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Greenhouse heating by solar air heaters on the roof

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ABSTRACT

A solar air heater (SAH) system was investigated experimentally for heating an innovative greenhouse in Baghdad, Iraq (33.3 °N, 44.4 °E). The innovative greenhouse combined a traditional greenhouse and a bank of solar air heaters on the roof as one structure. This arrangement did not affect the required solar radiation inside the greenhouse for winter heating when compared with a conventional greenhouse. An energy balance method was used to calculate the heating load. This differs from the previous standard method which does not include soil heat storage. The soil surface heat gain was considered in the present work and was found to contribute 13–19% of the heating load required. Six solar air heaters with a single glass cover and a 'V' corrugated absorber plate connected in parallel were mounted on the greenhouse roof. Tests were carried out in the winter season of 2012. The mass flux of air through the collectors was varied from 0.006 to 0.012 kg/s.m^2. An air mass flux of 0.012 kg/s m^2 was found to provide about 84% of the daily heat demand to keep the greenhouse inside air temperature at 18 °C. The summation of a would be stored energy from the SAHs and a stored free solar heat inside the greenhouse can cover all the daily heating demand with an excess of approximately 46%.

1. Introduction

Heating of a greenhouse is one of the most energy consuming activities during the winter periods. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in a greenhouse [1]. Due to the relatively high cost of energy, only a small number of greenhouse owners can offered the use of auxiliary heating systems. The use of low cost and alternative heating system is therefore, important for a greenhouse to provide optimum indoor conditions during winter months.

Different renewable energy sources can be applied in horticulture like geothermal, solar, and biomass energies instead of using fossil fuels which are used up to now [2]. The source receiving most serious consideration for greenhouse heating is solar energy [3]. There are two types of agricultural greenhouses that utilize solar energy for heating purposes; passive and active solar greenhouses. Passive greenhouses are utilized as a collector and designed for maximizing the solar heat gains. Active greenhouses are equipped with solar systems that utilize a collecting system, which is separate from the greenhouse cell, with an independent heat storage system [1].

The existing passive solar greenhouse heating systems utilize water storage, rock bed storage, phase change material storage, movable insulation (thermal screens/curtains), ground air collector, north wall storage and mulching [4]. These systems are capable of maintaining the inside air temperature 2–4 °C higher than the outside temperature. Water storage tanks/barrels can be placed either at the north side of the greenhouse [1] or at the center of the greenhouse [5]. These tanks/barrels act as insulators and during the night as radiators.

Al-Amri [6] employed a section of the southern inclined roof of an experimental gable shaped greenhouse as a solar water heater connected to an insulated water storage tank. It was reported that the productivity of tomato was enhanced by 46.67%. Heating by SAHs on the roof of a greenhouse was not cited in the literature.

2. Greenhouse description

A single slope novel greenhouse measuring 3.8 m × 2 m (7.6 m^2 floor area), without crops, was constructed at Baghdad University, Baghdad, Iraq as shown in Fig. 1. The greenhouse was built from wooden frames made with poles measuring 100 mm × 50 mm. Ordinary single 4 mm glass was used for the transparent cover. The aperture areas were recessed to hold the glass sheets which were held in place with wooden strips measuring 10 mm × 50 mm. The glass periphery was covered with silicon sealant to prevent leakage of water and air.

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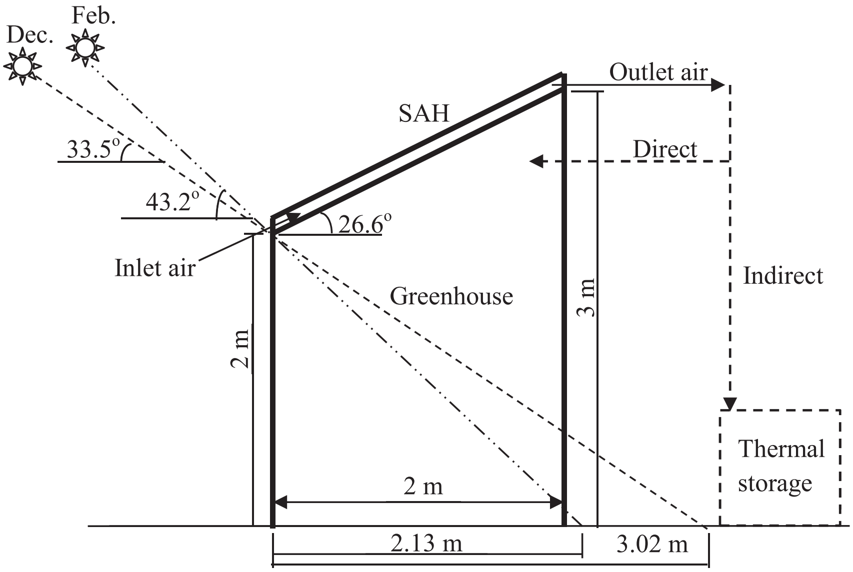

Fig. 1. Sun altitude angle and irradiation of greenhouse floor at solar noon.

The back height of the greenhouse is $H = 3$ m which is an actual greenhouse height in traditional greenhouses. As the other front height is 2 m, the gable slope became 26.6°. The greenhouse integrates roof mounted SAHs. This eliminates solar radiation from the roof. However, the solar radiation through the walls provided adequate heat gain for warmth in the greenhouse in Iraq. This is due to the low sun altitude in winter which allows sun rays to cover the diurnal heating load (Fig. 1). Comparison between temperature differences for the greenhouse before and after installing the SAH's on the roof is shown in Fig. 2 for a clear sky in December. Clearly, the inside air temperature for both greenhouses have the same behavior and values which confirms the validity of the above statement. The higher values in the present greenhouse in the late afternoon is due to the reduction in the surface area that exchanges heat with the surrounding as compared with the traditional greenhouse which includes the roof area, i.e. less heat loss in this novel greenhouse.

Six collectors measuring 2.3 m × 0.6 m were used to cover the greenhouse roof. Fig. 3 depicts a cross section of the SAH. Thermal energy supplied by SAH could be used in two ways. Direct supply of hot air for heating the greenhouse during the day or directed to thermal energy storage for night demand as shown in Fig. 1.

3. Mathematical modeling

3.1. Heating load calculation method

An energy balance method was used in the present work to calculate the heating load which differs from the previous standard method. The standard method [7–9] does not include the effect of soil heat storage. Abdel-Ghani and Al-Helal [10] presented an analysis for the portions of solar radiation absorption in the various greenhouse components. However, they did not carry out heating load estimation or the contribution of soil heat storage to this load. The soil surface heat gain was considered in the present work. Heat loss from greenhouses is caused primarily by transmission through the structural cover (q_{tr}) plus infiltration (q_{inf}) of outdoor air.

$$\text{Heat loss} = q_{tr} + q_{inf} \tag{1}$$

where q_{tr} is estimated by the following equation [9];

$$q_{tr} = Ur(T_g - T_a) \tag{2}$$

Also, q_{inf} is calculated by Ref. [8];

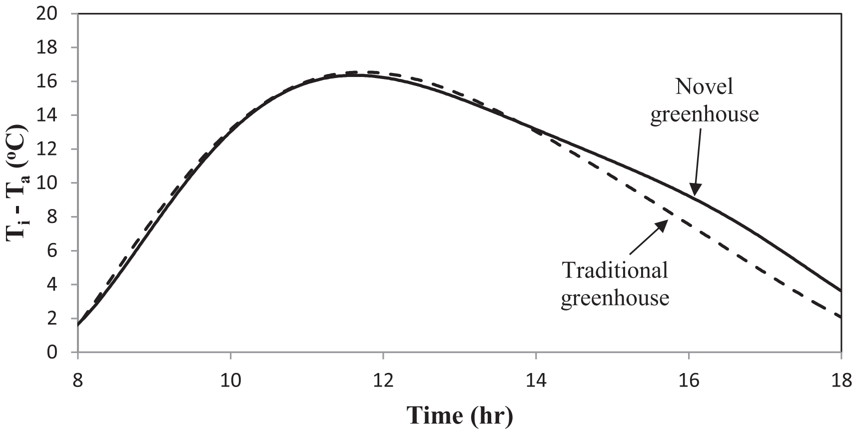

Fig. 2. Comparison of temperature differences for the present novel greenhouse and traditional greenhouse for clear sky in December.

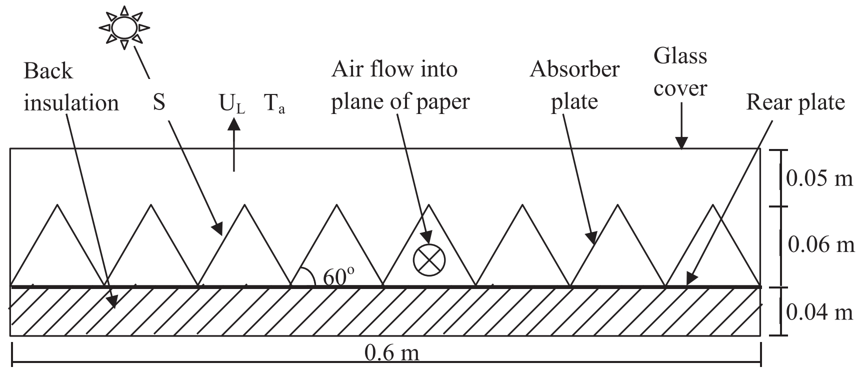

Fig. 3. A schematic of V-corrugated solar air collector.

$$q_{\mathrm{inf}} = \rho c_p N \frac{H}{3600}\left(T_{\mathrm{g}} - T_{\mathrm{a}}\right) \tag{3}$$

The sources of heat gain are solar and soil gains. The solar heat gain of the greenhouse is calculated by the following equation [6];

$$q_{\mathrm{sg}} = \tau H_{\mathrm{gl}} \tag{4}$$

The heat gain from the soil surface to the interior air of the greenhouse due to convection and radiation is calculated in this work as;

$$q_{\mathrm{co},s-i} = h_{\mathrm{co},s-i}(T_{\mathrm{s}} - T_{\mathrm{g}}) \tag{5}$$

and

$$q_r = \varepsilon_s \sigma \left(T_{\mathrm{s}}^4 - T_{\mathrm{g}}^4\right) \tag{6}$$

Thus, the total heat gain is;

$$\text{Heat gain} = q_{\mathrm{sg}} + q_{\mathrm{co},s-i} + q_r \tag{7}$$

The heat load of the greenhouse will be [8];

$$\text{Heat load} = \sum \text{Heat loss} - \sum \text{Heat gain} \tag{8}$$

$$\begin{aligned}\text{Heat load} = {} & \left[Ur + \rho c_p N \frac{H}{3600}\right](T_{\mathrm{g}} - T_{\mathrm{a}}) - \Big[\tau H_{\mathrm{g}} + h_{\mathrm{co},s-i}(T_{\mathrm{s}} - T_{\mathrm{g}}) \\ & + \varepsilon_s \sigma \left(T_{\mathrm{s}}^4 - T_{\mathrm{g}}^4\right)\Big]\end{aligned} \tag{9}$$

3.2. Solar air heaters

At steady state, the useful energy gain of a collector is the difference between the absorbed solar radiation and the thermal losses [11]:

$$Q_u = A_c F_R [S - U_l (T_i - T_{\mathrm{a}})] \tag{10}$$

where F_R is the heat removal factor which can be calculated as [11]:

$$F_R = \frac{Gc_p}{U_l}\left[1 - \exp\left(\frac{-F' U_l}{Gc_p}\right)\right] \tag{11}$$

Also, the useful energy can be determined experimentally as;

$$Q_u = Gc_p (T_o - T_i) \tag{12}$$

The outlet air temperature from the solar air heater is then,

$$T_o = T_i + \frac{Q_u}{Gc_p} \tag{13}$$

This allows comparison of the measured outlet temperature T_o with that calculated using Q_u from Eq. 10 which represents a theoretical value.

A measure of collector performance is the collection efficiency which is defined as the ratio of the useful gain over some specified time period to the incident solar energy over the same time period [11]:

$$\eta = \frac{Q_u}{A_c I} \tag{14}$$

4. Experimental measurements

Hourly solar radiation was measured during the day with a Kipp and Zonen pyranometer model CMP22 having a measuring range of up to 4000 W m^{-2} (error < 5 W m^{-2}). Ambient air, greenhouse air, air inlet and outlet of SAH, and soil temperatures were recorded at 15 min intervals using eighteen calibrated thermistor sensors LM35, having a measuring range of −55 to 150 °C (error 0.25 °C at room temperature). These sensors were connected to a data acquisition system manufactured by Lab-Jack Company of Lakewood, Colorado, USA, model U3 LV. One sensor was placed outside the greenhouse in the shade at 1 m height for ambient temperature. Six sensors were placed inside the greenhouse at 1.5 m height shaded from direct sunlight for greenhouse air temperature. Three sensors were placed in the soil at a depth 0.01 m for soil surface temperature inside the greenhouse. Six other sensors were buried in the soil at 0.1, 0.2, and 0.5 m. Three inside and three outside the greenhouse to measure soil sub-layer temperatures. Two sensors were placed at the inlet and outlet of the SAH. Fig. 4 shows the location of the pyranometer and thermistor sensors inside and outside the greenhouse.

Winter experimental tests were carried out to assess the amount of solar heat obtainable for heating the greenhouse. Experimental data was collected for the months of December 2012 to March 2013 with each test starting at 8 a.m. and terminated at 4 p.m. Preliminary tests were conducted over a wide range of mass flow rate. The final selected values of 0.006, 0.009, 0.0096, and 0.012 kg/m^2s were found to cover a reasonable range of results for hot air temperature and SAH performance. Initially an average volume flow rate was taken from five measurements across the SAH outlet. The mass flow rate was then corrected for density variation with temperature by the ideal gas law. The area unit in the mass flux is the SAHs apertures area. The mass flux was fixed throughout the day for any one experiment.

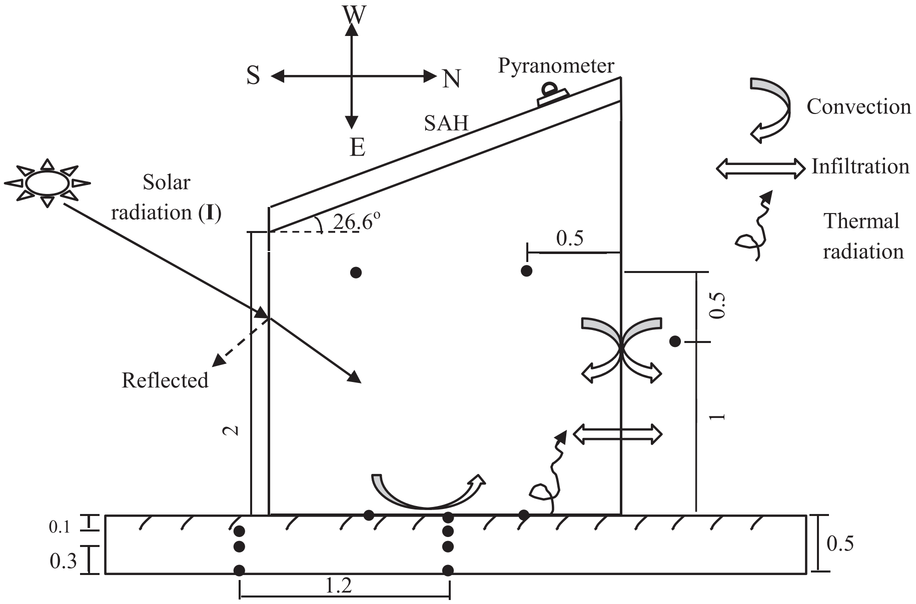

Fig. 4. Side view of the greenhouse with experimental measuring points: (•) temperature sensors. Dimensions are in meters.

5. Results and discussions

5.1. Greenhouse heating load

Fig. 5 shows hourly variation of the heating load of the greenhouse for typical winter days based on the method of Refs. [7–9] described by equations 1, 4, and 8. It can be seen that the maximum heating load occurs between 6 and 7 a.m. for these months. No heating is needed in the periods where the load curves intersect the zero load line. The starting and ending times of heating and cooling requirements are denoted on the figure. If the inside air temperature is less than the design 18 °C, a certain quantity of heat should be supplied. Otherwise, ventilation or evaporative cooling is required.

In the present work, the heat stored in the greenhouse soil and later radiated and convected to the greenhouse interior air is included as a heat gain. A comparison between the two methods is shown in Fig. 6. This figure represents the heating load for a cold partly cloudy day in January 2013. The heating load obtained by the standard method is higher than the value obtained by the present energy balance method. Adding the soil heat gain to the standard method results in agreement with the present heating load estimation procedure as shown in Fig. 7.

The effect of solar radiation intensity on the soil heat gain appears clearly in Fig. 8. This represents the second part of a heating source. The average value of the soil heat gain was 51 and 35 W m^{-2} of floor area for clear and partly cloudy skies, respectively. It represents 13–19% of the maximum heating load in the two cases in January. Maximum January heating load was approximately 265 W m^{-2}.

5.2. Performance of SAH

The collectors employed for winter space heating were a single pass air heaters with a 'V' corrugated plate absorber and a single glass cover. They were manufactured for this investigation from locally available materials. The absorber was a 'V' corrugated galvanized steel sheet 0.7 mm thick painted mat black. It was attached to a flat rear plate to compose triangular air passages of equal 70 mm sides. 20 mm fiberglass insulation was used as rear insulation. The collector housing was built of 20 mm wood boards.

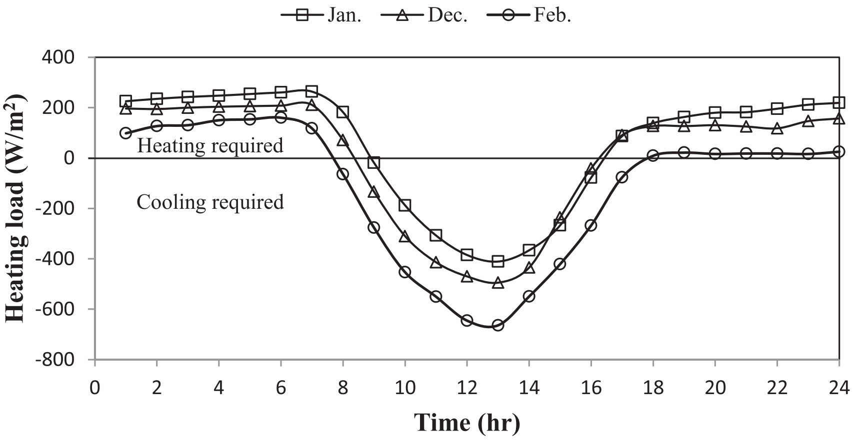

Fig. 5. Hourly variation of heating load of the greenhouse for typical winter days based on the method of Refs. [7–9].

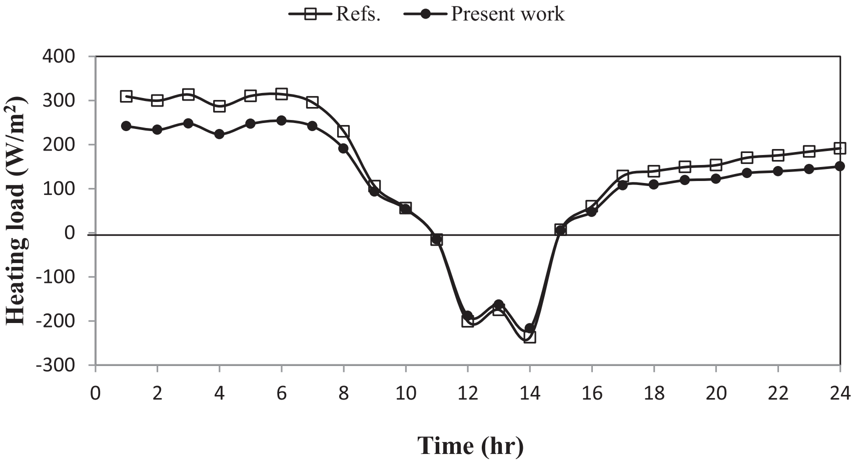

Fig. 6. Heating load estimation by the present work and Refs. [7–9] on 17-1-2013.

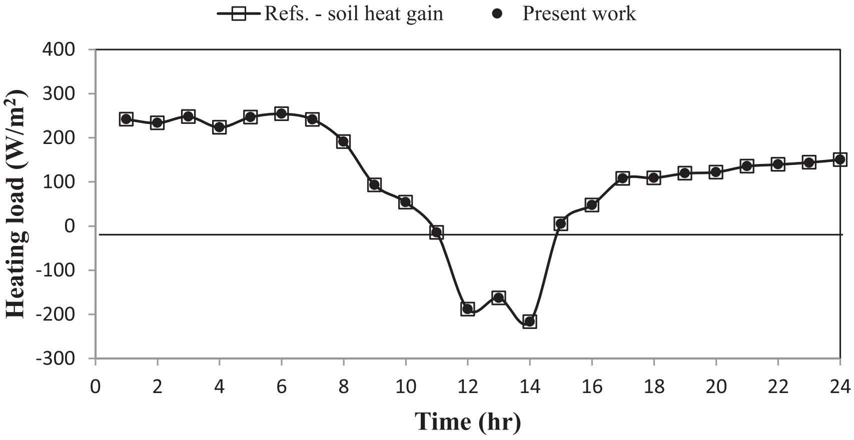

Fig. 7. Agreement of heat load between present work and that of Refs. [7–9] when soil heat gain is added.

The effect of mass flow rate on the useful energy is illustrated in Fig. 9. The useful energy increases with increasing air mass flux. As the mass flux increases, the collector energy is picked up at a faster rate which reduces the outlet air temperature. The slope of the line for each hour is slightly different. The shift in the curve upwards with each hour is due to the increase in solar radiation intensity which is more pronounced at the early hours than at midday. The solar radiation intensity at each hour is given on each line.

The variation of ambient temperature, which is also the collector inlet air temperature, and the outlet air temperature for different air mass fluxes are plotted versus time of day in Fig. 10. The outlet temperature increases with time from 9 a.m. to midday and starts

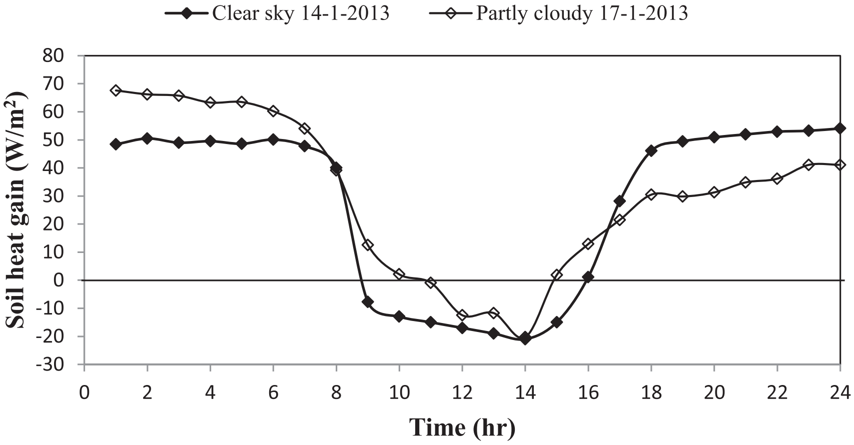

Fig. 8. Comparison between soil heat gain for clear and partly cloudy winter days.

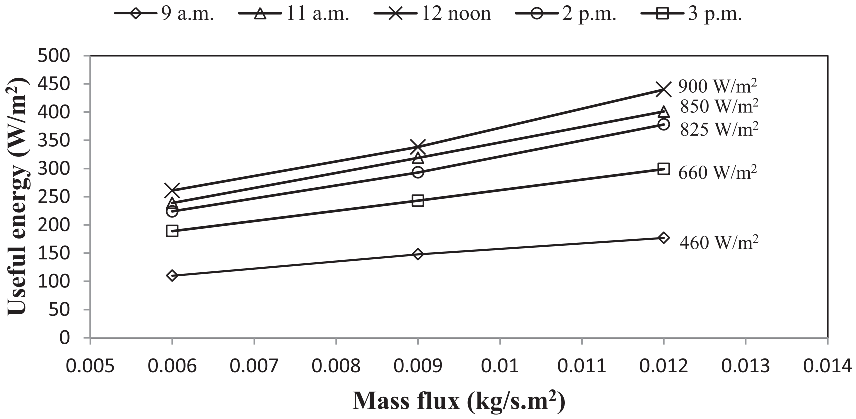

Fig. 9. Variation of useful energy with air mass flux.

to decrease due to the reduction in solar radiation intensity. It is clear from the results presented for typical winter days that the magnitude of the outlet temperature depends on the mass flux employed, ambient temperature and strongly on solar radiation. This agrees with results in the published research [12,13]. Higher air outlet temperatures are obtained with lower mass fluxes and vice versa. It is observed from Fig. 10 that both experimental and theoretical values are in agreement.

The operation curve of the SAH was obtained from experimental results for clear days in the working period for winter as shown in Fig. 11. The useful energy, required collector area and the mass flux can be determined by using this curve. There is a scatter in experimental data points on both sides of the average efficiency line. The reason for this is due to the varying operating conditions. In addition, changes in wind speed during the experiment, the assumed optical properties that depend on the incident angle come together to cause the scatter as expected. This result is similar to the results obtained by Refs. [14,15]. The value of intersection point of the average efficiency line with the vertical axes is 68%. The experimental instantaneous efficiency for winter may be given as;

$$\eta = 0.68 - 7.07\frac{(T_o - T_i)}{I} \tag{15}$$

The constants in this equation are within normal values for such collectors.

5.3. Solar heating system performance

The preferable inside air temperature of the greenhouse in winter differs according to plant type [7]. Therefore, an average value of 18 °C is adopted in this work. The present bank of SAHs supply heated air directly to the greenhouse for heating or for storing heat in a suitable thermal storage for use in other periods when solar heat is inadequate.

In order to calculate the heat demand (H_d) to maintain the greenhouse at the desired temperature, an energy balance is used between the heating load (H_L) calculated by Eq. 9 and the useful energy picked up by the bank of SAHs calculated by Eq. 12 as follows;

$$H_d = H_L - Q_u \tag{16}$$

The result for the hourly heat demand on a typical winter clear sky day in January is shown in Table 1. Negative values of the equation indicate a cooling load. Therefore, such values are transferred to the heat storage column. Thus, only positive values are listed in the heat demand column. It is obvious, that an efficient thermal energy storage would be very appropriate to store solar energy during the day for use at other heat demand hours.

Assuming a rock bed thermal storage (Q_{rs}) system with a recovery rate of 80% [16], the heat that could be provided by this storage to the greenhouse would be;

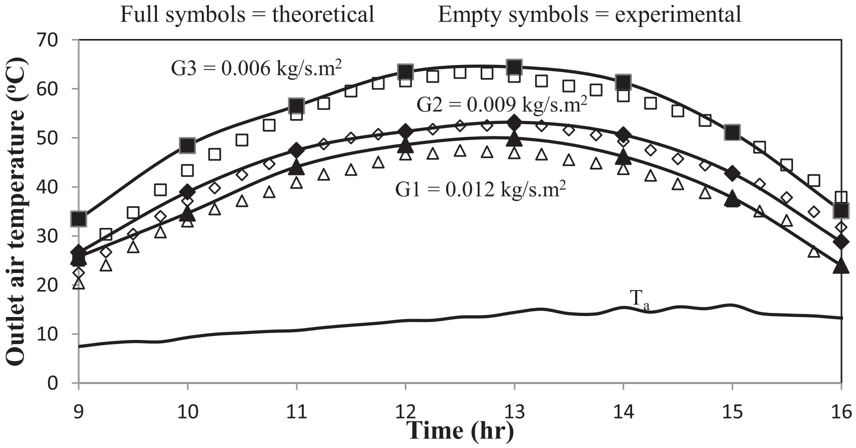

Fig. 10. Comparison between theoretical and experimental outlet temperatures of SAH for different mass fluxes.

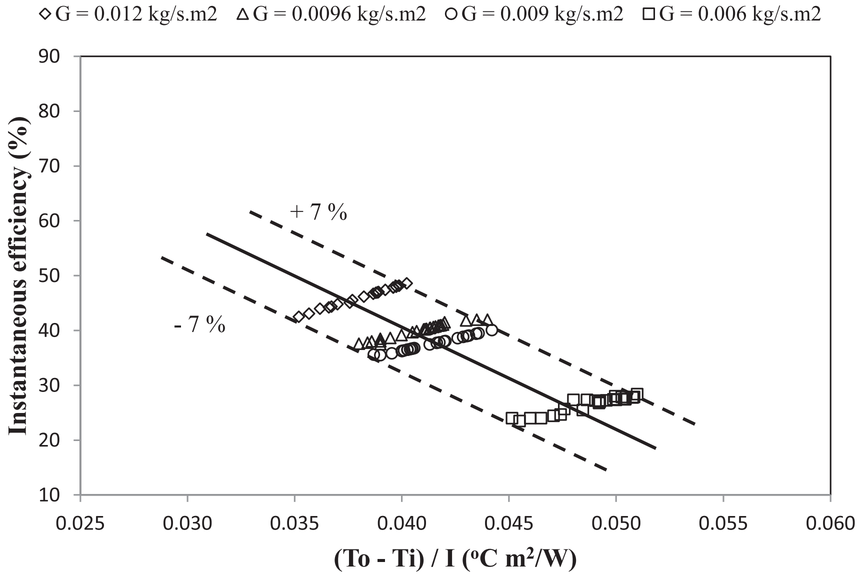

Fig. 11. Winter operation curve.

$$\text{Heat supply} = \text{Heat stored} \times 0.8 = 71.31 \times 0.8 = 57.05\ \text{MJ} \tag{17}$$

$$Q_{rs} = \frac{\text{Heat supply}}{\text{Total heat demand}} = \frac{57.05\ \text{MJ}}{67.47\ \text{MJ}} = 84\% \tag{18}$$

Therefore, the air mass flux $G = 0.012$ kg/s.m^2 through the SAHs, in the present work, could provide about 84% of the daily heat demand to keep the greenhouse inside air temperature at 18 °C during night time. As for December and February, the heating load is lower as shown in Fig. 5. Thus, the situation would be much better for the greenhouse microclimate.

Table 1
Heat demand for the greenhouse for clear sky (13/1/2013).

Hour	Heat gain from[a] SAHs (Q_u) (MJ)	Heat loss from greenhouse (H_L) (MJ)	Heat demand for greenhouse (H_d) (MJ)	Possible heat stored (MJ)	Free heat gain inside greenhouse (MJ)
1	0	4.84	4.84	0	0
2	0	5.05	5.05	0	0
3	0	5.29	5.29	0	0
4	0	5.42	5.42	0	0
5	0	5.62	5.62	0	0
6	0	5.75	5.75	0	0
7	0	5.91	5.91	0	0
8	1.37	3.88	2.51	0	0
9	6.00	(−0.30)	0	6.00	0.30
10	8.73	(−4.78)	0	8.73	4.78
11	10.87	(−6.30)	0	10.87	6.30
12	11.85	(−10.60)	0	11.85	10.60
13	11.80	(−11.12)	0	11.80	11.12
14	10.26	(−10.28)	0	10.26	10.28
15	7.70	(−6.70)	0	7.70	6.70
16	4.10	(−2.16)	0	4.10	2.16
17	0	1.61	1.61	0	0
18	0	2.53	2.53	0	0
19	0	3.10	3.10	0	0
20	0	3.53	3.53	0	0
21	0	3.56	3.56	0	0
22	0	3.91	3.91	0	0
23	0	4.33	4.33	0	0
24	0	4.51	4.51	0	0
Total			**67.47**	**71.31**	**52.24**

[a] Heat gain from SAH at $G = 0.012$ kg/s m^2.

Another point should be taken into consideration. Greenhouses can be considered as a large solar collector having no air inlet and outlet [16]. Thus, the excess free solar heat inside the greenhouse during the day should be utilized by another type of heat storage such as phase change material for later release at night time. For purposes of estimation, an energy recovery rate of 0.8 [17] will be assumed for this second storage which will be termed Q_{ps}. The exploitation of this excess energy is necessary to compensate the shortage in heat demand for heating the greenhouse at night. In Fig. 5, the free heat gain inside the greenhouse during the period 9 a.m. to 4:30 p.m., i.e. the negative values of heating load, are moved to the last column of Table 1. The free solar heat gain (Q_{ps}) inside the greenhouse is 52.24 MJ. Thus, the heat that could be provided by the second storage to the greenhouse would be;

$$\text{Heat supply} = \text{Heat stored} \times 0.8 = 52.24 \times 0.8 = 41.8\ \text{MJ} \tag{19}$$

$$Q_{ps} = \frac{\text{Heat supply}}{\text{Total heat demand}} = \frac{41.8\text{MJ}}{67.47\text{MJ}} = 62\% \tag{20}$$

Therefore, the excess heat generated inside the greenhouse could provide about 62% of the daily heat demand to maintain the inside air temperature of the greenhouse at 18 °C. In short, the summation of stored energy from the SAHs and the stored free solar heat inside the greenhouse can cover all the daily heating demand with an excess of approximately 46%, i.e. the total stored heat (Q_{ts}) will be,

$$Q_{ts} = Q_{rs} + Q_{ps} = 84\% + 62\% = 146\% \tag{21}$$

5.4. Overall heating system assessment

Greenhouses are a field of effective utilization of renewable energies and solar energy in particular. Solar energy is usually intermittent in winter. It needs to be stored on clear days for heating at night. To meet the required winter heating load two important heat sources for possible storage have to be considered. First is the free solar gain inside the greenhouse during the day which could provide about 62% of the daily heat demand for heating for clear sky days. This of course, requires a day time interior storage for later heat release. Second is the useful energy picked up by a bank of SAHs that should be stored in a usual rock bed or other storage means. In the present work, the combination of possible heat storage from free solar gain inside the greenhouse and the useful energy from SAHs meets the heat demand for heating with 46% excess energy that could be used for other purposes. The ratio of collecting area of SAHs to the floor area of the greenhouse, in the present investigation, is equal to one.

To find out the appropriate collecting area of SAHs with the inclusion of free solar gain inside the greenhouse, the following procedure is suggested.

$$\begin{aligned}\text{Heat required from storage} &= \text{Total heating load} - 0.8 \\ &\quad \times \text{Free solar gain} \\ &= 67.47 - 0.8 \times 52.24 = 25.67\ \text{MJ}\end{aligned} \tag{22}$$

$$\begin{aligned}\text{Heat required from SAHs} &= \text{Heat required from storage} \\ &\quad + 20\%\ \text{storage loss} \\ &= 25.67 + 0.2 \times 25.67 = 30.8\ \text{MJ}\end{aligned} \tag{23}$$

For design purposes, an average value of solar intensity for the period 9 a.m. to 4 p.m., which is the working period of the SAHs in winter, should be taken for design calculation. The measured average value of solar irradiance for January is 725 W/m^2. Assuming an average value of SAHs efficiency at 40% (see Fig. 11). The picked up energy is obtained from Eq. 13.

$$Q_u = \eta \times I = 0.4 \times 725 = 290\ \text{W}\big/\text{m}^2$$

$$\begin{aligned}\text{Area of SAHs} &= \frac{\text{Heat required from SAHs}}{Q_u} \\ &= \frac{30.8\text{MJ}\,\frac{10^6\text{J}}{\text{MJ}}}{290\,\frac{\text{J}}{\text{sm}^2} \times 8\text{hr} \times \frac{3600\text{s}}{\text{hr}}} = 3.7\text{m}^2\end{aligned} \tag{24}$$

$$\frac{\text{Area of SAHs}}{\text{Floor area of the greenhouse}} = \frac{3.7}{7.6} = 48.7\% \tag{25}$$

$$\frac{\text{Area of SAHs}}{\text{Roof area of the greenhouse}} = \frac{3.7}{8.5} = 43.5\% \tag{26}$$

From Eq. 15, the temperature difference across the SAHS equal;

$$\frac{\Delta T}{I} = \frac{0.68 - 0.4}{7.07} = 0.04\,\frac{\text{m}^2\,{}^\circ\text{C}}{\text{W}}$$

$$\Delta T = 0.04 \times 725 = 29\ {}^\circ\text{C}$$

The air mass flux through the SAHs is equal to (Eq. 12);

$$G = \frac{Q_u}{\Delta T \cdot c_p} = \frac{435}{29 \times 1005} = 0.015\,\frac{\text{kg}}{\text{sm}^2}$$

This means that a bank of SAHs covering 43.5% (or say 45%) of the greenhouse roof area can provide the daily heating load with an air mass flux of 0.015 kg/s.m^2.

6. Conclusions

Based on the results the following conclusion can be drawn:

1. The energy balance method used for heating load calculation has been improved considering soil surface heat gains. This gives agreeable results with experimental values.
2. The greenhouse soil heat provides 13–19% of the heating load. Inclusion of this heat source reduced the heating demand for a greenhouse.
3. The summation of stored energy from the SAHs and the stored free solar heat inside the greenhouse can cover all the daily heating demand with an excess of approximately 46%.
4. A bank of SAHs covering 45% of the greenhouse roof area can provide the daily heating load of the novel greenhouse.

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Nomenclature

A: area (m^2)
c_p: isobaric mass heat capacity (J/kg K)
F': collector efficiency factor
F_R: heat removal factor
G: mass flux (kg/s m^2)
H: back height of greenhouse (m)
H_d: heat demand (W/m^2)
H_{gl}: global solar radiation on horizontal surface (W/m^2)
H_L: heating load (W/m^2)
I: incident solar radiation (W/m^2)
N: number of air changes per hour (h^{-1})
Q: energy (MJ)
Q_u: useful energy (W/m^2)
q: heat transfer rate (W/m^2)
r: ratio of glazing surface area to soil surface area
S: absorbed solar radiation (W/m^2)
T: temperature (°C)

U: overall heat transfer coefficient (W/m^2 K)

Greek symbols

ε: emissivity
η: efficiency
ρ: density (kg/m^3)
τ: transmittance
σ: Stefan–Boltzmann constant (W/m K)

Subscripts

a: ambient
c: collector
co: convection
g: greenhouse
i: inside air/inlet
inf: infiltration
l: loss
m: measured
o: outlet
r: thermal radiation
s: soil
sg: soil gain
$s\text{-}i$: soil to inside air
tr: transmission