第19卷 第5期 农业工程学报 Vol 19 No. 5
2003年 9月 Transactions of the CSAE Sept 2003

Substrate heating system with solar energy for greenhouse

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Abstract: Aiming at solving the problem of lower temperature, which restrains plant development, production and quality in greenhouse during wintertime, a system was introduced which could store solar energy in substrate maintain the soil temperature to meet the crop requirement for growing well. This research was conducted mainly by mathematical simulation and the regression analysis in the SAS Software. The result showed that the system could efficiently increase the soil temperature and reduce range of soil temperature fluctuation in the greenhouse during wintertime. And there was a transition layer of the substrate temperature between the storing one and heating one, in which the temperature did not vary with the time, but the others did. The research proved that the simulation result showed good agreement with the measured one. The difference method was used to calculate the heat diffusion coefficient and it was accurate enough. It was also confirmed that the optimizing areas ratio of solar collector of the system to cultivation field is 1∶5, which could meet crop growth requirement all the year round in the study situation. In a word, the system could accomplish the goal of storing solar energy in summer and utilizing in winter, storing it in daytime and utilizing in nighttime, storing it in sunshiny day and utilizing in cloudy day, for raising substrate temperature to meet the plant growth requirement without any other energies.

Key words: greenhouse; solar energy; substrate heating; numerical simulation
CLC number: S214.3; S625.3; S625.4 **Document code**: A **Article ID**: 1002-6819(2003)05-0197-07

1 Introduction

One of the variables with the greatest influence on the physiological response of plant is soil temperature. The roots of crop are frequently subjected to temperature below the optimum level for the yield[1~3]. Consequently, the use of soil heating systems may be convenient and beneficial to both the yield and quality of products. Thus the greenhouse soil heating installations have become standard technical equipment in modern greenhouse facilities[4~6]. Therefore, various authors successfully tested the use of heat in the environment where roots of the crops grow, and the heat was usually supplied by warm water pipes with the gas, coal or oil as energy resources[4~7, 13~19].

An alternative solution for substrate heating is the use of a solar energy collecting-heating system which combines all the advantages common to the rest of the systems, such as cleanliness in the consumption, security and continuity in the supply, easy control and versatile application with economic operation[8~10]. These advantages can compensate for the higher price of facility with respect to other resources.

Analysis and definition of phenomena occurring in the course of heat and mass transfer in the substrate enables the development of mathematical models of the process, each model calculating different variables in this process. Using these models, it is possible to compare heating systems for maximum efficiency. In some published papers, fragmentary research results have been provided, but a comprehensive analysis is adj still lacking, especially for solar greenhouse[7~9]. The objectives of this work were (a) to define the solar substrate heating system configuration and the operating conditions to produce the best energy and economic results and (b) to model a heated substrate by the solar energy heating system for solar greenhouse in order to predict the substrate temperatures and to estimate the power efficiency and thermal structure of heated substrate.

2 Material and methods

2.1 Experimental greenhouses

The experiments were conducted in a 234 m^2 solar greenhouse with popular structure in China[1~4, 7, 9], which was located in the north part of Beijing. In the greenhouse, there were two identical areas of 39 m × 6 m, which were thermally insulated from each other and given identities Ⅰ and Ⅱ. In the area Ⅰ, the heating system was installed for optimum soil temperature, meanwhile the Ⅱ was taken as the comparison. Throughout the experiment, cucumbers

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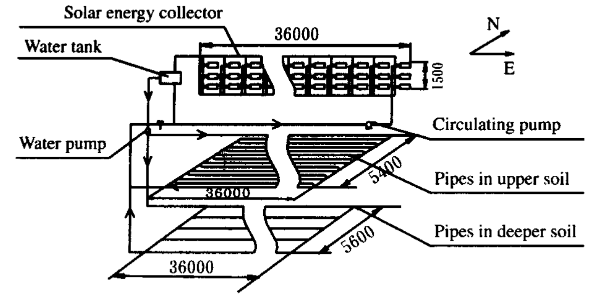
Received date: 2003-07-01
Foundation item: Project from Ministry of Education, China (2002); Administrative Office of Study Abroad of Shaxi Province (98066)

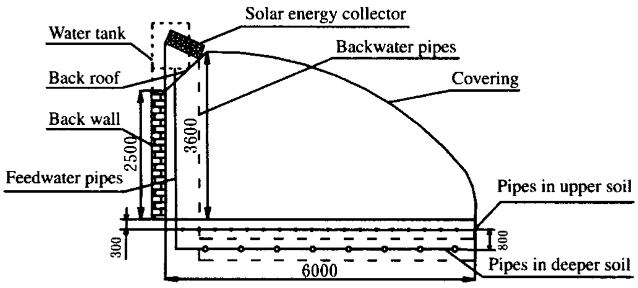
Biography: Wang Shuangxi, Professor, Engineering and Technology College, Shanxi Agricultural University, Taigu 030801, China were cultivated in both areas of the greenhouse.

2.2 Solar energy substrate heating system

As shown in Fig. 1 shown, the solar energy substrate heating system includes three parts: the solar energy collector with the width of 150 cm, similar to the width of the back roof of the solar greenhouse, length of 3600 cm, almost the same length of the greenhouse, and height of 40 cm installed on the back roof of the solar greenhouse. The installed highest point is just 40 cm higher than the ridge height of the greenhouse. The substrate heating part by means of PVC pipes buried in the upper soil and storing part by means of steel pipes buried in the deeper soil, and the circulating part included water tank and pump.



a. Plan view



b. Cross section

Fig. 1 Diagram on installation of solar substrate heating system

The pipes were equidistant from each other to ensure a uniform distribution of the heat. The diameter of the PVC pipes buried at depth of 30 cm was 7.5 cm, and the distance between one pipe and its neighbors was also 30 cm, for heating soil directly. Steel pipes with diameter of 14 cm were buried at depth of 80 cm with distance between one and the other being 80 cm too, for increasing the thermal inertia of the system and substrate and making the best use of heat at night, or cloudy day and so on. Because of the short distance between pipes, the whole substrate layer in which the pipes were placed was considered to have a uniform temperature[13,17~19]. This allowed heat conduction to be considered as one-dimensional instead of two-dimensional and the experimental design to be simplified with sensors placed only in the vertical dimension[14~17]. The set point temperature for the heating of the substrate was 18℃ measured at a depth of 20 cm, for the storing water in steel pipes was 80℃ and for the heating water in PVC pipes was 60℃, the temperature values were reported by Romero, Martinez and Wu et al[10,12~15,17].

1.3 Experimental designs

The design parameters in this investigation of the solar substrate heating installation with two kinds of depth were those which either could heat the substrate directly or could accumulate the heat generated by the solar energy collector for gradual release to the crop roots when there was no sunshine. In both pipes, a device mounted monitored water temperature and flow. Using the monitoring device, coefficients of heat exchange between pipes and soil could be calculated. In the course of the study, heating was available on demand in solar energy collector throughout the investigation. And the heating system was switched on automatically when the substrate temperature fell below 18℃.

The following conditions were monitored during the two years research (Apr. 2001～Apr. 2003): air temperature, radiation and humidity both inside and outside the greenhouse, the substrate temperature inside the greenhouse. The temperature of the substrate was measured at 30 min intervals using RHLOG-11 (made in Tsinghua Tongfang, China), in which the sensors were placed at different depths as shown in Fig. 2.

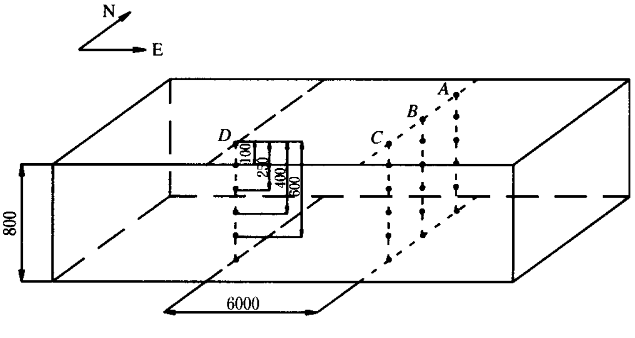


Fig. 2 Sensor placement for measuring substrate temperature of greenhouse

The air and soil humidity was measured also at 30 min intervals, using RHLOG-Ⅳ (made in Tsinghua Tongfang, China). The radiation and air temperatures both inside and outside the greenhouse were recorded by means of Hobo-boxcar (made in U.S.A).

3 Numerical simulations

3.1 Model of calculating coefficient heat diffusion (α)

Heat transfer by conduction in substrate has been defined by the conductivity equation

$$c\rho\frac{\partial T}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2} \tag{1}$$

Where, T is the temperature of substrate, K; t is the time, s; λ is the thermal conductivity of substrate, W/(m · K); ρ is the substrate density, kg/m^3; c is the volumetric heat capacity, J/(m^3 · K).

For simplification, assuming c, ρ and λ as constant.

In the case of the solar greenhouse, for solving the above equation, the following assumptions were made:

1) The substrate is porous, homogeneous and isotropic.

2) The heat transfer in the substrate occurs exclusively through conduction, while the contact resistance at the interface between the heating pipe and substrate is neglected.

3) At any time, the temperature of substrate varies almost in the same way on the given horizontal surface except for the boundary.

4) During the very short time, the heat diffusion coefficient is constant in the limited thickness of the substrate, for the moisture content and the heating pipe materials are also constant in the entire analysis process.

5) The temperature of soil surface varies similarly in sine function with the time of a day-night.

Thus, equation (1) can be expressed as

$$\begin{cases} \dfrac{\partial T}{\partial t} = \alpha\dfrac{\partial^2 T}{\partial x^2} \\ T(x, t) = T_0 + A\sin\omega t \ (x = 0, \ t \geq 0) \end{cases} \tag{2}$$

Where, T_0 is the average temperature of soil surface; $\omega = 2\pi/p$, p is the periodicity of the soil surface heat variation, here the value is as a day-night time, s. $\alpha = \lambda/c\rho$, a is the coefficient of heat diffusion, m^2/s. A is the daily amplitude of the substrate temperature variation. These equations with initial-boundary conditions were solved by the differential method[13~16]. The result is

$$T(x, t) = T_0 + A e^{-x\sqrt{\pi/(\alpha p)}}\sin\left[\frac{2\pi}{p}\left(t - \frac{x}{2}\sqrt{\frac{p}{\alpha\pi}}\right)\right] \tag{3}$$

Where, $T(x, t)$ is the variation of the temperature at any depth of the substrate at any time.

2.2 Initial and boundary conditions of the model

As discussed above, the coefficient of heat diffusion is essential in the model for the necessity of discussion as follows. There are many elements, such as soil texture, soil structure, soil aeration and saturated water content which influence the heat diffusion of the substrate, and it is difficult to define them either mathematically or experimentally. Fortunately, the coefficient of heat diffusion can be defined in equation (2) by the difference method. In equation (2), it could use difference as a substitute for differential and it is

$$\begin{cases} \partial T/\partial t = [T_i(t + \Delta T) - T_i(t)]/\Delta T \\ \partial^2 T/\partial x^2 = [T'_{i+1}(t) - 2T'_i(t) + T'_{i-1}(t)]/\Delta x^2 \end{cases} \tag{4}$$

Where the subscript i denotes the each separate node in the space of the substrate. Then substituting equation (4) for equation (2) and simplying gives

$$\frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{\alpha_{i+\frac{1}{2}}^{j+\frac{1}{2}}(T'_{i+1} - T'_i) - \alpha_{i-\frac{1}{2}}^{j+\frac{1}{2}}(T'_i - T'_{i-1})}{\Delta x^2} \tag{5}$$

Where the superscript j denotes the each time when the substrate temperature is measured or calculated. Furthermore, assuming the α being equal anywhere at an indicated depth of the substrate, the result is

$$\alpha = \frac{\Delta x^2}{\Delta t} \cdot \frac{T_i^{j+1} - T_i^j}{T'_{i+1} - 2T'_i + T'_{i-1}} \tag{6}$$

With $T' = (T^{j+1} + T^j)/2$, where Δt is the time interval, s; Δx is the depth space between upper and deeper substrate, m.

The initial and boundary conditions may be beyond human control or may be caused by human action, such as heating. The temperatures of substrate surface and substrate base, throughout the simulation, were the upper and deeper boundary conditions, while the temperatures of all the nodes at the beginning of the simulation were the initial condition, Boundary and initial conditions were measured and supplied to the model throughout the simulation time. When heating in operation, the model did not calculate the temperature of the node where the heating pipe was placed. It was a heat source and thus it was included within model as an additional boundary condition. That was not a model input, but a function that was estimated and included in the computer programmer. When the heating pipe was not in operation, the temperature of the node where the pipe was placed was also calculated using the model.

3 Result and discussion

3.1 Estimating α

For the most vegetation, the depth of 10~25 cm is the likely depth of the greatest root density, following the recommendation of Merbaum, Li, et al[6, 10 12~14]. Wu, Chang, Ma and Yang also pointed out that the greatest root concentration of the crops, such as aubergine, cucumber and tomato[1~3, 6~7, 10~12], was centralized near the depth of 15 cm in the substrate. Therefore, in the equation (6) making Δx is 15 cm, t is 1 h, and with the measured data of the substrate temperature in area Ⅰ, the α_{I} of the heated soil in Ⅰ is calculated as shown in table 1, the value of α_{I} is

$$\alpha_{\mathrm{I}} = (1/n)\sum_{i=1}^{6}\alpha_i = 9.77 \times 10^{-3}\ cm^2/s$$

The α_{II}, the heat diffusion coefficient for area Ⅱ, as comparison, is calculated as shown in table 2. The result of the α_{II} is as

$$\alpha_{\mathrm{II}} = (1/n)\sum_{i=1}^{6}\alpha_i = 8.04 \times 10^{-3}\ \mathrm{cm}^2/s$$

Table 1 Calculated results of α_{I} for Ⅰ

No.	1		2		3		4		5		6	
	j	$j+3\Delta t$	j	$j+3\Delta t$	j	$j+4\Delta t$	j	$j+\Delta t$	j	$j+3\Delta t$	j	$j+2\Delta t$
T_{i+1}	14.36	14.23	14.11	13.98	13.98	13.86	16.37	13.86	16.71	16.37	15.67	15.44
T_i	15.67	15.56	15.56	15.44	15.44	15.32	15.44	15.32	15.56	16.14	16.37	16.25
T_{i-1}	16.71	16.71	16.71	16.71	16.71	16.60	16.48	16.60	16.48	16.60	16.71	16.71
α_i	9.98×10^{-3}		10.42×10^{-3}		10.41×10^{-3}		8.33×10^{-3}		8.76×10^{-3}		10.71×10^{-3}	

Table 2 Calculated results of α_{II} for comparison area Ⅱ

No.	1		2		3		4		5		6	
	j	$j+\Delta t$	j	$j+\Delta t$	j	$j+\Delta t$	j	$j+\Delta t$	j	$j+\Delta t$	j	$j+\Delta t$
T_{i+1}	13.11	12.98	12.85	12.73	12.6	12.47	15.32	15.67	14.36	14.11	13.98	14.11
T_i	14.23	14.11	14.11	13.98	13.98	13.86	16.82	16.71	14.96	14.84	14.72	14.84
T_{i-1}	14.36	14.36	14.36	14.36	14.36	14.36	17.28	17.28	14.48	14.48	14.60	14.48
α_i	7.98×10^{-3}		8.55×10^{-3}		7.98×10^{-3}		9.05×10^{-3}		6.94×10^{-3}		7.73×10^{-3}	

Comparing the a_{I} with a_{II}, it is the heated substrate with higher temperature that possesses the greater coefficient of heat diffusion in value than that of unheated one. That is to say, besides the natural elements, the heat diffusion of the substrate could be easily regulated through heating by human being.

3.2 Validation of the model

In order to investigate the varying pattern of the substrate temperature with the depth during a day-night time, the nonlinear regression analysis was conducted by using the computer program of SAS. The data were analyzed with substrate depth from 0 to 25 cm during the time from November 2002 to March 2003; the regressive results are shown in table 3 as simulation. In Fig. 3 and 4, the simulations are compared with the measured ones.

In the table 3, it is obviously demonstrated that the heated substrate in Ⅰ, which is heated by solar energy collecting—heating system, owns the higher mean temperature of 1.08℃ than that of the unheated one in comparison Ⅱ. In other words, it is the deeper pipes acting as accumulator in system that can raise the temperature of the thermostatic layer of substrate up to more than 1℃, which is much beneficial for the crop production when there is no sunshine for a longer time. Moreover, the smaller varying amplitude of 1.22℃ in Ⅰ means that the heated soil temperature is more harmonious for crop root growth.

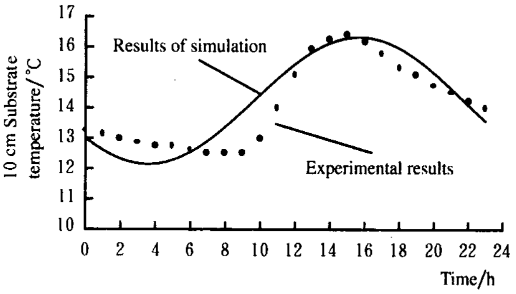


Fig. 3 Experimental results vs the simulation of 10 cm substrate temperature

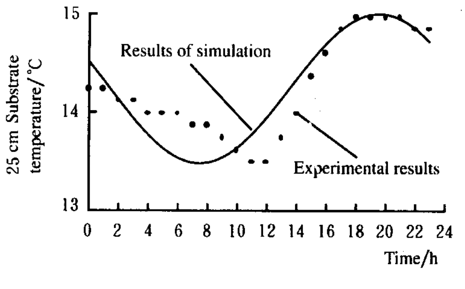


Fig. 4 Experimental results vs the simulation of 25 cm substrate temperature

Table 3 Results of nonlinear regression analysis of varying temperatures of substrate

	∂	Regression equation	Amplitude/℃	R^2
Ⅰ	3.52×10^{-3}	$Y_1 = 15.32 + 2.88e^{-6.1}$ $\sin(0.26t - 6.1x - 1.83)$	2.88	0.95
Ⅱ	2.89×10^{-3}	$Y_2 = 14.24 + 4.1e^{-6.73}$ $\sin(0.26t - 6.73x - 1.83)$	4.10	0.95

The higher heat diffusion coefficient of 0.63×10^{-3} in the heated substrate of Ⅰ could helpfully make the air temperature in the greenhouse to be reasonable for crop growing during the wintertime. The analysis further showed that the coefficient of heat diffusion could significantly be affected by different factors such as heating intensity and water content in the substrate.

The comparison between the measured and theoretically calculated temperature data showed that the suggested mathematical models correctly defined the temperature changes in substrate heated by the system. And they could be a kind of useful tool with which to assess and predict the varying trend of substrate temperature, the energy consumption of heating, and to evaluate the efficiency of the design parameters in heating system.

For the relationship of the air temperature with the substrate one, the results of regression analysis are shown in table 4.

Table 4 Regression analysis of the air temperatures with soil temperature in Ⅰ ℃

	Regressive equation	R^2
Inside air temperature (Y) to substrate one (t_s) of surface	$Y = 7.98 + 0.6t_s$	0.99
Inside air temperature (Y) to substrate one (t_s) of 10 cm	$Y = 16.16 + 0.1t_s$	0.93

Here a fact should be pointed out that the outside ambient temperature in daytime is practically no bound up with the soil temperature, due to the ventilation and solar radiation, thus the regression analysis was carried out from the 14:00 pm to 8:00 am. As a result, the analysis indicated that degree of the soil temperature influencing the air one in a greenhouse distinctly varied with the depth of the substrate. The deeper it goes in the substrate, the less it affects air temperature, with the degree decreasing from 6 to 1 point (Fig. 2) as the depth from zero to 10 cm. This finding may prove the two kinds of ideas: one is that accumulating the heat in the deeper substrate when the upper soil heat is adequate, and using it when the soil heat is deficient are feasible, efficacious and reasonable; the other one is that the higher surface temperature of the substrate is beneficial to the lower air temperature for the crop growing well.

The measured results also show that the depth of 40 cm was the layer of transition for the substrate temperature. That is to say, there was no temperature variation at this depth anywhere in both Ⅰ and Ⅱ. It was more than 2℃ that the heated substrate owned the fundamental temperature than the unheated one from this depth to deeper ones after heated for an week. From the depth of 40 cm to 80 cm, the temperature varying amplitude became greater with the substrate being deeper, for the heat accumulating pipes buried at the depth of 80 cm in Ⅰ, but there was practically no temperature varying of the substrate at the same depth of Ⅱ. On the contrary, upwards of the depth 40 cm, the temperature varying amplitude was evidently smaller in Ⅰ than that in Ⅱ, where the mean temperature was about 1.5℃ higher in the former than the latter. In a word, the heating system made this contrary effect with the depth of 40 cm as the layer of the transition in the researched situation. And as known well, the moderate temperature varying in the plant roots zone is advantageous to the crops growing.

3.3 Ratio of the collecting area to heated area and its effect

In the course of the study, to determine the area of solar energy collector, the heat energy balance on the soil heat collection and output should be conducted for the optimum substrate heating. The analysis has been affected by the recurrent element of the installation. Leaving out the process, the following should be mentioned: the air temperature in greenhouse is on the constant basis of 15℃ and changeable uniformly over this basis anywhere in it at a time. The ambient temperature outside greenhouse is -12℃, the characteristics of the heat diffusion in the base of the greenhouse are all the same at any direction and position. Thus, the average supplementary heat for the testing greenhouse was 90713.41 kJ, which was calculated with the data from Apr. 2001 to Apr. 2002; the efficiency of the collector was 41.2%, which was determined by experiment at the testing site; the accumulated value of irradiance was 7640 kJ/m^2, which was the average value from 1990 to 1998. Finally, the analysis indicates that the optimum ratio of the solar energy collecting area to the heated area could be 1∶5. Fortunately, the further exacting text has verified this ratio as a fact, which is reasonable for the optimum substrate heating in researched situation.

The heating function of the system in cloudy weather is shown in Fig. 5 and 6, which was the substrate temperature varying on December 23, 2002 (the fifth day of the cloud with snow). Comparing the Fig. 5 for heated substrate with Fig. 6 for unheated one, conclusions can be drawn that the system can enhance the air temperature of the greenhouse being more than 1.3℃, the upper layer substrate temperature (0～40 cm) more than 2.2℃ and the deeper layer one (40～80 cm) more than 2.6℃ averagely. The Fig. 5 and 6 also reveals that the deeper pipes of the system own the more power (2.6℃) than the upper ones (2.2℃) to maintain the temperature of the substrate at the higher temperature for a longer time.

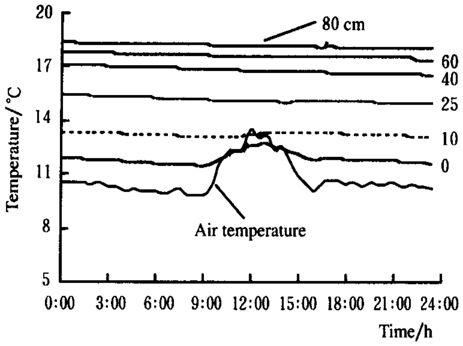


Fig. 5 Temperature varying trend on the cloudy day in Ⅰ

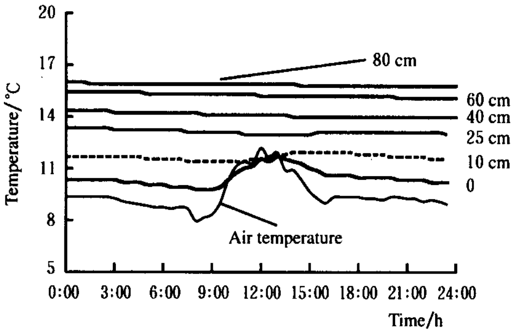


Fig. 6 Temperature varying trend on the cloudy day in Ⅱ

By the way, for the economics, the system was able to save the coal of 2700 kg monthly during the winter of 2002 with consuming the electricity of no more than 87 kW·h, for system operating to make the substrate temperature reasonable. But the price of the system is relatively high that makes the payoff period be more than 6 years. However, it should be believed that with the improvement of the technology, the system could be further perfected with practicable price.

5 Conclusions

1) The solar energy system can efficiently increase and maintain the soil temperature to meet the plant-growing requirement.

2) Although the coefficient of heat diffusion varies with many factors of the soil, and is difficult to be determined, the difference method is effective for handling with it accurately to meet the cases of the substrate heating of greenhouse.

3) There is a transition layer for the substrate temperature between the storing pipes and heating one. The temperature does not vary with the time in the transition layer, but the others do.

4) The soil temperature influencing the air one in a greenhouse distinctly varies with the depth of the substrate. The deeper it goes in the substrate, the less it affects on air temperature.

5) The optimum ratio of the solar energy collecting area to the heated area could be 1∶5, that is reasonable in the substrate heating in the researched situation.

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节能温室太阳能土壤蓄热加温系统的研究

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摘 要: 为了改善节能温室冬天植物栽培生产地温低, 严重影响植物生长发育, 影响温室生产产量和品质的问题。以数学模拟和回归实验相结合的方法, 研究了温室土壤的太阳能蓄热加温系统。研究结果表明: 系统能有效的提高地温, 减少地温的变化幅度; 在以加热管形成的浅层土壤温度层和以蓄热管形成的深层土壤温度层之间具有一个过渡层, 和其它层不一样, 这个过渡层的温度是不随时间变化的; 以 SAS 软件拟合的非线性方程为基础的土壤温度场的数学模型的模拟结果与实验结果吻合较好; 选用差分法计算的土壤热扩散率精确度高, 符合实验及生产实际要求; 由温室热平衡方程确定的太阳能集热器面积与温室种植面积的优化比例为 1∶5, 经试验验证, 在目前技术状态下, 该比例能满足作物冬季生长对土壤温度的要求。总之, 研究的太阳能蓄热系统实现了太阳能夏天贮冬天用、日间贮夜间用、晴天贮阴天用的目的, 从而在不消耗任何二次能源的条件下, 能满足温室作物的正常生长要求。

关键词: 温室; 太阳能; 土壤加温; 数学模拟