wall surface area. The wall is provided with 6 2m-wide and 1.5m-high wet-curtain cooling system. The fan is installed south of the greenhouse, and one fan is installed.

Figure 2 : The experimental greenhouse

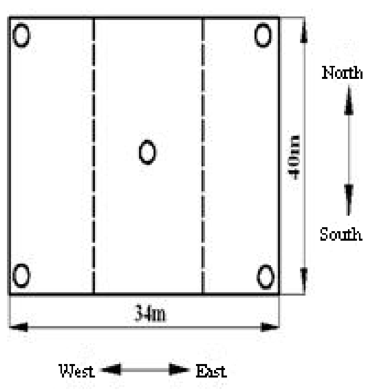

Figure 3 : Mensuration dots distribution of greenhouse

Test method

The main factors, such as indoor temperature, are distributed unevenly as the inner greenhouse environment is affected by many factors. 5-spot measurement method is applied in order to reduce the errors for the measured values of these factors, namely, 4 corners and a center 1.5m above the ground are selected in the greenhouse. The individual sampling time is 10s and the time interval is 5s. The measured values of 5 spots for inner greenhouse environmental factors are averaged as shown in Figure 3.

The test is mainly based on the "facility and environmental lab". Small agricultural meteorological station is used to determine the outdoor wind velocity, temperature, humidity and solar radiation intensity with a record step by 10min. The temperature and humidity are measured using the multi-channel temperature and humidity recorder in each spots with a record step by 10min. The temperature of covering layer is measured with thermal resisters. According to the test conditions, the calculated heat capacity H_c=2.116×area of covering layer =211.6×A_c; the measured absorption rate of solar radiation of covering materialα_c=0.1, the reflectivity f_c=0.1 and the transmissivity τ_c=0.8. The absorption rate of solar radiation in plants α_p=0.55, the reflectivity f_p=0.1, the reflectivity of ground solar radiation f_s=0.1.

RESULT AND ANALYSIS

Simulation and analysis of temperature in covering layer in greenhouse production stage

Test I was done in the multi-span plastic greenhouse of Shanxi Agricultural University in 12~25, Nov. 2012. The basic greenhouse structure is illustrated in Figure 2. The test is designed to mainly understand the influence of covering layer on greenhouse in early winter. In the test, the cucumber growth is at harvesting period. During the test, the outer solar radiation, air temperature and relative humidity are lower. The change of temperature in covering layer is mainly subject to the indoor air temperature, solar radiation and wind velocity.

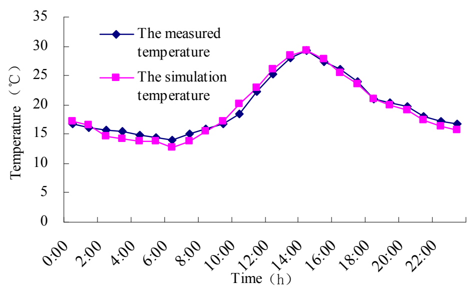

Figure 4 : The comparison between actual temperature and simulation temperature in November

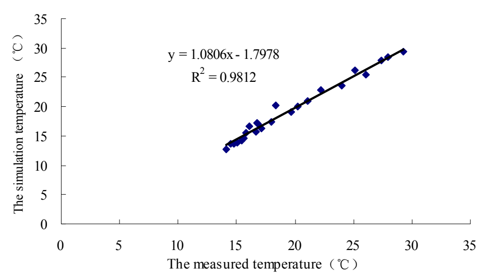

Figure 5 : The fitting between actual temperature and simulation temperature in November

Figure 4 shows the comparative analysis between measured average temperature and simulative value of covering layer in greenhouse. As you can see from Figure 4, the measured temperature is not completely consistent with the simulative temperature in the covering layer. In most of the time, the calculated temperature is higher or lower than the real temperature in the covering layer, but both are more consistent. In particular, the error is less between 11:00~17:00. The correlation coefficient test (Figure 5) shows that the regression equation y=1.0806x-1.7978, the correlation coefficient R^2=0.9812, the regressive straight line is fit well, the estimated standard error RMSE is 0.82, the simulative and measured values are deviated less up to a better accuracy, the average relative error RE is 4.21%, the relative error between simulative and measured temperatures in covering layer falls within ±1.08 and the simulation results are in good agreement with the experimental data.

Simulation and analysis of temperature of covering layer in greenhouse idle stage

Test II was done in the multi-span plastic greenhouse of Shanxi Agricultural University in 17~26, Nov. 2012. In the test, the cucumber have been harvested, the ventilation window on both sides of the greenhouse have opened. In the winter when the crops are not growing in the greenhouse, the plant item may be omitted in the temperature model of covering layer under the present study, namely, the model is converted to:

$$H_c\left(\frac{dT_c}{dt}\right)=h_{cr}A_c(T_r-T_c)-h_{ca}A_c(T_c-T_a)+\alpha_c sA_c-f_c sA_c+f_s\tau_c sA_c=h_{cr}A_c(T_r-T_c)-h_{ca}A_c(T_c-T_a)+(\alpha_c-f_c+f_s\tau_c)sA_c$$

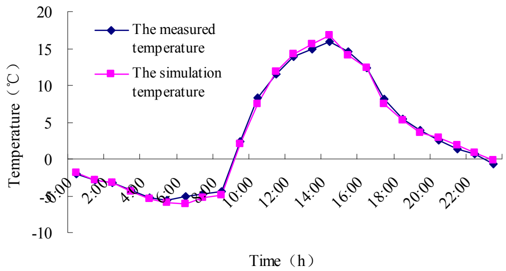

Figure 6 : The comparison between actual temperature and simulation temperature in December

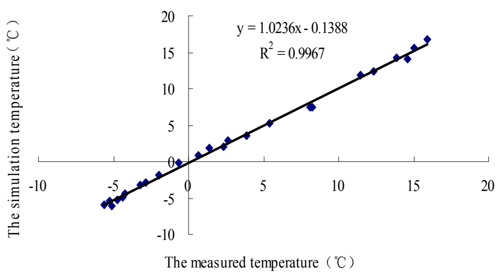

Figure 7 : The fitting between actual temperature and simulation temperature in December

Figure 6 shows the comparable analysis of averaged measured and simulative temperature of greenhouse covering layer in December. As you can be seen from the Figure 6, the temperature of covering layer rise with the rising of the sun in the cold winter; the indoor temperature decreases and the temperature of covering layer declines quickly with the with the sun setting; Within the daytime when the solar radiation is intense (10:00~16:00), the simulative temperature of covering layer is lower than the measured temperature thanks to the outside weather temperature and solar radiation. At night, the simulative temperature of covering layer is slightly higher than the measured temperature thanks to the indoor temperature lower than the outdoor one. When the indoor air exchanges heat with the covering layer, it brings away the partial heat of the covering layer so that the temperature of covering layer declines. The correlation coefficient test (as shown in Figure 7) shows that the regression equation y=1.0236x-0.1388, the correlation coefficient R^2=0.9967, the regression straight line is fit well, the estimated standard error RMSE is 0.46, the simulated value is less deviated from the measured value up to a higher accuracy. The average relative error RE is 9.75%, the absolute error between the simulative and measured temperatures of the covering layer falls within ±0.38□. The simulative result is in good agreement with the experimental data.

CONCLUSION AND DISCUSSION

The present study creates the thermal environment steady-state model of plastic multi-span greenhouse from the basic theories, such as the heat transfer, mass transfer and local climate conditions; highlights on the solution of the thermal environment model of the greenhouse covering layer; and verifies the simulative model according to the experimental data. The results shows that the average absolute error falls within ±1.08□ between simulative and measured temperature of covering layer, the average relative error of model is 4.21%, the estimated standard error RMSE is 0.82 during the greenhouse production in early winter; the average absolute error falls within ±0.38□ between simulative and measured temperature of covering layer, the average relative error of model is 9.75%, the estimated standard error RMSE is 0.46, the model has a fine fitting accuracy during the greenhouse idle period.

For heat transfer model of covering layer in the plastic multi-span greenhouse created under the present study, is established in this study, only the cucumber is considered in model verification experiment, and no other crop is verified and simulated and no heat radiation is considered. Owning to the experimental condition restriction, only one factor, namely the temperature of covering layer in greenhouse, is simulated. This inevitably leads to the errors for verifying the model accuracy. In forward study, we will continue to simulate the other restrictive factors and other crops with expectation to score a better simulative overcome and further verify the model accuracy.

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