Winter performance of a solar energy greenhouse in southern Manitoba

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The thermal performance of a solar energy greenhouse (SEG), a technology that has been effectively used in China to grow vegetables and flowers, was investigated under winter conditions in southern Manitoba. A 30-m by 7-m solar greenhouse was constructed in Elie, Manitoba (50°N; 97°W). The greenhouse had an insulated (3.6 m^2°C/W, or RSI-3.6) solid north wall to store solar energy in the daytime and to release thermal energy in the nighttime, and a thermal blanket (RSI-1.2) over the glazed surface (single layer plastic) in the nighttime to minimize the heat loss. The experiment was conducted from February to April, 2005. On the coldest day in February, the lowest nighttime temperature recorded inside the greenhouse was 1.6°C when the outdoor temperature was -29.2°C. The mean night indoor temperature was 2.4°C while the mean outdoor temperature was -13.1°C in February. The solar radiation had more influence on the greenhouse temperature than did the outdoor temperature. The average daily energy storage by the north wall was 166 MJ (or 2635 kJ/m^2 of wall surface area), which was about 10% of the available solar energy received in the greenhouse. The average daily energy release by the wall was 159 MJ (2523 kJ/m^2), which was 4% less than the stored amount. The average amounts of energy stored and released by soil in the greenhouse were 724 and 567 kJ/m^2 (floor area) per day, respectively. Based on the average measurements of temperature and solar radiation, it was estimated that about 19 hours of supplemental heating would be required per day in February to maintain the greenhouse temperature above 10°C. The amount of required supplemental heat was estimated to be between 2 and 17 W/m^2 when the thermal blanket was applied on the plastic cover of the greenhouse.
Keywords: greenhouse, solar energy, temperature.

La performance thermique d'une serre à l'énergie solaire (SES), une technologie qui a été utilisée de manière efficace en Chine pour produire des légumes et des fleurs, a été étudiée en conditions hivernales dans le sud du Manitoba. Une serre solaire de 30 m par 7 m a été construite à Elie, Manitoba (50°N et 97°O). La serre était dotée d'un mur solide et isolé (3,6 m^2°C/W, ou facteur RSI de 3,6) sur sa façade nord pour l'emmagasinage de l'énergie solaire durant la journée et la libération de cette énergie thermique durant la nuit ; une couverture thermale (facteur RSI de 1,4) recouvrait la surface exposée (couche simple de plastique) durant la nuit pour minimiser les pertes de chaleur. L'étude s'est déroulée de février à avril 2005. Durant la journée la plus froide de février, la température nocturne la plus faible qui a été enregistrée dans la serre était de 1,6°C alors que la température extérieure était de -29,2°C. La température moyenne nocturne dans la serre était de 2,4°C pour une température moyenne extérieure de -13,1°C en février. La radiation solaire a eu plus d'influence sur la température de la serre que la température extérieure. Le stockage quotidien moyen d'énergie par le mur nord était de 166 MJ (correspondant à 2635 kJ/m^2 de surface), ce qui représentait environ 10% de l'énergie solaire disponible reçue dans la serre. La quantité journalière moyenne d'énergie libérée par le mur s'est élevée à 159 MJ (2523 kJ/m^2), ce qui correspond à 4% de moins que la quantité emmagasinée. Les quantités moyennes d'énergie emmagasinées et relâchées par le sol dans la serre se sont respectivement élevées à 724 et 567 kJ par m^2 de surface de plancher et par jour respectivement. Sur la base des valeurs moyennes de température et de rayonnement solaire, les besoins en chauffage d'appoint pour maintenir une température ambiante supérieure à 10 ºC dans la serre durant le mois de février ont été estimés à 19 heures par jour environ. Les besoins en chauffage d'appoint ont été évalués entre 2 et 17 W/m^2 lorsque la couverture thermale recouvrait les parois de plastique de la serre.
Mots clés: serre, énergie solaire, température.

INTRODUCTION

In cold climates, a substantial amount of supplemental heating is required to run greenhouses in the winter season. According to the Commission of the European Communities (1986), more than 75% of thermal energy consumption in agriculture is devoted to greenhouse heating in northern countries. This shows that reducing consumption of fuels for greenhouse heating is of paramount importance to the existence of horticulture in the future (FAO 1987). Most greenhouses in Manitoba are heated with either natural gas or LPG (liquified petroleum gas) and heating constitutes a major cost in greenhouse production. The recent increases in energy price have caused greenhouse growers to seek energy efficient technologies to reduce their operating costs.

Solar energy may provide the most cost effective means for greenhouse heating. In the middle and northern China, simple, inexpensive, and energy conserving solar energy greenhouses have been used to produce vegetables in winter, late fall, and early spring since the1980s (FAO 1994). Although winter temperature is low in Manitoba, there is no lack of solar radiation. Taking Winnipeg as an example, the mean hourly global solar radiation can be as high as 260 W/m^2 (on a horizontal surface) during daytime (9:00h to 16:00h) in January, with a peak of about 450 W/m^2 at noontime (Environment Canada 1990). This significant amount of solar energy provides opportunities for the Manitoba greenhouse growers to reduce or even eliminate supplemental heating for operating their greenhouses during winter or early spring.

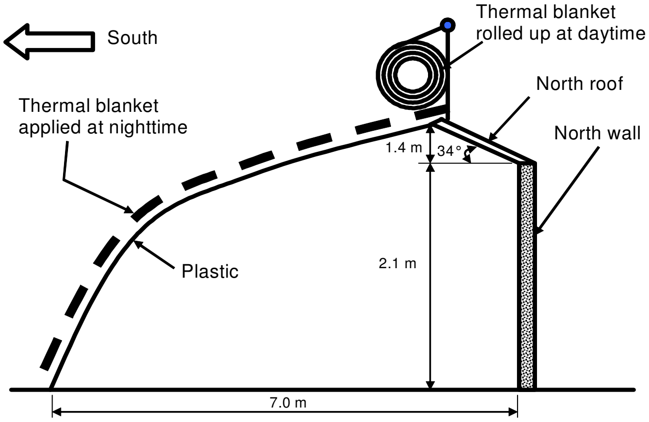

Fig. 1. Side view of the solar energy greenhouse. The greenhouse length was 30 m.

The amount of solar energy indicated above may be sufficient to maintain the desirable greenhouse temperature in the daytime. However, the challenge is to maintain the greenhouse temperature after sunset with little or no supplemental heating. Although there has been much reporting on the use of solar energy greenhouses in China, few systematic studies were conducted, in particular, for high latitude regions. The objective of this study was to evaluate the thermal performance of a passive solar energy greenhouse for winter conditions in southern Manitoba (50° N).

MATERIALS and METHOD

Solar energy greenhouse

A solar energy greenhouse (SEG) 7-m wide and 30-m long was tested in this study. The main components of the greenhouse included steel framing, a single-layer plastic cover, a north wall for storing solar energy, and a thermal blanket (Fig. 1). The plastic cover formed the enclosure on the south side of the greenhouse, while the north wall and a small section of insulated roof formed the enclosure on the north side. Two insulated walls (RSI-3.6) formed the enclosures on the east and west ends. The greenhouse was constructed so that during the daytime the inside surface of the north wall was fully exposed to direct solar radiation. As the air in the greenhouse cooled down in the nighttime, energy absorbed by the north wall was radiated back to the room. The north wall consisted of a 2-mm thick inside and outside sheathing of corrugated galvanized sheet steel, 152-mm of sand, 13-mm plywood, and 152-mm fibreglass insulation (Fig. 2). The fibreglass insulation provided thermal resistance of about RSI-3.5. A portion of the inside surface of the north wall was painted black to assess the advantage of having a darker colour for maximum absorption of solar energy. The north wall was designed as a heat reservoir and also blocked the wind from the north, thus reducing heat loss caused by air infiltration.

The plastic cover was a single layer of 6-mil polyethylene, which has a solar radiation transmissivity of 0.90 (Tyco Plastics, Minneapolis, MN). The thermal blanket used to minimize heat loss during the nighttime was made of cotton with an approximate RSI of 1.2. A winch system was used to operate the thermal blanket, i.e., rolling it up in the daytime and placing it over the plastic cover in the nighttimes. During the experiment, the blanket was rolled up at about 9:00h and down at about 18:00h.

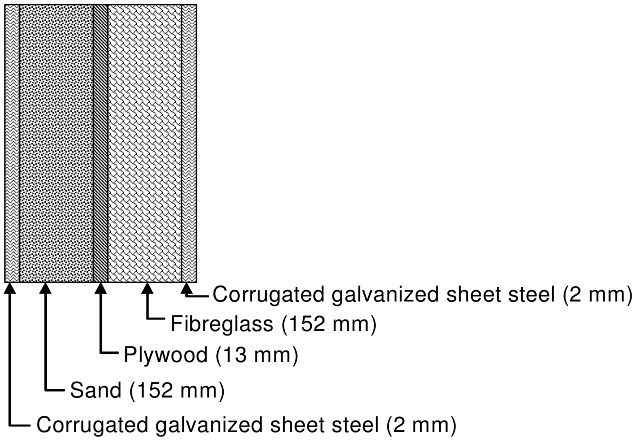

Fig. 2. Structure of the solar energy storage (north) wall.

Temperature and solar radiation monitoring

The indoor air temperature, outdoor air temperature, soil temperature, and the temperature profile across the north wall were recorded every 10 minutes by using T-type thermocouples and a computer controlled data acquisition system (HP3852A, Hewlett-Packard, Palo Alto, CA). The room temperature was recorded at three different locations 1.5, 3.0, and 4.0 m above the ground. The soil temperature was monitored at three locations, specifically, near the north wall, south end, and in the middle of the room at depths of 20, 150, and 300 mm at each location. Temperature across the north wall was monitored for both painted and unpainted sections at three depths of 10, 60, and 100 mm from the inside surface of the wall.

A portable weather station (WatchDog™ Model 550, Spectrum Technologies, Inc., Plainfield, IL) was placed approximately 2 m above the ground near the solar greenhouse to collect on-site weather information. Global solar radiation, outdoor temperature, relative humidity, and wind speed and direction were recorded every 5 minutes.

Energy balance calculation

The solar energy that is received by the greenhouse is either lost to the outside by conduction through the greenhouse envelope and by convection through infiltration or stored in the greenhouse. Mathematically, the energy balance equation is written as:

$$Q_{in} = Q_{cd} + Q_{cv} + Q_{st} \tag{1}$$

where:

Q_{in} = solar radiation received in greenhouse (W),
Q_{cd} = conduction heat loss through greenhouse envelope (W),
Q_{cv} = heat loss through infiltration (W), and
Q_{st} = heat stored in greenhouse (W).

It should be noted that the conversion of sensible heat to latent heat by plant transpiration was assumed to be negligible because there were only a few plants in the greenhouse. The received solar radiation is the amount of the global solar radiation (G) penetrating through the glazed surface of the greenhouse, determined as:

Table 1. Thermal resistance of greenhouse envelope components.

Section	Area (m^2)	Resistance (m^2 °C/W)
North wall	63.0	3.59
End walls	55.3	3.64
North roof	45.0	3.50
Plastic without blanket	235.6	0.14
Plastic with blanket	235.6	1.35

$$Q_{in} = \tau G \tag{2}$$

where:

τ = transmissivity of glazed surface, and
G = global solar radiation (W).

The conduction heat loss through the greenhouse envelope, which includes the north wall, two end walls, north roof, and plastic cover (a thermal blanket at night), is calculated by:

$$Q_{cd} = \frac{A}{R}\Delta T \tag{3}$$

where:

R = overall thermal resistance (m^2 °C/W),
A = total surface area of greenhouse envelope (m^2), and
T = temperature difference between the inside and outside air (°C).

The overall thermal resistance of the greenhouse is calculated as:

$$\frac{A}{R} = \frac{A_{nw}}{R_{nw}} + \frac{A_c}{R_c} + \frac{A_r}{R_r} + \frac{A_{sw}}{R_{sw}} \tag{4}$$

where:

A_{nw}, A_c, A_r, A_{sw} = areas of north wall, plastic/blanket cover, roof, and end walls, respectively, (m^2) and
R_{nw}, R_c, R_r, R_{sw} = thermal resistance of north wall, plastic/blanket cover, roof, and end walls, respectively (m^2 °C/W).

The areas and thermal resistances for various sections of the greenhouse envelope are listed in Table 1. The heat loss due to air infiltration is calculated as:

$$Q_{cv} = V_i V \rho_a C_a \Delta T \tag{5}$$

where:

V_i = air exchange rate by infiltration (s^{-1}),
V = volume of greenhouse (m^3),
ρ_a = air density (kg/m^3), and
C_a = specific heat capacity of air (J kg^{-1} °C^{-1}).

The amount of heat stored in the greenhouse is primaryily in the north wall and soil, and is determined as:

$$Q_{st} = Q_{wall} + Q_{soil} \tag{6a}$$

$$Q_{wall} = C_{wall}\rho_{wall}V_{wall}\Delta T \tag{6b}$$

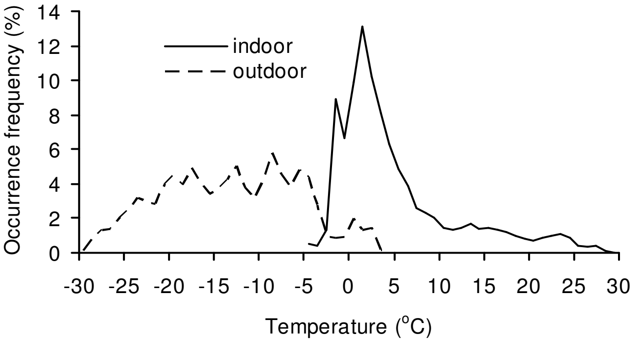

Fig. 3. Distributions of measured indoor and outdoor temperatures in February, 2005.

$$Q_{soil} = C_{soil}\rho_{soil}V_{soil}\Delta T \tag{6c}$$

where:

Q_{wall}, Q_{soil} = heat stored in north wall and soil, respectively (W)
C_{wall}, C_{soil} = specific heat capacity of wall and soil, respectively (J kg^{-1} °C^{-1}),
ρ_{wall}, ρ_{soil} = density of wall and soil, respectively (kg/m^3),
V_{wall}, V_{soil} = volume of wall and soil, respectively (m^3), and
$\Delta T_{wall}, \Delta T_{soil}$= rate of change in wall and soil temperature, respectively (°C/s).

RESULTS and DISCUSSION

Greenhouse temperatures

February was the coldest month during the test period. Therefore, the following discussion on temperatures is focused on the February conditions as the worst scenario. The temperature inside the greenhouse varied from -4.9 to 28.5°C, while the outdoor temperature fluctuated between -29.2 and 4.5°C (Fig. 3). It was noticed that the lowest indoor temperature occurred on a cloudy day, not on the day with the lowest outdoor temperature (-29.2°C). The mean indoor and outdoor temperatures were 5.2 and -13.1°C, respectively. The mean night indoor temperature was 2.4°C. The distribution of outdoor temperature was fairly symmetric, whereas the indoor temperature distribution was skewed (Fig. 3). The frequencies of the indoor temperature being below 0, 5, and 10°C were 18, 65, and 81%, respectively. The daily average temperature (DAT) inside the greenhouse varied from -1.0 to 10.6°C, while the outdoor DAT was between -23.9 and 2.6°C (Fig. 4). On average, the indoor DAT was 18°C higher than the outdoor DAT. It appears that the indoor temperature was influenced more by solar radiation than by outdoor temperature (Fig. 4). The coefficient of correlation between the indoor DAT and outdoor DAT was 0.21, whereas the coefficient was 0.78 between the indoor DAT and the daily average solar radiation.

The indoor temperature started to rise as soon as the thermal blanket was rolled up (9:00h) and started to decrease after 16:00h. Typically, the highest temperature inside the greenhouse was recorded in the afternoon between 13:00h and 16:00h. Figure 5 shows the hourly outdoor and indoor temperatures for

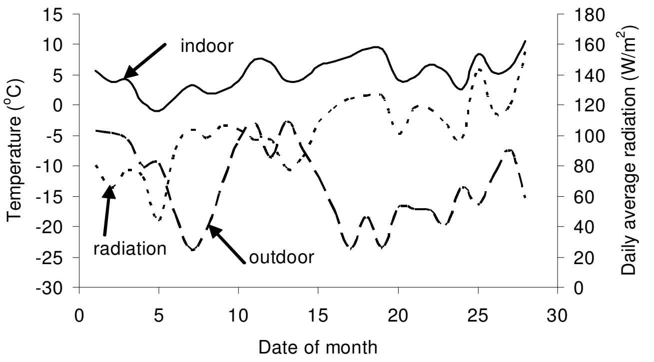

Fig. 4. Daily average temperatures and solar radiation in February, 2005.

the coldest day (February 19, 2005) during the experimental period. The minimum outdoor temperature was as low as –29.2°C and the minimum nighttime temperature inside the greenhouse was 1.6°C. Although February 19 had the lowest outside temperature, it was a clear sunny day with an average solar radiation of 330 W/m^2 between 8:00h and 17:00h and a peak value of 523 W/m^2 at 12:50h. The solar radiation kept the greenhouse temperature at a maximum of 24°C between 14:00h and 15:00h.

To further examine the effect of solar radiation on the greenhouse temperature, the temperature profiles for two different days with different amounts of solar radiation were compared – February 13 with a measured daily solar energy of 6.48 MJ/m^2 and February 28 with 13.32 MJ/m^2 (Fig. 6). Although the daytime outdoor temperature on February 28 was 10°C colder than February 13, the inside temperature was 18°C higher. The night temperature on the February 28 was 4 to 10°C higher than that on the February 13.

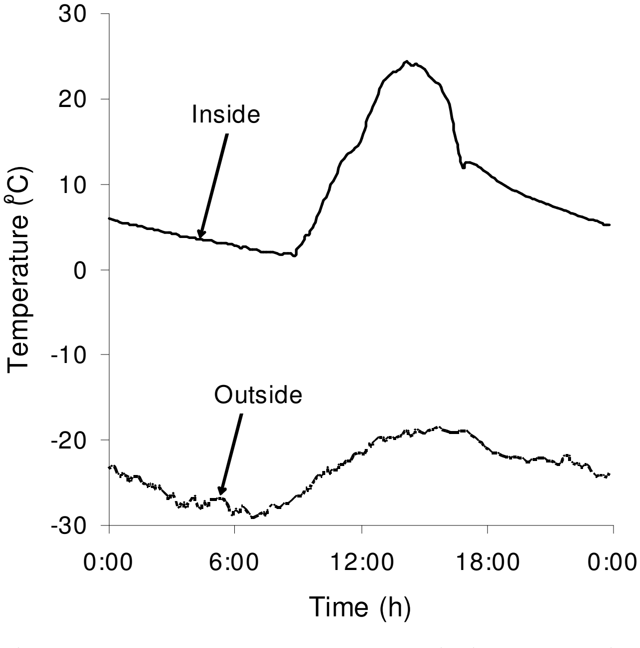

Fig. 5. Hourly temperatures recorded inside and outside the greenhouse on February19, 2005.

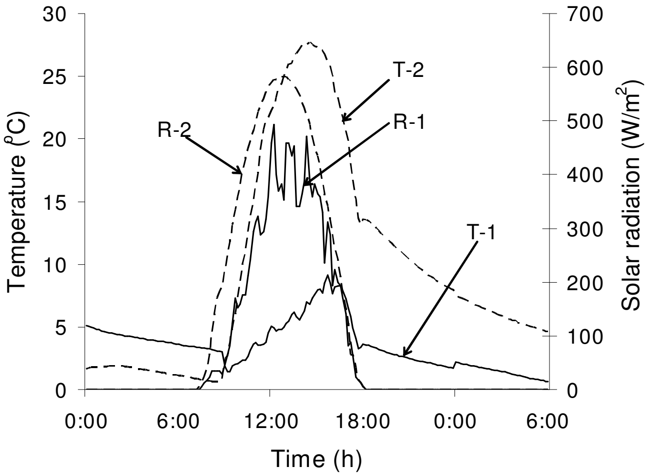

Fig. 6. Impact of available solar radiation on the greenhouse room temperatures. T-1 and T-2 show the temperature and R-1 and R-2 the global solar radiation recorded on February 13 and 28, respectively.

Solar (north) wall temperature and stored energy

The wall surface temperature (at 10-mm depth) started to rise right after the thermal blanket was opened at 9:00h and temperatures at 60-mm and 100-mm depths followed (Fig. 7). The wall surface reached the maximum temperature between 15:00h and 16:00h. The temperature rise deep inside the wall lagged slightly. The maximum temperature was reached between 16:00h and 17:00h, and between 17:00h and 18:00h at depths of 60 and 100 mm, respectively. The highest temperatures recorded in February were 18, 15, and 14°C at 10, 60, and 100-mm depths, respectively. In the nighttime the outer layer of the wall cooled faster than the inside layers. The minimum temperature occurred right before the thermal blanket was lifted (9:00h).

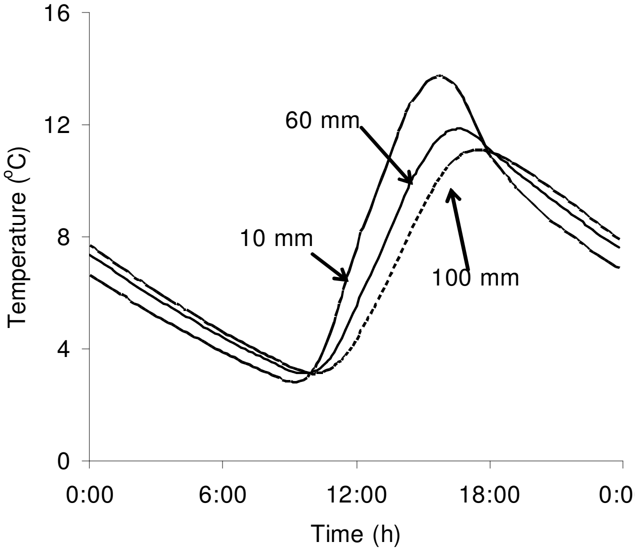

Fig. 7. Hourly average temperature recorded across the north wall in February.

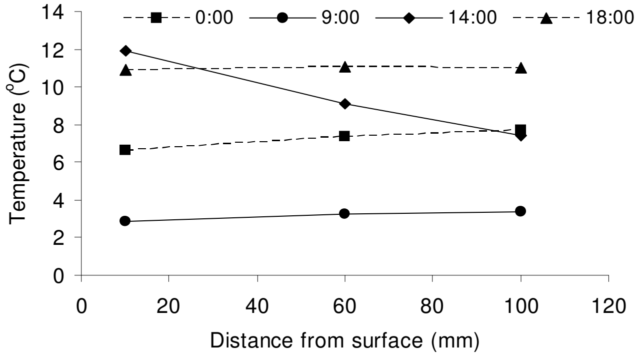

Fig. 8. Temperature gradient within the north wall (monthly average for February) at different times (9:00h and 14:00h are times when the lowest and highest temperatures occurred, respectively.

The temperature distribution across the wall was approximately linear (Fig. 8). A weighted average temperature (linear interpolation) was calculated to represent the wall temperature as:

$$T_{wall} = \left(\frac{T_{10}+T_{60}}{2}\right)\left(\frac{60-10}{100-10}\right)+\left(\frac{T_{60}+T_{100}}{2}\right)\left(\frac{100-60}{100-10}\right) \quad (7)$$

where

T_{wall} = weighted average temperature of north wall (°C), and

T_{10}, T_{60}, T_{100} = measured temperatures at depths of 10, 60, and 100 mm, respectively, (°C).

The impact of surface colour on wall temperature was apparent (Fig. 9). The black surface resulted in an average temperature of about 4 to 5°C higher than the unpainted silver surface of galvanized steel in the daytime. This difference was statistically significant ($P < 0.05$). The difference diminished in the nighttime.

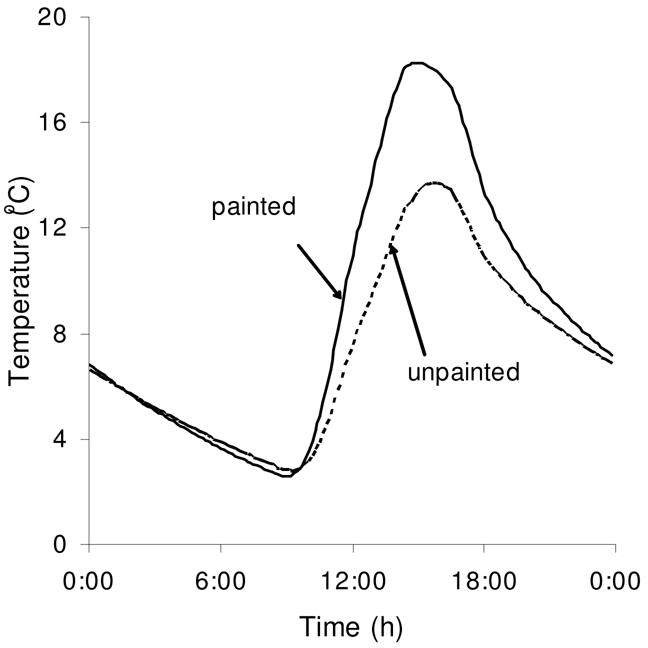

Fig. 9. Temperatures recorded at depth of 10 mm for the painted (black) and unpainted (silver) surface of north wall.

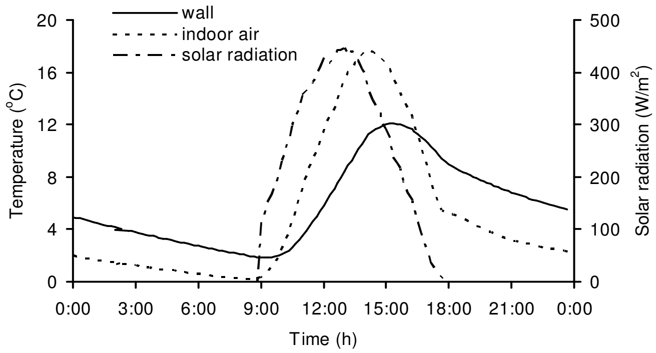

Fig. 10. Monthly average temperature of north wall recorded in February 2005.

In the month of February, the wall temperature was on average 2.7°C higher than the room air temperature in the nighttime and 4.1°C lower in the daytime (Fig. 10). The largest difference of 7.1°C occurred at 13:00h. The rise of wall temperature after opening the thermal blanket lagged behind both solar radiation and indoor air temperature. The highest wall temperature occurred at 15:20h, while solar radiation and indoor air temperature peaked at 13:00h and 14:10h, respectively.

To use Eq. 6b for determining the amount of energy stored in or released from the north wall, the temperature change rate was calculated as the difference between two consecutive measurements of wall temperature divided by the time interval (10 minutes) between the two measurements. A positive rate (temperature rise) indicates that energy was stored in the wall, whereas a negative rate (temperature decrease) means that energy was released from the wall to the room. Other parameters used in the calculation were: specific heat capacity of sand $C_{wall} = 0.92$ kJ kg^{-1} °C^{-1} and density $\rho_{wall} = 2240$ kg/m^3.

The wall started to store solar energy as soon as the thermal blanket was lifted at 9:00h (Fig. 11). A peak rate of 9.65 kW (average for February) occurred at 13:30h. The daily cumulative energy storage in the wall was 166 MJ (2635 kJ/m^2 of wall

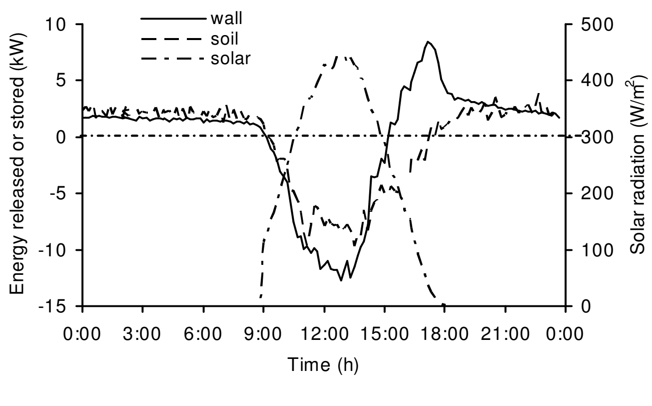

Fig. 11. Energy stored (-) in and released (+) by north wall and soil, based on average temperature measurements for February.

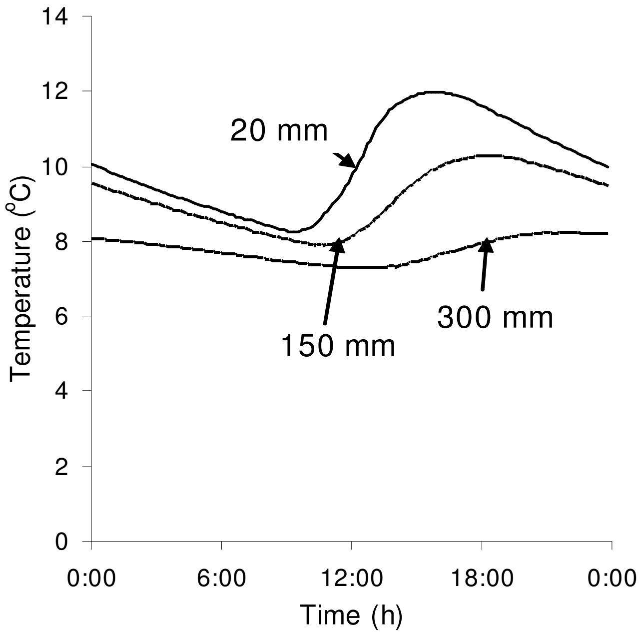

Fig. 12. Average temperature of the soil inside the greenhouse measured at various depths.

surface area). The average daily solar energy, measured as global radiation over the entire greenhouse floor area, was 1882 MJ. Assuming the plastic cover had a transmissivity of 0.90, the solar energy potentially available to the greenhouse was 1694 MJ. This indicates that the north wall of the greenhouse stored about 10% of the available solar energy.

The wall started to release energy to the greenhouse after 15:20h, although the solar radiation at 15:20h was still strong (237 W/m^2) (Fig. 11). The rate of energy release increased quickly from 15:20h to 17:10h, reached a peak of 8.41 kW and then decreased quickly to 3.29 kW at 18:30h (immediately after the thermal blanket was applied). The release rate decreased over the night gradually to about 1.0 kW immediately before the thermal blanket was lifted in the morning (9:00h). The daily energy release was 159 MJ (2523 kJ/m^2), which was only 4% less than the stored amount (166 MJ). This means almost all the solar energy absorbed by the wall in the daytime was released to the room in the nighttime.

Soil temperature and stored energy

The soil temperature at 300-mm depth stayed almost constant (the variation was within 1°C) at about 8°C (Fig. 12). The soil temperature at 20-mm depth started to increase about 30 min after the thermal blanket was lifted, from 8.3°C at 9:30h to a peak of 12.0°C at 15:40h, or a rise of 3.7°C. After peaking, the soil temperature decreased gradually until the next morning when the blanket was lifted again. The soil temperature at 150 mm did not start to increase until about 11:00h and peaked at 18:30h. The total increase was 2.4°C (from 7.9 to 10.3°C).

Based on the temperature profiles at the three depths discussed above, it could be seen that a soil layer up to 300-mm deep acted as a heat storage medium. However, the temperature distribution along the soil depth could not be determined accurately because of limited measurements (only three depths). Therefore, the temperature change term ΔT_{soil} in Eq. 6 could not be obtained for determining the amount of heat stored or released by the soil. Furthermore, Eq. 6 does not account for the conversion between sensible heat and latent heat due to soil moisture changes. To estimate heat storage by soil, the measured temperatures at depths 20 and 150 mm were averaged and used as a nominal soil temperature, and a nominal heat capacity was introduced to modify Eq. 6c.

$$Q_{soil} = K_{soil}\Delta T_{soil-n} \qquad (8)$$

where:

ΔT_{soil-n} = change in average temperature measured at depths 20 and 150 mm and

K_{soil} = nominal heat capacity that replaces the actual heat capacity of the soil in Eq. 6c.

To determine K_{soil}, Eq. 1 was applied for the period when the thermal blanket was on and no solar radiation was received, or $Q_{in} = 0$.

$$0 = Q_{cd} + Q_{cv} + Q_{st} \qquad (9)$$

Substituting Eqs. 3, 5, and 6 into Eq. 9 yields:

$$Q_{soil} = \left(\frac{A}{R} + V_i V \rho_a C_a\right)\Delta T - C_{wall}\rho_{wall}V_{wall}\Delta T_{wall} \qquad (10)$$

The measured indoor and outdoor temperature differences (ΔT) and north wall temperature changes (ΔT_{wall}) for the period from 18:00h to 9:00h (the blanket was on) were used in Eq. 10 to determine Q_{soil}. The determined Q_{soil} value and measured soil temperature were then used in Eq. 8 to calculate the nominal heat capacity of the soil K_{soil}. From the property values listed in Table 1, the total area of the greenhouse envelope (A) was calculated to be 398.9 m^2 and the overall thermal resistance 2.21 m^2°C/W (with the thermal blanket).

The infiltration in greenhouses varies with the type and the age of construction. For new double-layer plastic greenhouses, the recommended design value for infiltration is 0.5 - 1.0 air exchange per hour (Hellickson and Walker 1983). Since the solar energy greenhouse had solid north and end walls and a thermal blanket over the plastic cover, the infiltration rate should be much lower than the conventional double-layer plastic construction. A conservative value of 0.25 air exchange per hour was assumed, or $V_i = 0.25/3600 = 6.94\text{x}10^{-5}\ s^{-1}$. The greenhouse volume was calculated to be 829.1 m^3. The density and specific heat of air were assumed to be 1.30 kg/m^3 and 1005 J°$C^{-1}kg^{-1}$, respectively. With these parameter values, the nominal heat capacity of soil (K_{soil}) was determined to be $6.4\text{x}10^7$ W/°C. Using K_{soil} and the measured soil temperature in Eq. 8, soil heat storage/release was estimated and is shown in Figure 11. The variation of soil heat storage/release throughout the day followed a similar pattern as that for the north wall, except there was no peak release in the late afternoon. The soil started to store energy slightly after the thermal blanket was lifted at 9:00h and continued until about 17:00h with the highest rate of 9.7 kW at 13:30h. The rate of energy release by the soil varied little in the nighttime (Fig. 11) with an average of 2.22 kW.

The daily cumulative energy storage by the soil was 152 MJ (or 724 kJ/m^2) while the daily release was 119 MJ (567 kJ/m^2).

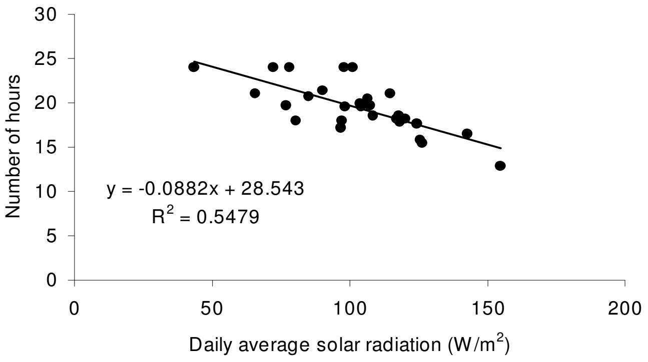

Fig. 13. Number of hours in a day when the indoor temperature fell below 10°C in the solar energy greenhouse, as affected by solar radiation.

This means that 33 MJ, or 22% of the stored energy, was retained in the soil. This retained energy was probably spent on warming the soil or evaporating moisture in the soil.

Supplemental heating requirement

The supplemental heating requirement for a greenhouse depends on the temperature maintained in the greenhouse. The following discussion is based on a night greenhouse temperature of 10°C, which is the lower limit for "warm" greenhouses suitable for a wide variety of plants. The measured temperature fell below 10°C about 81% of the time in the solar greenhouse (Fig. 3). In other words, supplemental heating would be required for about 19 hours a day on average to maintain the greenhouse above 10°C. The recorded hours when the indoor temperature fell below 10°C ranged from 12 to 24 hours per day. The required heating hours decreased with the solar radiation (Fig. 13), and were affected little by the outdoor temperature (Fig. 14). The amount of required supplemental heat (Q_{sup}) was determined from Eq. 11 and the result is shown in Fig. 15.

$$Q_{\text{sup}} = Q_{cd} + Q_{cv} - Q_{in} - Q_{st} \tag{11}$$

Supplemental heating was required from 16:00h in the afternoon to 10:30h the next morning (Fig. 15). Two peaks occurred, one immediately before the blanket was applied and the other one immediately before the blanket was lifted. The thermal blanket was not applied until 18:00h, and therefore heat loss through the plastic cover was overwhelmingly high (36 kW without blanket vs 6 kW with blanket). As the solar radiation continued to decline from 16:00h to 18:00h, the energy input by solar radiation and heat release by the north wall and soil could not compensate for the heat loss. Therefore, the required supplemental heat increased rapidly and reached a peak value of 152 W/m^2. For the same reason – the high rate of heat loss and insufficient solar radiation, a peak of 102 W/m^2 occurred immediately after the thermal blanket was lifted (9:00h). When the thermal blanket was on from 18:00h to 9:00h, the supplemental heat requirement increased gradually from 2 to 17 W/m^2. Optimizing the opening and closing times for the thermal blanket could eliminate the peak demands for supplemental heating. Therefore, a supplemental heating system could be sized based on the demand of 17 W/m^2 or 3.6 kW for the greenhouse tested.

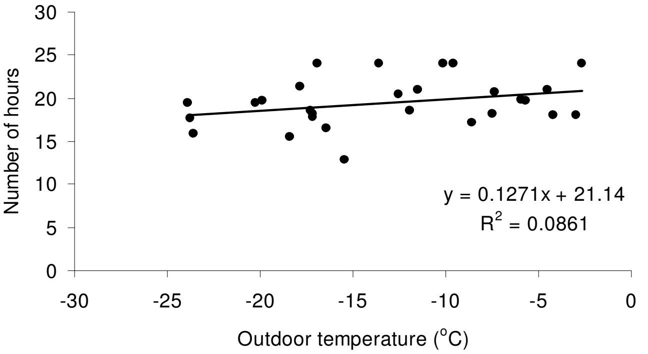

Fig. 14. Number of hours in a day when the indoor temperature fell below 10°C in the solar energy greenhouse, as affected by the outdoor temperature.

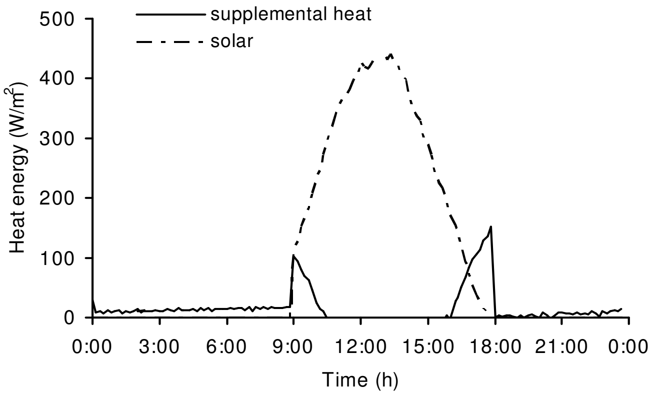

Fig. 15. Supplemental heat required to maintain the indoor temperature above 10°C in the solar energy greenhouse, based on average temperature and solar radiation measurements for February.

CONCLUSIONS

1. The solar energy greenhouse maintained the indoor temperature above 0, 5, and 10°C 82, 35, and 19% of the time, respectively, while the outdoor temperature fluctuated between -29.2 and 4.5°C. The mean night indoor temperature was 2.4°C while the mean outdoor temperature was -13.1°C in the month of February.
2. Solar radiation had more influence on the greenhouse temperature than did the outdoor temperature.
3. The solar storage (north) wall of the greenhouse stored about 10% of the available solar energy. The daily energy storage in the wall was 166 MJ (or 2635 kJ/m^2 of wall surface area) and energy release 159 MJ (2523 kJ/m^2). This means nearly all solar energy absorbed by the wall in the daytime was released to the room in the nighttime.
4. Not all energy stored in the soil in the daytime was released to the greenhouse as sensible heat in the nighttime. The average daily energy storage by soil was 724 kJ/m^2, whereas the average daily release was 567 kJ/m^2.
5. To maintain the night temperature at 10°C in the greenhouse, supplemental heat up to 17 W/m^2 would be required for 19 hours per day in the month of February. The operation of the thermal blanket (opening and closing times) should be optimized to avoid the high demand for supplemental heat.

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