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Solar Energy - Latent Heat Storage System for Greenhouse Heating

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ABSTRACT

Two types of solar energy - latent heat storage system have been developed to minimize the fossil fuel consumption and maximize the solar energy utilization in greenhouse heating during the winter season. The one was installed on the greenhouse floor, and the other in the underground of the greenhouse. Sodium sulphate decahydrate was selected as a highly concentrative solar energy storage medium and its unstable thermo-physical properties were adjusted by some additives. Thermal efficiency of them was analyzed by numerical and experimental method.

INTRODUCTION

The traditional agriculture is a process for the bioenergy production from the solar energy by the crops in the natural weather conditions, but in these days the modern agriculture may be approached to the produce of the bioenergy in the natural weather as well as in the artificial weather conditions.

To control the weather conditions artificially in the protected agriculture the use of fossil fuel consumption may be increased rapidly. For example the consumption of fossil fuel for greenhouse heating in accordance with the increase of greenhouse cultivation area has been increased rapidly every year, therefore it is desirable to minimize the fossil fuel consumption and to maximize the solar energy utilization for the greenhouse not only for the high quality and low cost crop production but also for the maintenance of the rural environment without pollution.

In this study, to maximize the solar energy utilization for greenhouse heating during the winter season, two types(Prototype I, Prototype II) solar energy - latent heat storage systems were constructed, and the thermal performance of the systems have been analyzed numerically and experimentally to obtain the basic data for the realization of greenhouse solar heating system.

MATERIALS AND METHODS

1. Selection and Stabilization of Phase Change Materials(PCM)

To minimize the consumption of fossil fuel of which the price fluctuation may be unstable and undesirable and to keep the rural environment without pollution, it is desirable to store solar energy concentratively in PCM for greenhouse heating during the winter season. $Na_2SO_4 \cdot 10H_2O$ has been selected as a solar energy storage material. And its unstable thermophysical properties has been stabilized with the addition of the nucleating and thickening agent. In consideration of the range of the air temperature variation in greenhouse, the melting point of PCM was controlled from 30℃ to 13~18℃ with the addition of urea, and for the degradation test of thermophysical properties of PCM, phase change cycles of 600 times has been repeated, the results were shown in Table 1.

2. Solar Energy - Latent Heat Storage System

For the greenhouse heating by solar energy, two types of solar energy - latent heat storage system have been developed as follows.

2.1 Solar energy-latent heat storage system installed on the greenhouse floor(Prototype I)

The solar energy - latent heat storage system(prototype I) has been installed on the floor of the greenhouse that the optimum area ratio for the greenhouse heating (the floor area / the wall area) was 0.65.

The size of prototype I(PI) was determined in consideration of the air temperature in greenhouse, the surplus solar energy, the greenhouse heating load and the thermal storage characteristics of PCM($Na_2SO_4 \cdot 10H_2O$). and PCM mass per unit area(m^2) of the greenhouse bed soil surface of 16.5 kg/m^2 could be determined by the greenhouse heating load.

As shown in Fig. 1, PI was consisted of part ① and part ②. Th solar energy could be stored in part ① by the radiation and cenvection heat transfer and in part ② by the only convection heat transfer.

For the part ①, PCM tubes(PCM melting point of 30℃, tube diameter of 50 mm) painted with non-glossy black color were arranged laterally on the pannel with the tilt angle of 50° toward the south.

Part ② was set up backward the part ①, and the PCM tubes(PCM melting point of 15℃, tube diameter of 30 mm) were arranged on the several horizontal shelves.

The solar thermal energy has been stored in the part ② by the forced convection that the heated air(20~25℃) in greenhouse was circulated by the air blower among the PCM tubes.

2.2 Solar energy-latent heat storage system installed in the underground of greenhouse(Prototype II)

Prototype II(PII) has been installed in the underground of greenhouse that the optimum area ratio for the greenhouse heating was 0.65. And the size of prototype II was determined by the same process as prototype I, and the PCM mass loaded in PII was also 16.5 kg/m^2. But in case of PII design, the forced convection of the heated air only was considered as the means of heat transfer, because it has been installed in the underground of greenhouse.

The phase change temperature of PCM has been controlled as about 13℃~17℃ by the addition of urea(melting point control agent) in consideration of greenhouse air temperature level and the rectangular tubes(20×70×450mm) filled with PCM have been arranged on the shelves of unit storage element (500×450×500mm) and PII was consisted of several unit storage elements as shown in Fig. 2.

To enlarge the cultivable area, PII has been installed in the depth of 1,100mm from greenhouse bed soil surface, and the bottom and walls of it have been insulated with styro-foam to prevent the heat loss to the soil layer.

And during the day to store in PCM the surplus solar energy in greenhouse and during the night to use the energy for greenhouse heating, the air in greenhouse has been circulated through the shelves loaded with PCM tubes.

3. Theoretical Investigation

In this study, the greenhouse - PII has been only analyzed by the theoretical model derived in section 3.1, because PII had more advantages than greenhouse - PI for the realization approach.

3.1 Governing equations of the energy balance of greenhouse - prototype II

As shown in Fig. 3, the thermal energy distribution of greenhouse - prototype II was visualized by thermal resistance network. And on the basis of this network, five thermal energy balance equations were derived at the five temperature nodal points.

3.1.1 The energy balance equation on the greenhouse cover

The energy balance equation at the temperature nodal point of the greenhouse cover in Fig. 3 was derived as follows.

$$Q^{sr}_{sun-c} + Q^{rad}_{c-sky} + Q^{rad}_{c-agr} + Q^{conv}_{c-aa} + Q^{conv}_{c-ia} + Q^{rad}_{c-f} + Q_c + Q_{wc} = 0 \quad (1)$$

where ;

Q^{sr}_{sun-c} : solar energy arrived on greenhouse cover(w)

Q^{rad}_{c-sky} : radiation heat transfer between greenhouse cover and sky(w)

Q^{rad}_{c-agr} : radiation heat transfer between greenhouse cover and outside ground(w)

Q^{conv}_{c-aa} : convection heat transfer between greenhouse cover and ambient air(w)

Q^{conv}_{c-ia} : convection heat transfer between greenhouse cover and the air in greenhouse (w)

Q^{rad}_{c-f} : radiation heat transfer between greenhouse cover and greenhouse floor(w)

Q_c : internal energy change of greenhouse cover(w)

Q_{wc} : energy change by moisture balance on greenhouse cover(w)

3.1.2 The energy balance equation in the air of greenhouse

In Fig. 3 the energy balance equation at the temperature nodal point of the air in greenhouse was derived as follows.

$$Q^{conv}_{ia-c} + Q^{conv}_{ia-f} + Q^{conv}_{ia-Lo} + Q^{vent}_{ia-aa} = 0 \quad \text{-----} \quad (2)$$

where ;

Q^{conv}_{ia-c} : convection heat transfer between the air in greenhouse and greenhouse cover(w)

Q^{conv}_{ia-f} : convection heat transfer between the air in greenhouse and greenhouse floor(w)

Q^{conv}_{ia-Lo} : convection heat transfer between the air in greenhouse and PCM surface(w)

Q^{vent}_{ia-aa} : ventilation heat transfer between the air in greenhouse and ambient air(w)

3.1.3 The energy balance equation on PCM surface

In Fig. 3 the energy balance equation at the temperature nodal point of PCM tube surface was derived as follows.

$$Q^{conv}_{Lo-ia} + Q_L + Q_{wLo} = 0 \quad \text{-----} \quad (3)$$

where ;

Q^{conv}_{Lo-ia} : convection heat transfer between the air in greenhouse and PCM tube surface(w)

Q_L : sensible and latent heat stored in PII or released from PII(w)

Q_{wLo} : energy change by moisture balance on PCM tube surface(w)

3.1.4 The energy balance equation on soil surface in greenhouse

In Fig. 3 the energy balance equation at the temperature nodal point of soil surface in greenhouse was derived as follows.

$$Q^{sr}_{sun\ f} + Q^{cond}_{f-ug} + Q^{conv}_{f-ia} + Q^{rad}_{f-c} + Q_{wf} = 0 \quad (4)$$

where ;

$Q^{sr}_{sun\ f}$: solar energy arrived on the soil surface in greenhouse(w)

Q^{cond}_{f-ug} : conduction heat transfer into soil layer(w)

Q^{conv}_{f-ia} : convection heat transfer between the soil surface and the air in greenhouse (w)

Q^{rad}_{f-c} : radiation heat transfer between the soil surface in greenhouse and the cover(w)

Q_{wf} : energy change(latent heat) by water evaporation from the soil surface in greenhouse(w)

3.1.5 Mass balance equation in greenhouse

The mass balance equation in greenhouse was derived as follows.

$$M_{wf} + M_{wc} + M_{wv} + M_{wLo} = 0 \quad (5)$$

where ;

M_{wf} : water evaporation from the soil surface in geenhouse(kg/sec)

M_{wc} : change of moisture content on greenhouse cover(kg/sec)

M_{wv} : change of moisture content by ventilation(kg/sec)

M_{wLo} : change of moisture content on the surface of PCM tubes(kg/sec)

The dew point temperature must be known for the calculation of the amount of water condensation on greenhouse cover and on PCM tubes. It was formulated as follows.

$$DPT = 5.994 + 12.41\,log(VPw) + 0.4273\{log(VPw)\}^2$$
$$(-50℃ \leq T \leq 0℃)$$

$$DPT = 6.983 + 14.38\,log(VPw) + 1.079\{log(VPw)\}^2$$
$$(0℃ \leq T \leq 50℃)$$

where ;

DPT : dew point temperature

VPw = RH×VPs : partial vapor pressure of atmosphere

VPs : saturation vapor pressure

RH : relative humidity

3.2 Numerical analysis

On the basis of thermal resistance network as shown in Fig. 3, the governing equations were derived. They were solved by Newton's method that is quite reasonable to approximate the solution of nonlinear systems of equations. The computer used in simulation was a IBM-PC Compatible(80386) mounted with numerical processor. And the program language used in simulation was Turbo-C.

The flowchart for programing was shown in Fig. 4.

4. Experimental Investigation

For the greenhouse heating, solar energy - latent heat storage systems, prototype I (PI) and prototype II (PII), as shown in Fig. 1 and 2, have been constructed and installed on the soil surface in greenhouse and in the underground respectively. And the thermal characteristics of the systems have been analyzed experimentally as follows.

4.1 Experimental equipment of greenhouse - PI

Two greenhouses in the same size were constructed toward the south, the one was equipped with PI and the other without PI. As shown in Fig. 5, the experimental equipment was consisted of the measuring system which in greenhouse made it possible to test the variation of the temperature, solar radiation and relative humidity.

The experiment has been performed in the natural weather conditions from March 3 to 30, 1991.

4.2 Experimental equipment of greenhouse - PII

In the greenhouse - PII system installed in the underground of greenhouse, the solar energy was stored only by forced convection(Fig. 2). For the experiment of the system, the equipment was consisted of the measuring systems which made it possible to test the variation of the temperature, solar radiation and relative humidity as shown in Fig. 6.

The experiment has been performed in the natural weather conditions from March 3 to 30, 1992.

RESULTS AND DISCUSSION

It is well known that if the solar energy would be used as much as possible for greenhouse heating in winter season, it makes possible to save the fossil fuel and to keep the rural areas without pollution.

For the realization of this purpose the two types(PI and PII) of the solar energy - latent heat storage system have been constructed. For comparing the thermal performance between the two systems, the greenhouse heating effect of PI and PII was analyzed numerically and experimentally, and the results may be summarized as follows.

1. Temperature Variation in Greenhouse - Latent Heat Storage Systems (PI, PII)

The solar radiation, the air temperature variation of inside and outside of greenhouse and the temperature variation of PCM filled in PI, PII on the sunny day and clouded day were shown in Fig. 7 and 8.

Figure 7 (a) shows the experimental results of the greenhouse - PI system performed on a sunny day. As shown in Fig. 7 (a), the maximum solar radiation on a sunny day during the winter season was 750 w/m^2 and the ambient air temperature was varied from the maximum temperature of 13.0℃ to the minimum temeprature of -5.0℃, and the maximum air temperature of 37℃ in the greenhouse equipped with PI was 3℃ higher than that of 34℃ in the greenhouse without PI.

And the air temperature of 37℃ is so high as to damage the crops cultivated in the greenhouse. At 5:00 a.m. the minimum air temperature of 4℃ in the greenhouse equipped with PI was 5.0℃ higher than that of without PI and 9.0℃ higher than the minimum ambient air temperature of -5.0℃.

Figure 7 (b) shows the experimental results of the greenhouse - PII system performed on a sunny day. As shown in Fig. 7 (b), the maximum solar radiation was 650 w/m^2, and the ambient air temperature was varied from the maximum temperature of 10.0℃ to the minimum temperature fo -7.0℃.

The maximum air temperature of 27℃ in the greenhouse equipped with PII was 7.0℃ lower than that in greenhouse without PII at 2:30 p.m. At 6:00 a.m. the minimum air temperature of 3.0℃ in the greenhouse equipped with PII was 6.0℃ higher than that in the greenhouse without PII and 9.0℃ higher than the minimum ambient air temperature of -6.0℃. These results showed that the greenhouse heating effect of PII was better than that of PI.

Figure 8 (a) shows an experimental result of greenhouse - PI system carried out on a clouded day. The solar radiation of the day was varied in the range of 90~270 w/m^2, and the ambient air temperature was varied from the maximum temperature of 9.0℃ to the minimum temperature of -1.0℃. In spite of the clouded day, the greenhouse solar heating effect by the latent heat could be gained, because at 4:00 p.m. the maximum air temperature of 19.0℃ in greenhouse with PI was about 4.0℃ higher than the PCM melting point of 15.0℃. The minimum air temperature of 6.0℃ in greenhouse with PI was 3.0℃ higher than that of without PI at 6:30 a.m. and 7.0℃ higher than the minimum ambient air temperature of -1.0℃. This result shows that the latent heat storage system(PI) gives a good effect to the greenhouse heating even on a clouded day.

Figure 8 (b) shows an experimental result of greenhouse - PII system carried out on a clouded day. The solar radiation of the day was varied in the range of 60~120 w/m^2. The air ambient temperature was varied from the maximum temperature of 1.0℃ to the minimum temperature of -2.0℃, and the greenhouse heating effect by the latent heat of PCM could hardly be expected, because at 4:00 p.m. the maximum air temperature of 11.0℃ in the greenhouse with PII was lower than the PCM melting point of 15.0℃.

But the greenhouse heating effect by the sensible heat of PCM before phase transition and that of soil layer could be expected. At 6:00 a.m. the minimum air temperature of 5.0℃ in greenhouse was 5.0℃ higher than that of without PII and was 7.0℃ higher than the minimum ambient air temperature of -2.0℃.

This results indicated that on a clouded day the greenhouse heating effect by the sensible heat should not be overlooked.

2. Solar Energy Storage Performance of Latent Heat Storage System(LHSS), (PI, PII)

Figure 9 (a) and (b) showed the thermal energy storage performance of PI, PII, and soil layer. The experimental duration was marked on the horizontal axis, the heat storage performance on the left vertical axis and the accumulative solar energy at the outside of greenhouse on the right vertical axis. As shown in Fig. 9 (a), the maximum heat storage performance of LHSS and Soil layer without crops in greenhouse with PI was 38% and 41% respectively at 11:00 a.m. and 12:00 p.m., but after the time. the performance of LHSS was higher than soil layer. Total thermal energy storage performance of greenhouse was up to the maximum value of 79% at 12:00 p.m. and after the time, it has been decreased as a curvilinear form.

And the maximum heat storage performance of soil layer covered with the crops in greenhouse with PI was 10%. As the soil surface in greenhouse would be covered with the crops in the practical situations, the total heat storage performance of greenhouse with PI was 46% at 11:00 a.m., which might be almost depended upon the solar enegy - latent heat storage system(PI).

The maximum performance of latent heat storage system(PII) in greenhouse without crops was 35% at 3:00 p.m., and the maximum heat storage performance of soil layer was 40% at 12:00 p.m. and then the heat storage performance of soil layer was higher than the latent heat storage performance until 2:00 p.m. but after the time, it was reversed. And the maximum of total heat storage performance for greenhouse heating was 67%, which has been maintained from 12:00 p.m. to 2:00 p.m.

For the heat storage performance of soil layer covered with the crops in greenhouse equiped with PII, the maximum performance was only 10%, which was considerably low compared to the latent heat storage system(PII), but as the soil layer would be covered with the crops in the practical conditions, the total heat storage performance of 40% at 2:00 p.m. might be almost depended upon the latent heat stored in PII. The discharging performance of latent heat of PI during the night was 26% and that of PII 28%.

These results showed that the global heat storage performance of the greenhouse with PI was 12% higher than that of the greenhouse with PII until 2:00 p.m., but the discharging performance of latent heat of PI was 2% lower than that of PII after 2:00 p.m.

3. Greenhouse Heating Effect of Latent Heat Storage System (LHSS), (PI, PII)

In this section, the greenhouse heating effect of PI and PII was analyzed according to the variation of minimum ambient air temperatures and solar radiations. The results may be summarized as follows.

3.1 The influence of minimum ambient air temperature on the greenhouse heating effect

In Fig. 10 the minimum ambient air temperature during the experiment was marked on the horizontal axis, and the temperature difference($\Delta T = T_{gh,LHSS} - T_{gh}$) of between minimum air temperature in greenhouse with PI or PII($T_{gh,LHSS}$) and minimum air temperature in grerenhouse without PI or PII(T_{gh}) was marked on the vertical axis. The temperature difference(ΔT) was considered as the greenhouse heating effect.

As shown in Fig. 10, in case of greenhouse with PI the greenhouse heating effect(ΔT) was linearly increased from 1.2 to 5.8℃ when the minimum ambient air temperature was decreased from 6.0 to -8.0℃. The greenhouse heating effect was just inversely proportional to the minimum ambient air temperature.

But in case of greenhouse with PII the greenhouse heating effect was hardly influenced by the minimum ambient air temeprature, which was changed from 5.0 to 7.0℃ when the minimum ambient air temperature was increased from -8.0 to 6.0℃.

These results could be expected because the heat storage and discharging effect by the ambient temperature of PII installed in the underground of greenhouse was small compared to that of PI installed on the soil surface in greenhouse.

3.2 The influence of solar radiation on the greenhouse heating effect

In Fig. 11 the solar radiation during the experiment was marked on the horizontal axis, and the greenhouse heating effect($\Delta T = T_{gh,LHSS} - T_{gh}$) was marked on the vertical axis. As shown in Fig. 11, the greenhouse heating effect of two systems(PI ,PII) was proportional to the solar radiation respectively.

4. Validations of Theoretical Model

The theoretical model based on the thermal energy balance in the greenhouse with PII had been derived in prior section, and the model could be verified as follows.

4.1 Validations of theoretical model for the air temperature variation in greenhouse without PII

Figure 12 showed the numerical and experimental values of the air temperature variation in the greenhouse without PII. As shown in Fig. 12, during the day the air temperature variation analyzed by the theoretical model was high a little compared to the the experimental values, whereas during the night the theoretical values were good agreed with the experimental values,

4.2 Validations of theoretical model for the air and PCM temperature variation in greenhouse with PII

As shown in Fig. 13, the greenhouse air temperatue variation analyzed by the theoretical model was good agreed with the experamental values until 12:00 a.m., but after the time the theoretical values were a little greater than the experiemntal values. For the temperature variation of PCM in PII, the theoretical values were good agreed with the experimental values, and then the range of phase change temperature analyzed by the theoretical model was longer than that of the experiment, this result may be caused by the unexpected heat loss of the system, but in general, the theoretical values were good agreed with the experimental values(Fig. 13).

CONCLUSIONS

To save fossil fuel for the protected horticulture heating and to reserve the rural environments without pollution, the two types of solar energy - latent heat storage systems(PI, PII) have been developed, and the heat storage performance of the systems were analyzed theoretically and experimentally. These results enabled us to obtain the basic data for design of latent heat storage system for greenhouse heating during the winter season.

1. The unstable properties of $Na_2SO_4 \cdot 10H_2O$ selected as solar energy storage medium has been stabilized and the melting point was controlled by urea addition for the greenhouse heating.

2. Two types of solar energy - latent heat storage systems(PI, PII) filled with PCM mass of 16.5 kg/m^2(kg/unit area of soil surface) enabled to control the greenhouse air temperature, on a sunny day the greenhouse heating effect was 6~7℃ and on a clouded day was 3℃.

3. In the case of the greenhouse bed soil covered with crops, the maximum heat storage performance of PI was 46% and that of PII 40%, whereas the heat

discharging performance of PI during the night was 30% and that of PII 33%.

4. Greenhouse heating effect of PI was inversely proportional to the minimum ambient air temperature, while that of PII was hardly influenced by the minimum ambient air tempeature. The greenhouse heating effect for all of two systems(PI, PII) was proportional to the solar radiation.

5. To predict the variation of greenhouse air temperature and the greenhouse heating load for the design of the solar energy - latent heat storage system, the theoretical model was derived, which has been verified by the experimental values.

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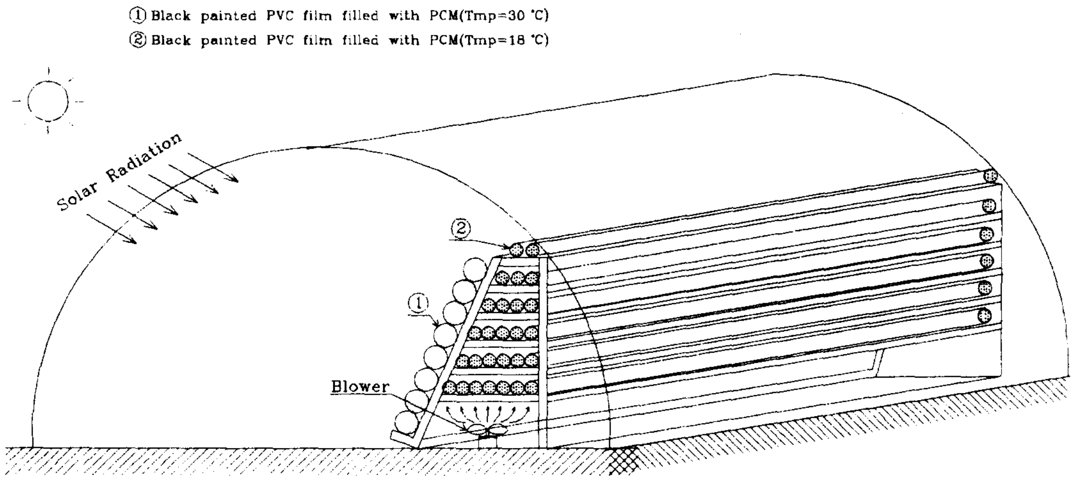
Table 1. Thermophysical properties of $Na_2SO_4 \cdot 10H_2O$ stabilized with the nucleating and thickening agent and treated by phase change cycles.

PCM (Industrial grade)	Nucleating agent (wt%)	Thickening agent (wt%)	No. of phase change cycles	Tm (℃)	Latent Heat (㎉/kg)	Cp(㎉/kg℃)	
						Solid	Liquid
$Na_2SO_4 \cdot 10H_2O$	3.0	1.5	0	16.7	46.0	0.517	0.798
			200	16.8	35.8	0.584	0.634
			400	16.5	36.8	0.599	0.637
			600	16.6	36.4	0.705	0.735



① : Solar energy storage part by the radiation and convection heat transfer
② : Solar energy storage part by the only convection heat transfer

Fig. 1 Solar energy-latent heat storage system installed on the floor of greenhouse(prototype I).

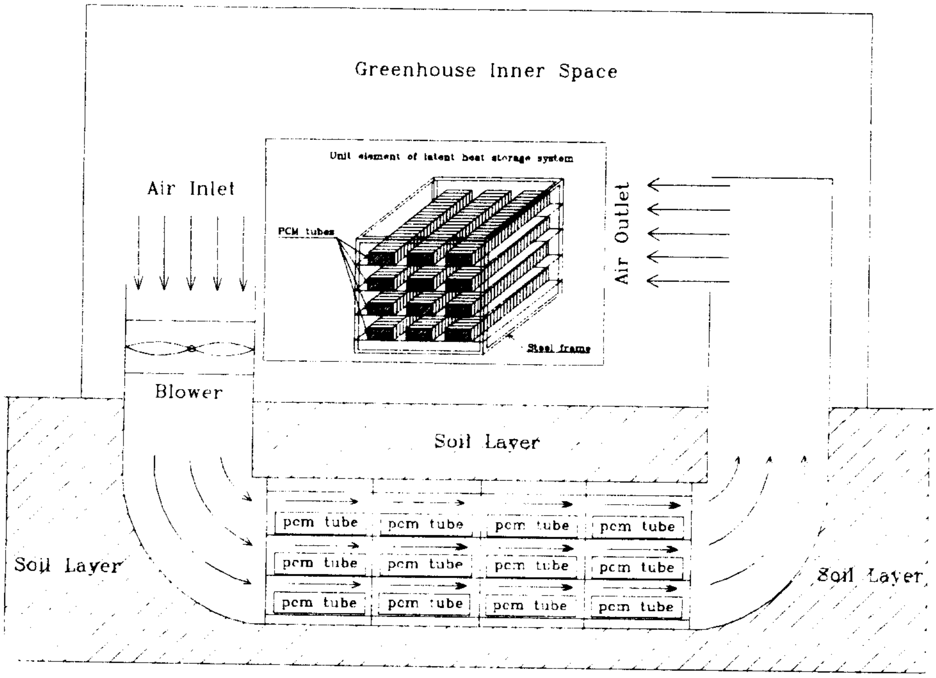


Fig. 2 Solar energy - latent heat storage system installed in the underground of greenhouse(prototype II)

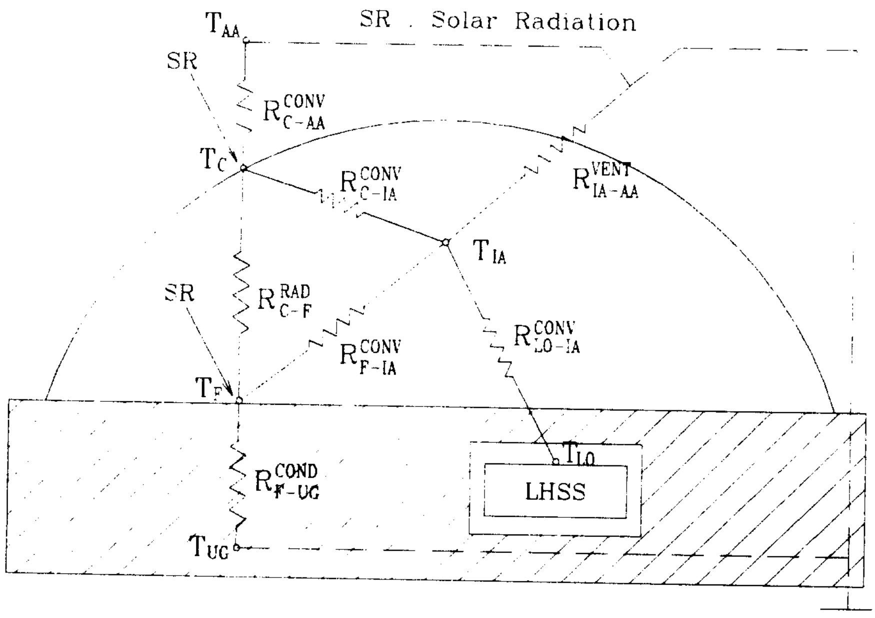


Fig. 3 Thermal resistance network of greenhouse - PII system.

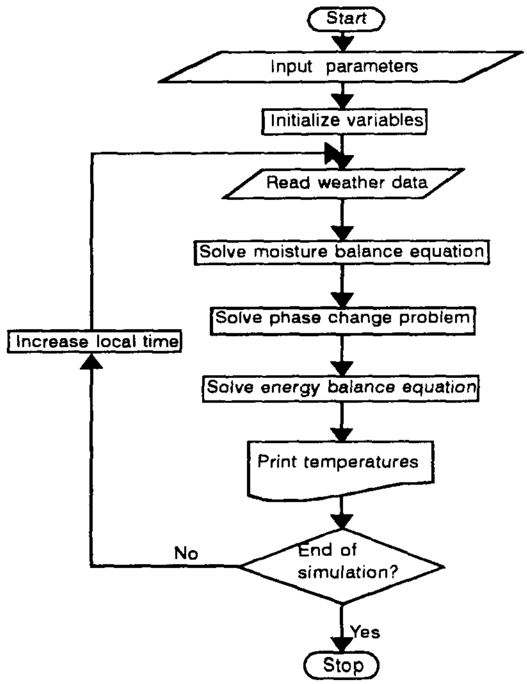


Fig. 4 Flowchart for computer programing to simulate the energy balance of the greenhouse - prototype II.

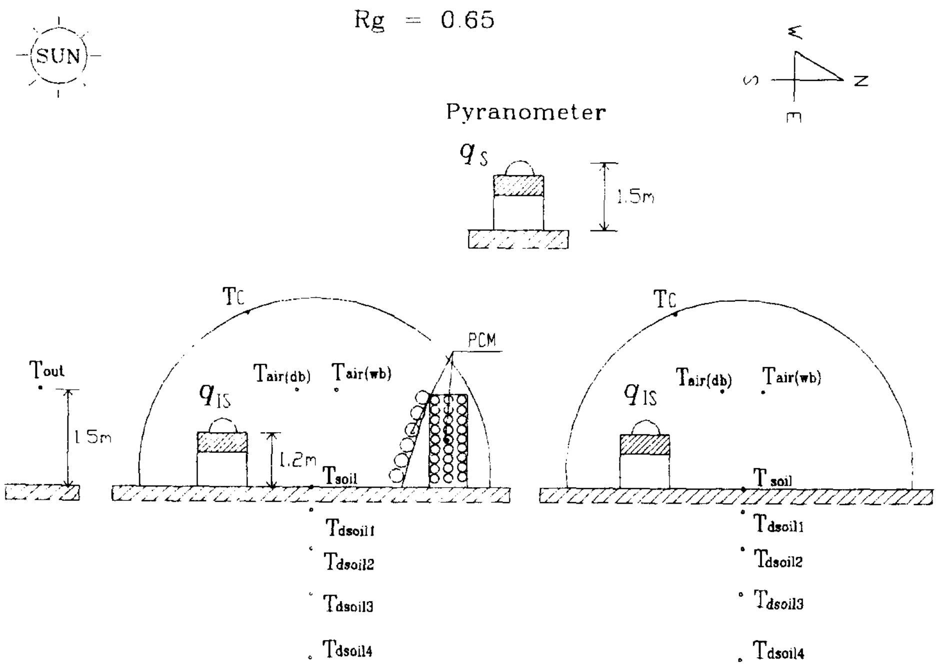


Fig. 5 Experimental equipment of greenhouse - PI(Latent heat storage system installed on the soil surface in greenhouse).

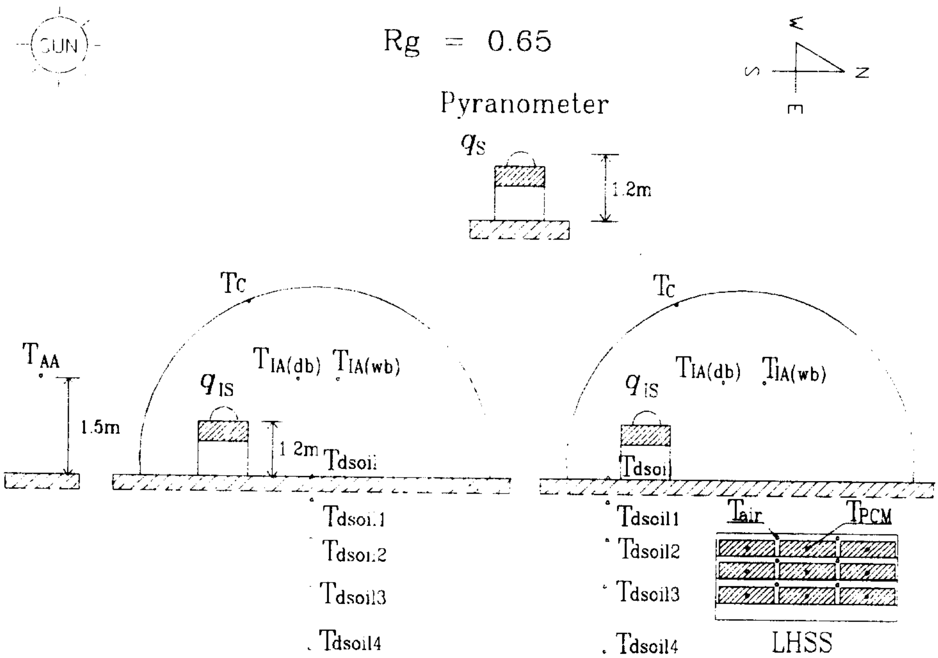


Fig. 6 Experimental equipment of greenhouse - PII.

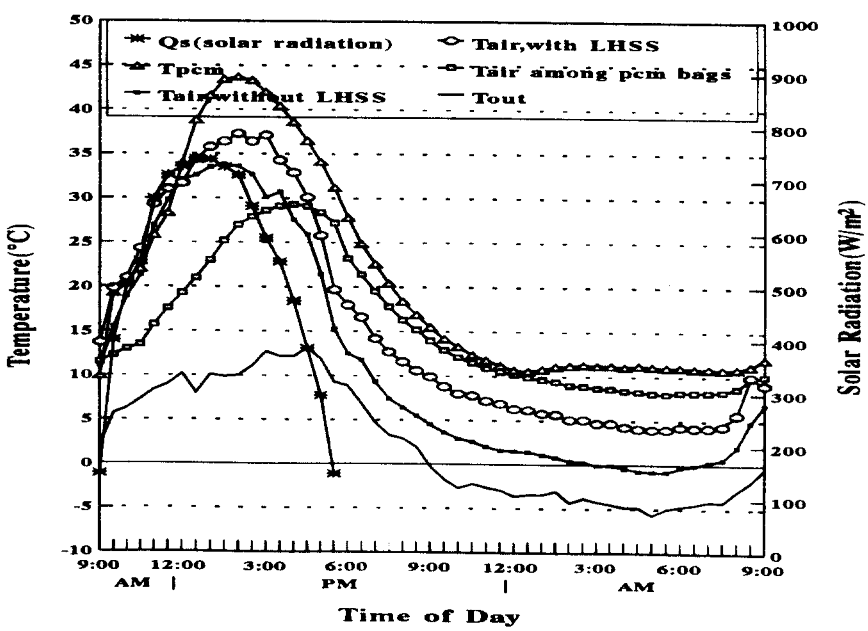


Fig. 7 (a) Temperature variation of ambient air, greenhouse air and PCM tube of PI, and solar radiation during a sunny day and night (March 3th ~ 4th,1991).

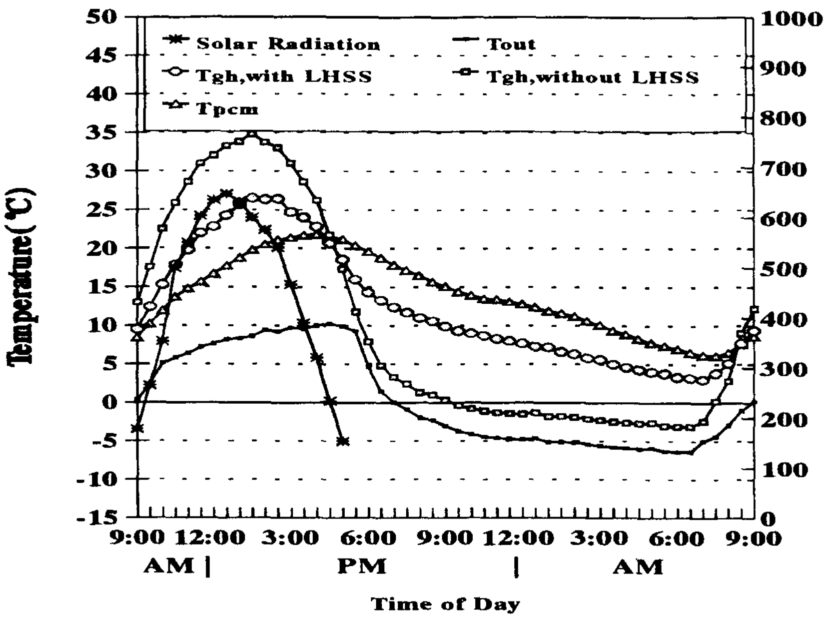


Fig. 7 (b) Temperature variation of ambient air, greenhouse air and PCM tube of PII, and solar radiation during a sunny day and night(March 8th~9th, 1992).

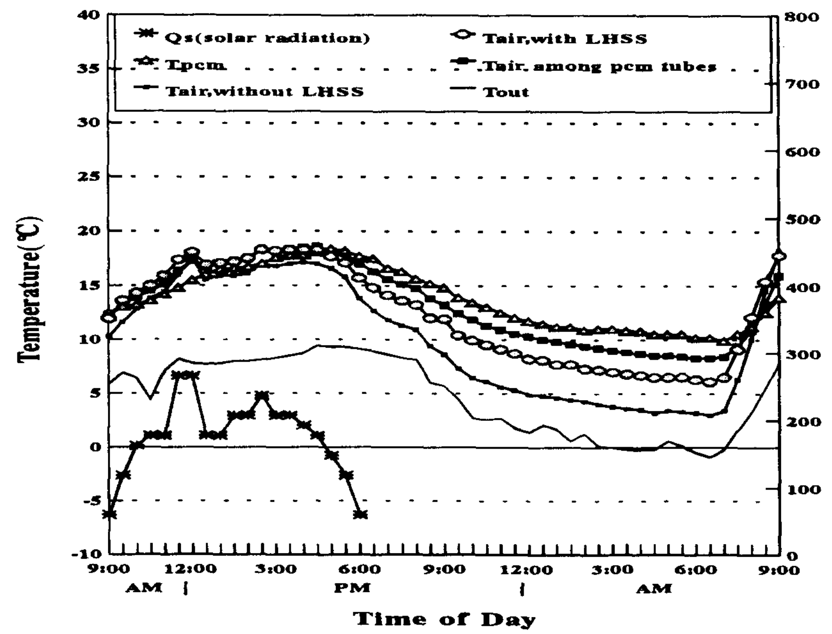


Fig. 8 (a) Temperature variation of ambient air, greenhouse air and PCM tube of PI, and solar radiation during a clouded day and night (March 22th ~ 23th, 1991).

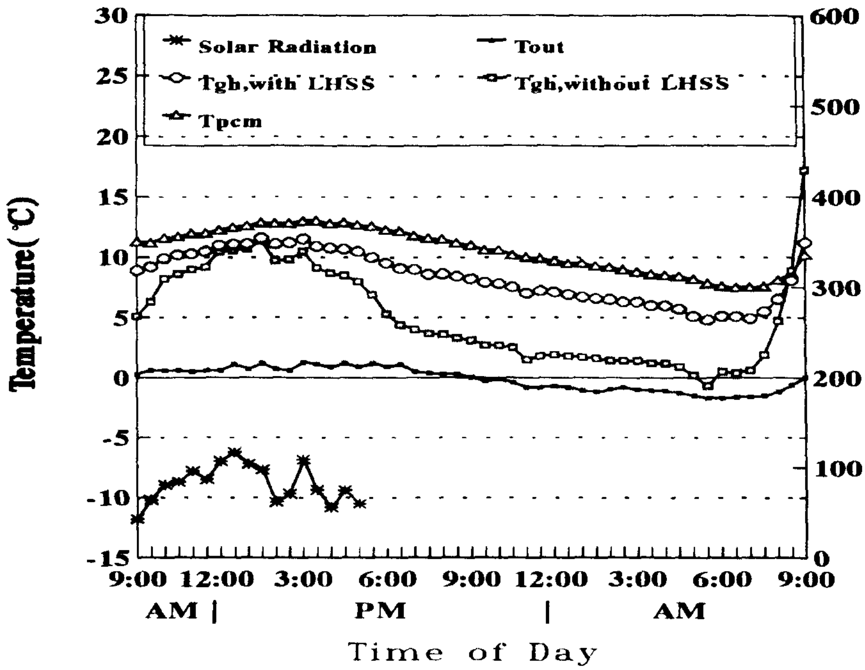


Fig. 8 (b) Temperature variation of ambient air, greenhouse air and PCM tube of PII, and solar radiation during a clouded day and night(March 5th~6th,1992).

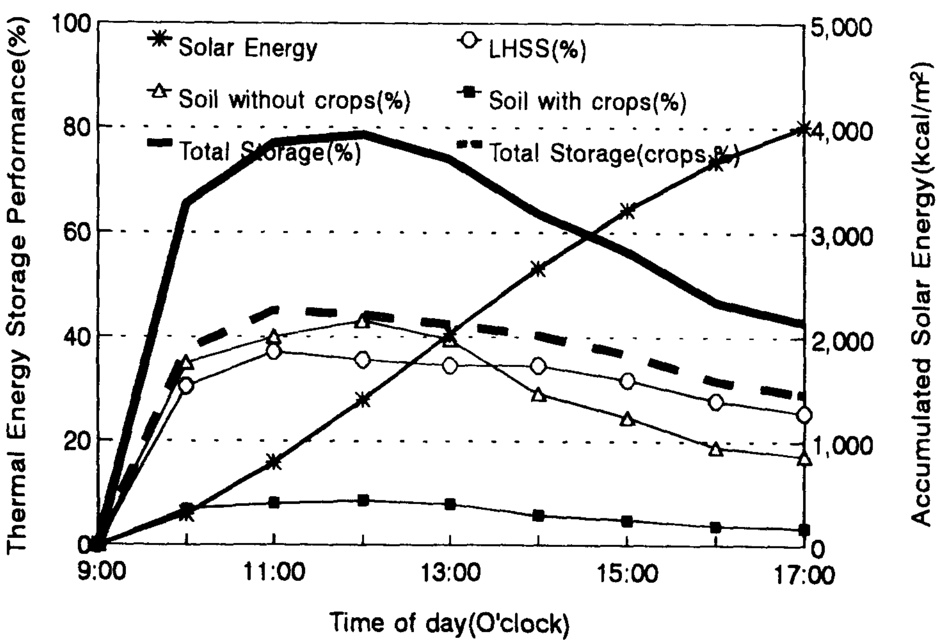


Fig. 9 (a) Solar energy storage performance of PI.

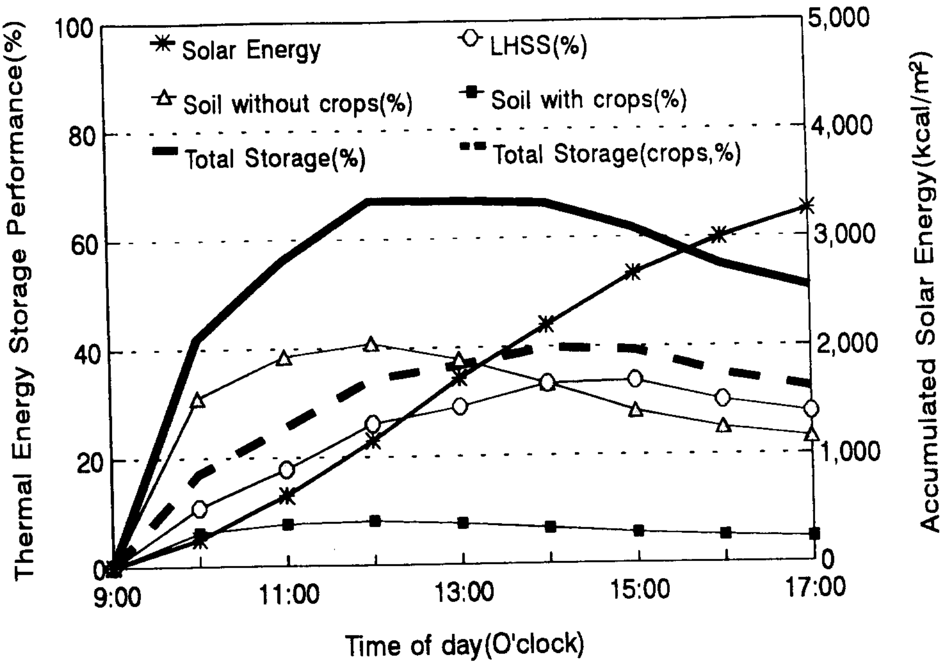


Fig. 9 (b) Solar energy storage performance of PII.

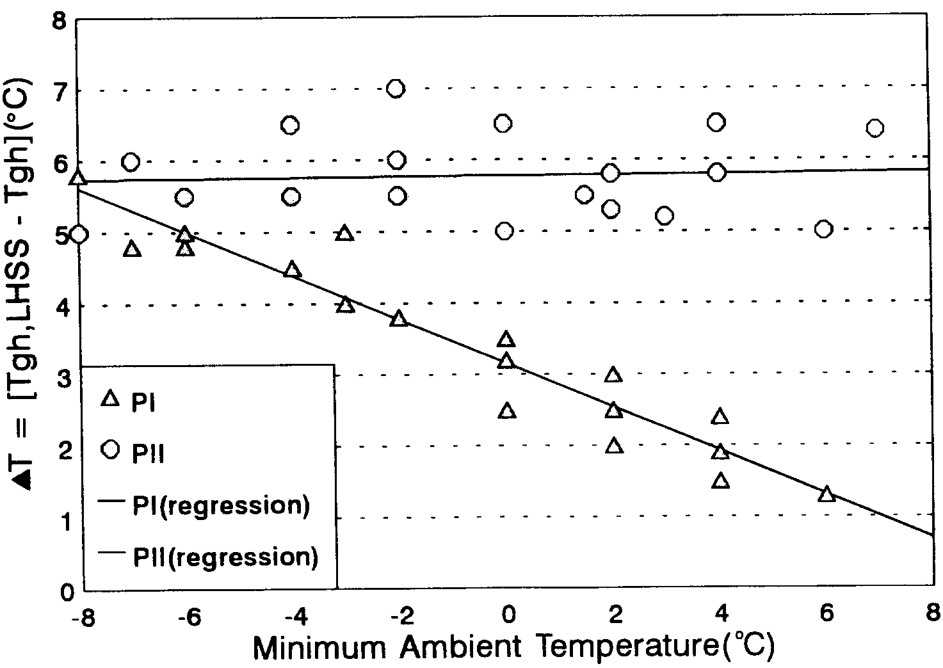


Fig. 10 Minimum ambient air temperature influence on the greenhouse heating effect.

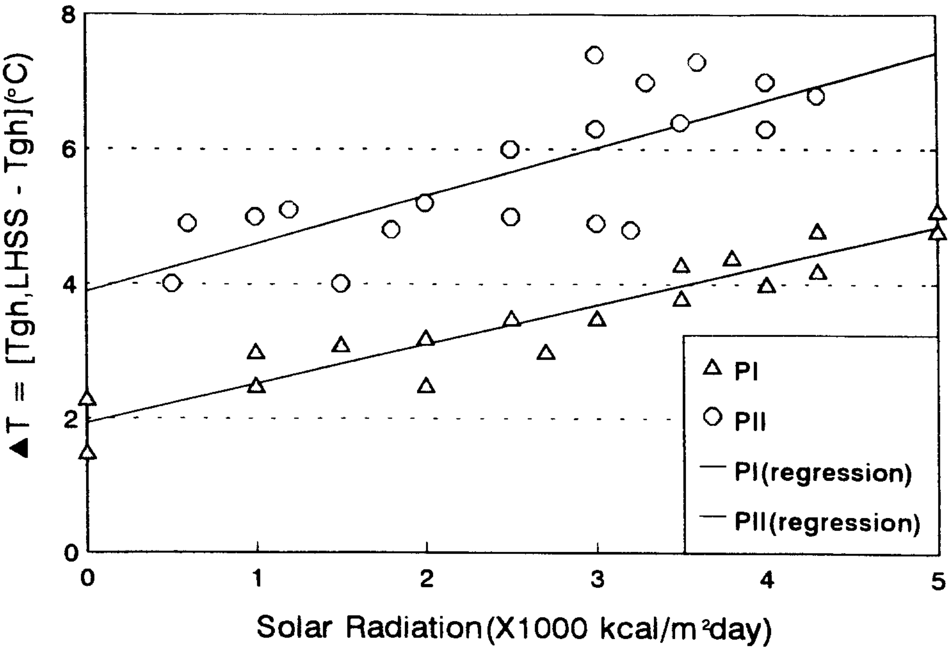


Fig. 11 Solar radiation effect on the greenhouse heating.

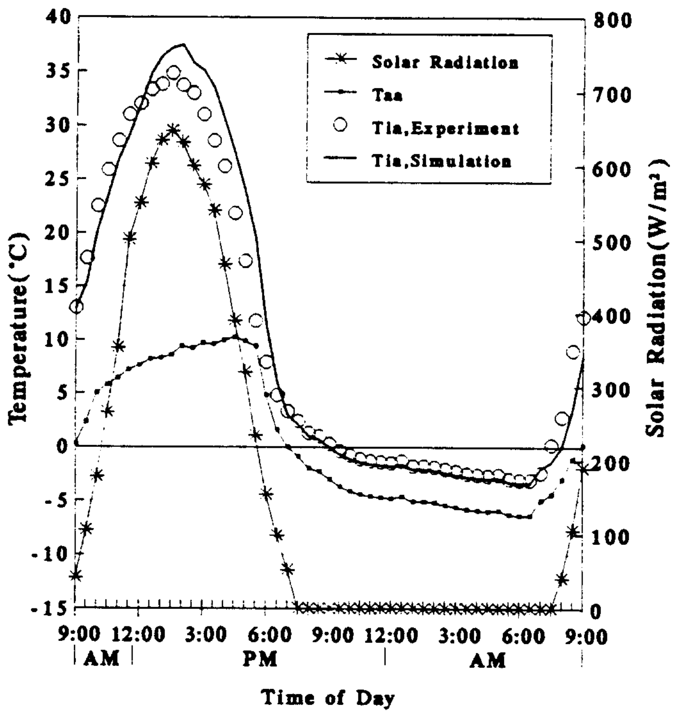


Fig. 12 Comparison between with the numerical and experimental values of air temperature variation in greenhouse without PII.

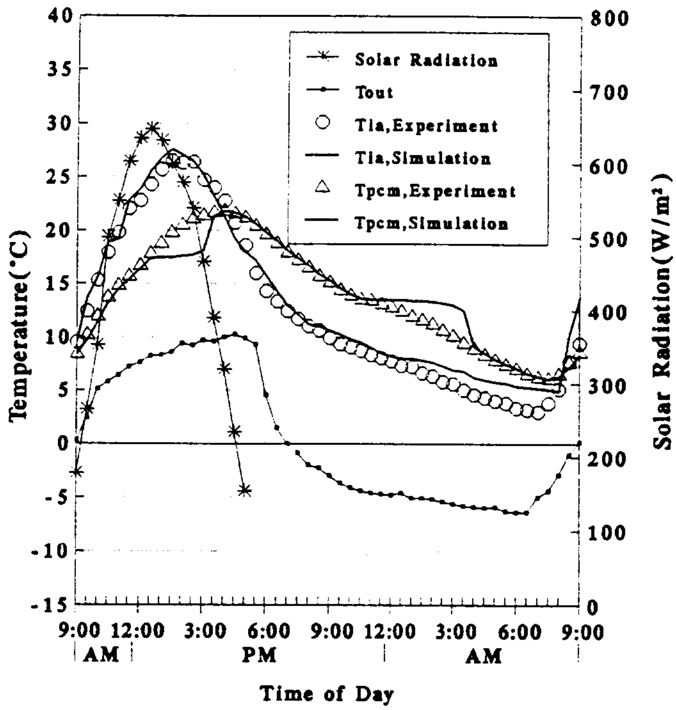


Fig. 13 Comparison between the experimental and theoretical value of the air and PCM temperature variation in greenhouse with PII.