HEATING A GREENHOUSE USING A SOLAR AIR COLLECTOR ASSISTED BY THERMAL STORAGE: A SIMULATION STUDY

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Abstract
Solar energy has an enormous contributions in numerous sectors. Among these sectors, agricultural greenhouses still receiving more interests to reduce the energy consumption which in turn mitigates the reliance of greenhouses to conventional energy sources and minimizes greenhouse gas emission (GHG). A greenhouse is an enclosed structure made of wood or metal frames covered with transparent materials such as glass, plastic, and fiberglass that allow solar radiation to enter the greenhouse. The primary objective of a greenhouse is to provide a shelter for plants against the harsh weather conditions such as strong winds and heavy rain. Further benefits of a greenhouse are to produce agricultural products out of season for both commercial sales and research purposes and attain better quality and quantity of plants as well. To maintain the microclimate of a greenhouse at an appropriate level which is more favorable for various crop growth, systems such as heaters, coolers, fans, thermostats, and other equipment must be used. However, in cold climates or arears with prolonged cloud cover, a greenhouse can be heated conventionally by burning fossil fuels and using electric heaters or by utilizing solar heaters that convert solar energy into thermal energy. In this study, MATLAB software was used to predict the heating load of a greenhouse using an energy balance method that takes into account the heat gain from soil. This is not considered in conventional methods. The results of heating load obtained revealed good agreement with those obtained from conventional methods when the soil heat gain is included. Two identical collectors in series of total area of 5.4m^2 were employed as a heating system. This arrangement provides an air outlet temperature of 30^{o}C with an air mass flux of 0.06 kg/s.m^2 at midday in January. In addition, a rock- bed thermal storage system was adopted to store the excess heat which can provide about 58.5% of the total heat demand, while the remaining amount can be supplied by an auxillary heating system.

Keywords: *Solar energy, Greenhouse, heating load, Solar air heater, Rock- bed storage*

1. Introduction

Food security is the most earnest issues in the world due to population growth and energy consumption. Therefore, the agricultural sector must be developed to meet the urgent challenge of crop production. A greenhouse is a structure covered with transparent material that utilizes solar energy to grow crops (Panwar et al., 2011). It is one of the most feasible solutions in this context because it provides controlled and favorable climatic conditions (air temperature, relative humidity, and solar radiation) against the harsh outdoor climate (Li et al., 2017). However, these conditions cannot be controlled in outdoor cultivation.

Heating, cooling, ventilation, fogging, CO_2 enrichment, lighting, and shading equipment are widely used to maintain the microclimate in a greenhouse at an appropriate level for the growth of various crops (Hassanien et al., 2016). Among these equipment, heating and cooling systems are the two major energy consuming systems in greenhouses. Heating systems consume about 65- 85% of the total energy consumption in greenhouses, which together with the cooling systems accounts for about 70- 85% of the total operating costs (Ahamed et al., 2019). Therefore, reducing the total operating costs have a vital role to make greenhouse production more economical and sustainable. Greenhouses are conventionally heated by burning fossil fuels or using electric heaters. The uncertain availability of fossil fuels and their high cost, have led to search for more reliable and sustainable alternative energy sources (Mostefaoui and Amara, 2019).

Geothermal, solar, and biomass energies can be used for greenhouse heating and mitigate the dependency of greenhouse on conventional resources. Solar energy, as a clean, abundant, and renewable energy source grabbed a lot of attention as viable option for heating agricultural greenhouses. Therefore, solar greenhouses that utilize solar energy can be categorized into two main types: passive and active solar greenhouses. Passive greenhouses are designed in a way to maximize solar heat gain as much as possible, while active greenhouses are designed to be integrated with various solar systems such as photovoltaic (PV), photovoltaic/ thermal (PVT), and solar thermal collector to capture solar energy (Gorjian et al., 2020).

The objective of this study was to develop a simulation model using MATLAB software to estimate the time-dependent supplemental heat demand in a gable shape solar greenhouse. An energy balance method was used to calculate the greenhouse heating load, which includes new terms not considered in the literature, such as solar and soil heat gains. A V-corrugated solar air heater was used to heat an agricultural greenhouse. Besides, it was assumed that a rock- bed storage system would be used to store excess heat energy during the day and release it at night.

2. Mathematical model

In the present study, a freestanding, gabled glasshouse with an east-west orientation with no plants inside and located in Baghdad city, Iraq (33.3ºN, 44.4ºE) was considered. It was assumed to have a length of 4 m, a width of 2 m, and central height of 3 m; 2 m to the eave and 1 m to the ridge.

2.1. Estimating the greenhouse heating load

In this work, an energy balance was adopted to estimate the heating load of the greenhouse. The heat exchanges between the greenhouse and the surroundings are illustrated in Fig.1.

To establish the equations for the energy balance, the following assumptions are made:

1. The orientation of the greenhouse is east-west.
2. Absorptivity and heat capacity of the enclosed air and the soil are included.
3. The storage capacity of the walls and the roof material was neglected.
4. The air and the soil surface temperatures are uniform.
5. No evaporation occurs from the soil.

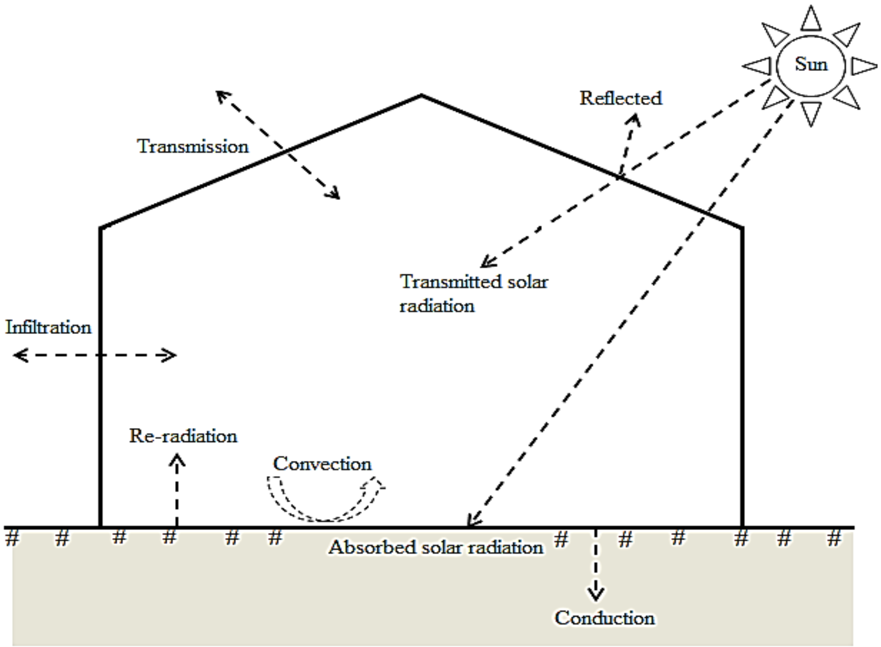

Figure 1. *The greenhouse under study and the heat exchange between it and the surroundings.*

The energy needed to maintain the inside temperature of the greenhouse at the favorable level can be written as:

$$\text{Heat load} = \sum \text{Heat loss} - \sum \text{Heat gain} \quad (1)$$

The calculations must consider solar energy load which is usually much greater for greenhouses than for conventional buildings (ASHRAE, 1997). Electric loads for lighting and fans are usually small.

Heat losses from greenhouses are mainly due to transmission through the structural cover (q_t) and infiltration of outdoor air (q_{inf}) which are calculated as (ASHRAE, 1997; Aldrich and Bartok, 1994):

$$q_t = U\, r\, (T_i - T_a) \quad (2)$$

$$q_{inf} = \rho\, c_p\, N\, \frac{H}{3600}\, (T_i - T_a) \quad (3)$$

Where;

T_a= ambient temperature,°C.

H= average height of greenhouse, m.

Thus,

$$Heat\ loss = q_t + q_{inf} \quad (4)$$

The greenhouse heat gain is caused primarily by solar and soil heat gains. The solar heat gain of the greenhouse (q_{sg}) can be calculated as (ASHRAE, 1997):

$$q_{sg} = \tau\, I_h \quad (5)$$

where (I_h) is the incident radiation on a horizontal surface, W/m^2.

The heat gain from the soil surface to the interior air of the greenhouse (q_g) has not been included in the standard heat load calculation presented by references (ASHRAE, 1997; Aldrich and Bartok, 1994; Mastalerz, 1977). However, it comprises both the convection and radiation modes and was calculated in this work as:

$$q_g = q_{co.} + q_r \tag{6}$$

The convection ($q_{co.}$) and the radiation (q_r) heat transfer rates between soil and inside air are calculated as:

$$q_{co.} = h_s\,(T_s - T_i) \tag{7}$$

$$q_r = \epsilon_s\,\sigma\,\left(T_s{}^4 - T_i{}^4\right) \tag{8}$$

Where;

h_s= convection heat transfer coefficient between soil and inside air, W/m^2.
T_s= soil surface temperature,°C.
T_i= inside air temperature,°C.

Thus,

$$Heat\ gain = q_{sg} + q_g \tag{9}$$

Therefore, the total heat load of the greenhouse will be:

$$Heat\ load = \left[\,U\,r\ + \rho\,c_p\,N\,\frac{H}{3600}\right]\,(T_i - T_a) - \left[\,\tau\,I_h + h_s(T_s - T_i) +\ \epsilon_s\,\sigma\,\left(T_s{}^4 - T_i{}^4\right)\right] \tag{10}$$

The definition of costants used in the above equations and their related values are given in Table 1.

***Table 1.** Physical and thermal properties used in the simulation.*

Description	**Value**
Air density, (ρ)	1.2 kg/m^3
Specific heat capacity, (c_p)	1010 J/kg.K
Soil heat capacity	1980000 J/m^3.K [11]
Soil surface emissivity (ϵ_s)	0.9
Soil surface absorptivity	0.8
Thickness of soil zero layer	0.5 m
Thickness of soil at b layer	0.45 m
Temperature at layer b	15 ºC
transmitance of glass cover, (τ)	0.9
Soil thermal conductivity	1.9 W/m.K [11]
No. of air chage per hour, (N)	1.25 hr^{-1} [8]
Overall heat transmission coefficient, (U)	6.246 W/m^2.ºC [8]
Average height of the greenhouse	2.5 m
cover to soil surface area, (r)	4.6642
Stefan-Boltzmann constant (σ)	5.67×10^{-8} W/m^2.K

2.2. Solar air heater

The useful energy gain of a collector (Q_u) is the difference between the absorbed solar radiation (S) and the thermal losses (U_l) (Duffie and Beckman, 2006):

$$Q_u = A_c F_R [S - U_l (T_i - T_a)] \tag{11}$$

Where (F_R) is the collector heat removal factor which is defined as the ratio of the actual useful energy collected to the useful energy collected if the entire absorber surface was at the temperature of the fluid entering the collector. It can be calculated as (Duffie and Beckman, 2006):

$$F_R = \frac{G\ c_p}{U_l} \left[1 - exp \left(\frac{-F' U_l}{G\ c_p} \right) \right] \tag{12}$$

Where;

G= is the air mass flux, kg.s^{-1}.m^{-2}.

F'= is the collector efficiency factor.

The collector efficiency (η) 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 is a measure of collector performance, it was calculated as (Duffie and Beckman, 2006):

$$\eta = \frac{Q_u}{A_c\ I_t} \tag{13}$$

Where;

A_c= is the collector area, m^2.

I_t= total incedent radiation, W/m^2.

3. The Simulation study

The MATLAB program and its language are used in this work for computer programming. The computation is composed of a main program and a number of subprograms which are coupled with each other and with the main program by FUNCTION commands.

Two simulation programs have been developed. The first is used to calculate the hourly heating demand (heating load) of the greenhouse based on the input data of the indoor microclimate (indoor air and soil surface temperatures), outdoor weather data (ambient temperature, relative humidity, and wind speed, and incident solar radiation), and the physical and thermal properties of the greenhouse construction materials (Table 1). The calculation involves an estimate of the maximum heat losses of the greenhouse, which are mainly transmission and infiltration losses. In addition, both solar and soil heat gains are considered. In the second simulation, the performance of the solar system used to heat the greenhouse is simulated. In this simulation, the global solar radiation on a south facing solar air heater, the hourly values of solar radiation absorbed by the collector, the useful energy, the air outlet temperatures, and the efficiency of the collector are determined. The design parameters of the collector used in the simulation are given in Table 2.

Table 2. *Design parameter of the simulated air heater.*

Description	Value
Absorber plate area, (A_c)	2.7 m^2
Length of collector	2.8 m
Width of collector	1.2 m
Thickness of collector	0.25 m
No. of triangular air ducts	13
Length of corrugation sides	0.075
Angle of corrugation	60^o
Mean absorber-cover spacing	0.07 m
No. of glass cover	1
Glass cover thickness	0.004 m
Glass cover emissivity	0.88
Glass extinction coefficient	20 m^{-1}
Glass index of refraction	1.526
Absorber plate emissivity	0.95
Rear plate emissivity	0.9
Thickness of black insulation	0.13 m
Thickness of side insulation	0.055 m
Wooden frame plate thickness	0.02 m
Glass thermal conductivity	1 W/m.K
Insulation thermal conductivity	0.038 W/m.K
Wooden frame thermal conductivity	0.059 W/m.K

4. Results and discussions

4.1. Greenhouse heating load

The greenhouse in the present work is considered as a solar collector with the soil as an absorber plate. Therefore, the solar radiation was taken as incident on a horizontal surface and not on the gable area. The hourly variation of total incident solar radiation for the horizontal surface on typical winter days is shown in Fig. 2. The peak value occurs at midday. It is about 575, 619, and 632 W.m-2 for December, January and November, respectively.

Fig. 3 shows the variation of ambient temperature that is taken from a meteorological web site (wunderground.com) for the same typical winter days of Fig. 2. These days represent the recommended average days for months (Duffie and Beckman, 2006).

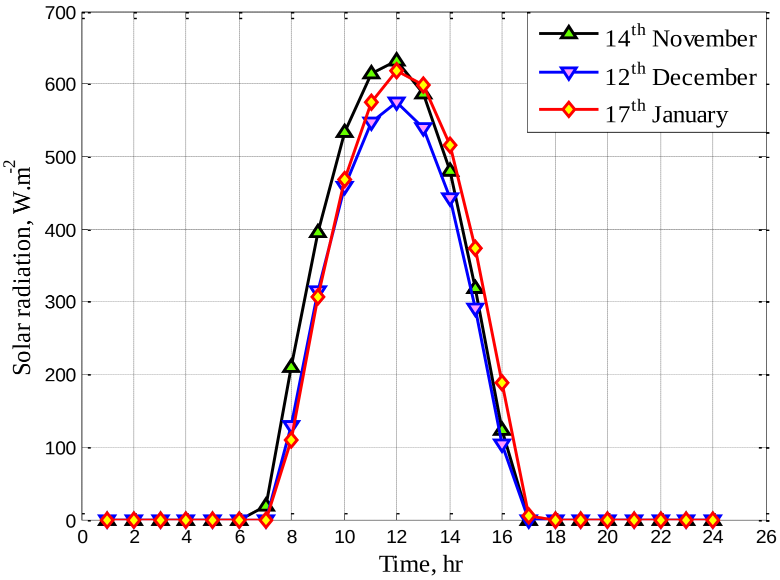

Figure 2. *Hourly distribution of global solar radiation for typical winter days.*

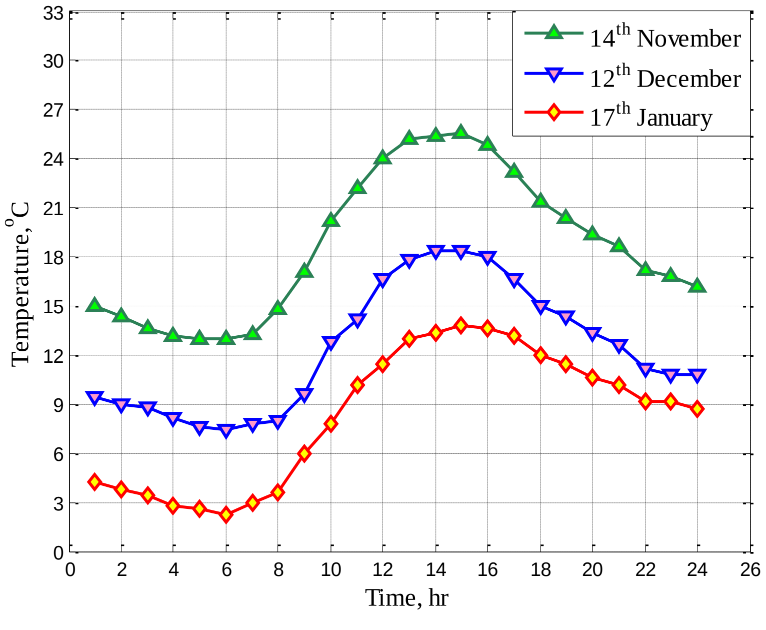

Figure 3. *Typical hourly variation of ambient temperature (wunderground.com).*

The total heating load estimated for typical winter days is shown in Fig.4. The maximum heating load occurs at 6 a.m. at a value of about 198, 353, and 499 W.m^{-2} in November, December, and January. It can be seen that the intersection of the load curves with the zero load line indicates the starting and ending times of the heating and cooling requirements. If the inside air temperature is less than the design 20°C, a certain quantity of heat should be supplied. Else, ventilation or evaporative cooling is required.

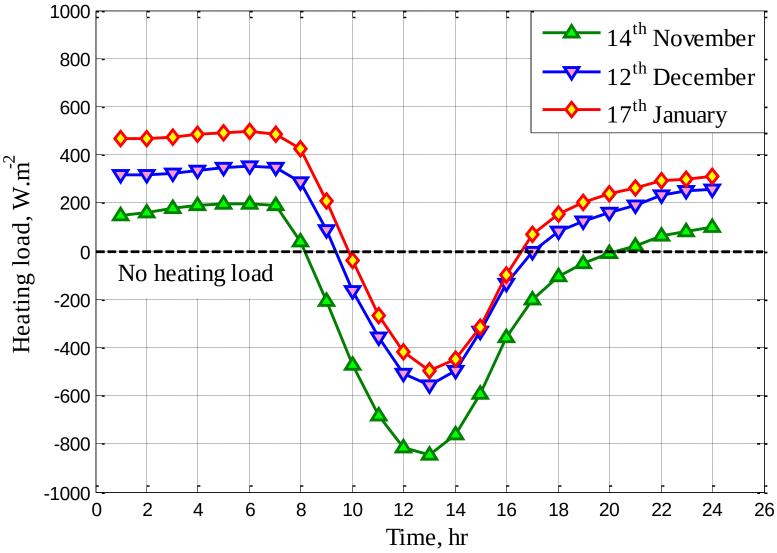

Figure 4. *Hourly variation of heating load of the greenhouse for typical winter days.*

A comparison between the present heat load calculation method and the standard method presented by Refs. (ASHRAE, 1997; Aldrich and Bartok, 1994; Mastalerz, 1977) which discard the soil heat gain is shown in Fig. 5.

The heating load obtained by standard method is higher than the value obtained by the present method. It was found that adding the soil heat gain to the standard method results in an agreement with the present heat load estimation procedure as shown in Fig. 6.

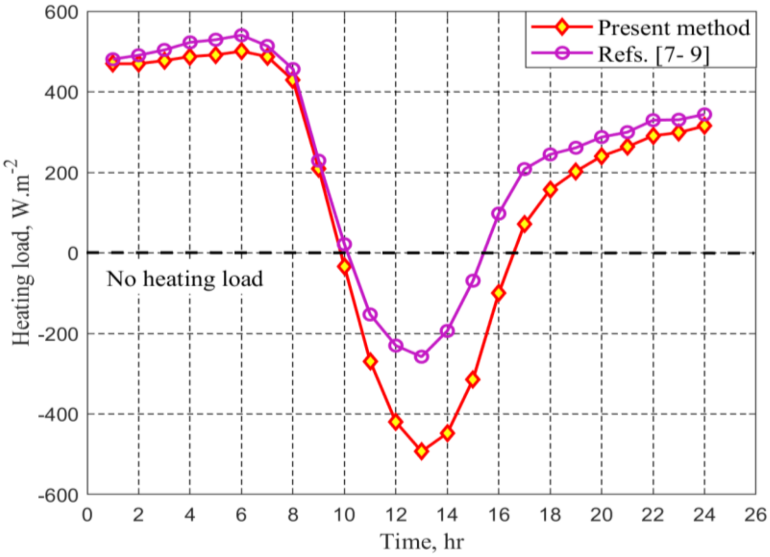

Figure 5. *The heating load estimated by the present and Refs. (ASHRAE, 1997; Aldrich and Bartok, 1994; Mastalerz, 1977) methods.*

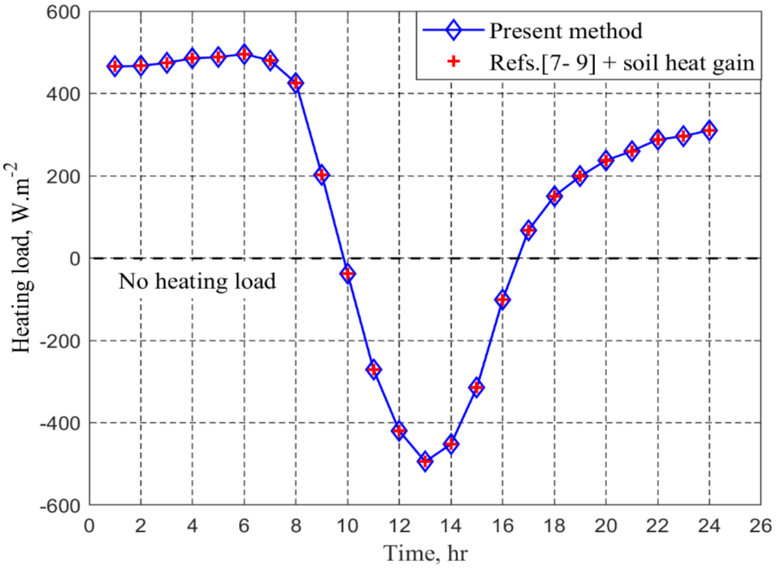

Figure 6. *The heating load estimated by the present and Refs. (ASHRAE, 1997; Aldrich and Bartok, 1994; Mastalerz, 1977) methods, but adding the soil heat gain.*

4.2. Solar air heater performance

The solar air heater simulated in the present work was used for heating the inlet air to the required temperature for the heating purpose in winter. It is a single glass cover, single pass heater with a V-corrugated absorber plate with a V-opening angle of 60° and the air flowing through the triangular passages formed by the corrugated absorber and the rear flat plate. To achieve the required air outlet temperature and air flow rate, two collector arrays were connected in parallel, each with two collectors connected in series.

The variation of air outlet temperature for two collectors in series for different air mass fluxes is shown in Fig. 7. It is obvious that when the air flow rate increases, the air outlet temperature from the two collectors in series decreases, whereas the instantaneous collection efficiency increases due to a higher heat removal factor which is associated with higher air flow rate as shown in Fig. 8.

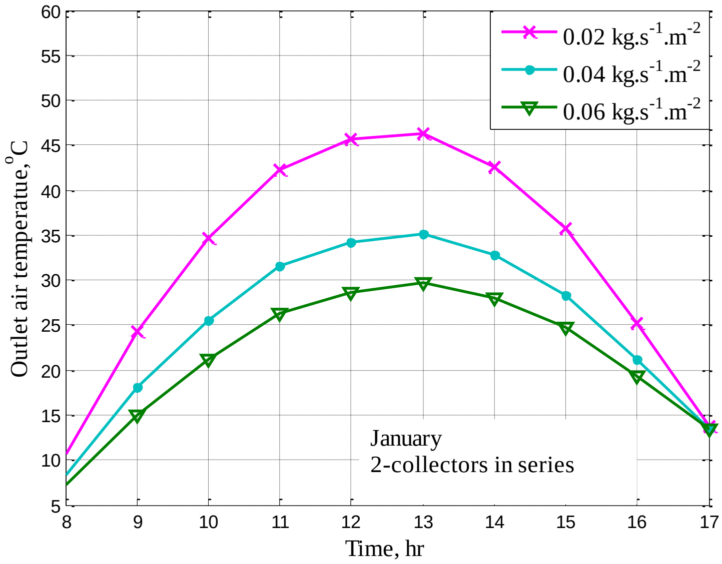

Figure 7. *Variation of air outlet temperature for various air mass flux.*

The useful energy gained from the collectors array for January 17 is shown in Fig. 9. As noted, the useful energy gained from the 2nd collector is less than that from the 1st collector because the heat losses from the 2nd collector are higher than that from the 1st collector due to the higher thermal losses which is attributed the higher inlet air temperature. The peak value of the energy gained from the collectors array is 473 W.m^{-2} of the collector area. It occurs at noon which is associated with the peak value of incident solar radiation.

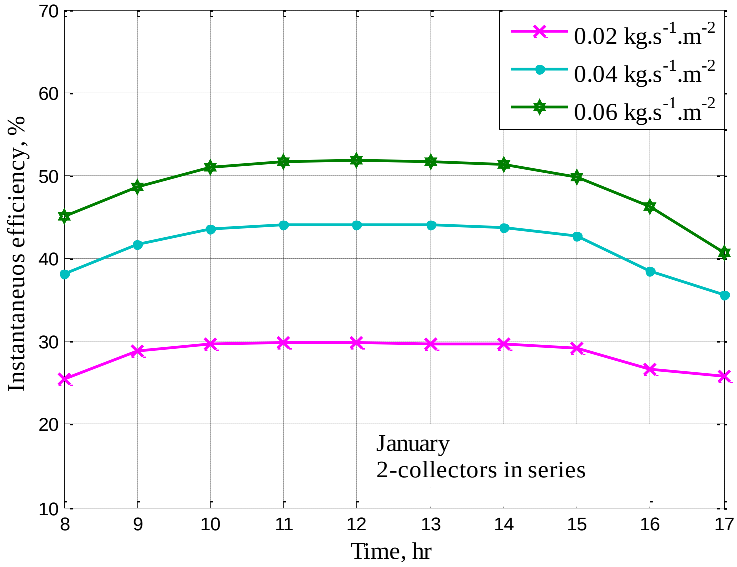

Figure 8. *Variation of collectors array efficiency for various air mass flux.*

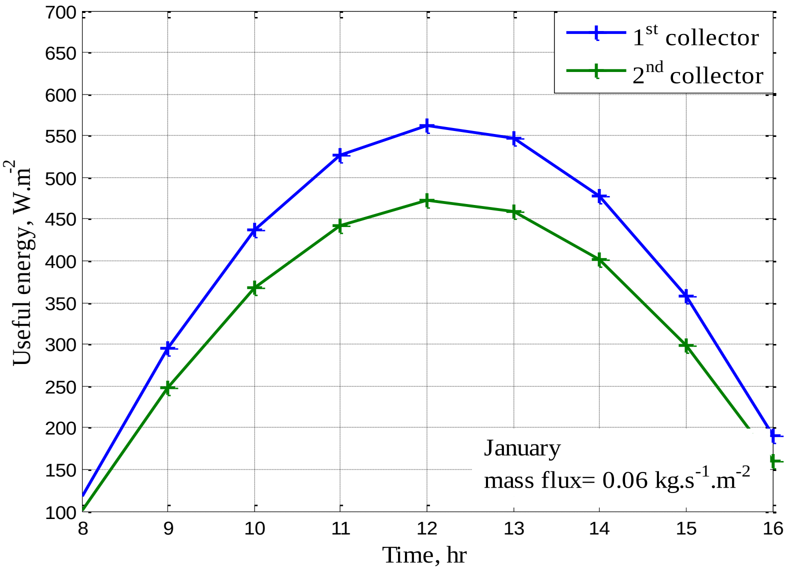

Figure 9. *Variation of useful energy gained for two collectors in series.*

Fig. 10 shows the variation of air outlet temperature for two collectors in series for the air mass flux of 0.06 kg.s^{-1}.m^{-2} of the collector area. The maximum air outlet temperature from this collector array is about 30°C for January, which is suitable for the supply air temperature in the winter season.

The variation of collection efficiency of the two collectors in series and for the same air mass flux of on January 17 is shown in Fig. 11.

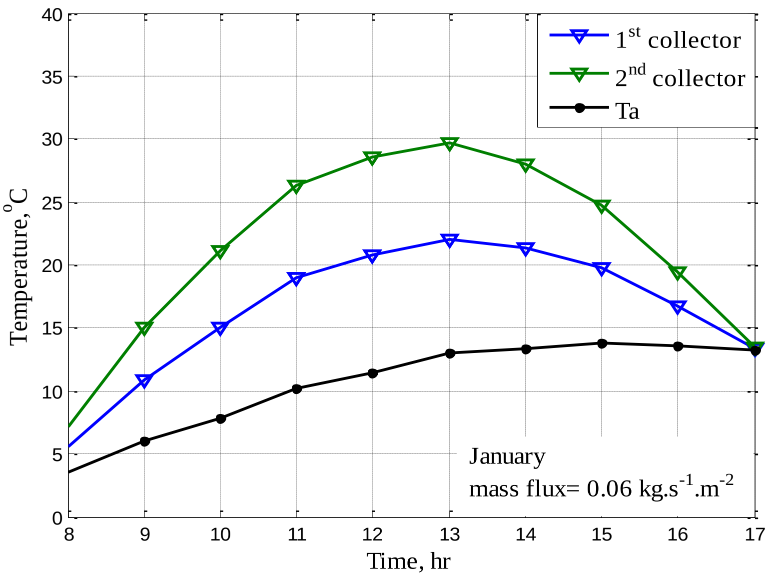

Figure 10. *Variation of* air *outlet temperature for two collectors in series.*

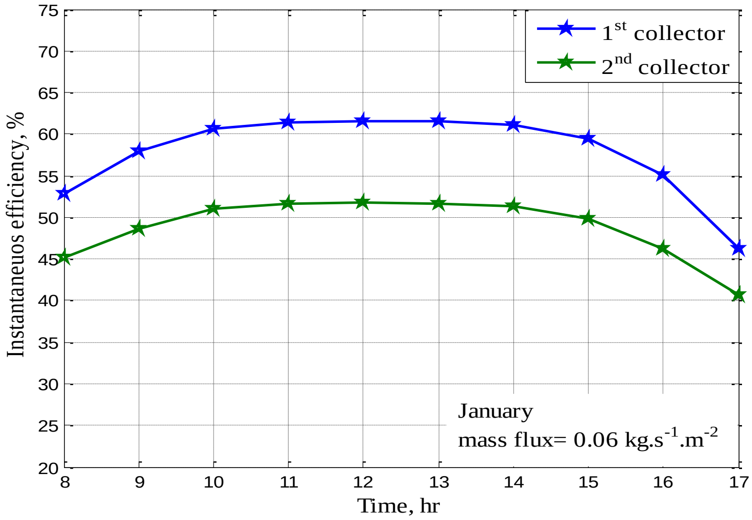

Figure 11. *Variation of efficiency for two collectors in series.*

The efficiency of the second collector is lower than that of the first collector due to the higher heat losses of the second collector compared to the first collector which is associated with the increase in the operating temperature of the collector which leads to an increase in heat losses from the collector to the environment thereby decreasing the collection efficiency. Also, the variation of the collection efficiency values between 10 a.m. and 2 p.m. is very small. This is mainly due to the combined effect of the absorbed solar radiation and the heat losses from the collector during the day.

In order to validate the results obtained in the present simulation of the solar air heater, the simulation results were compared with the results obtained by Refs. (Moneer, 1997; Joudi and Mohammed, 1986). as shown in Figs. 12 & 13.

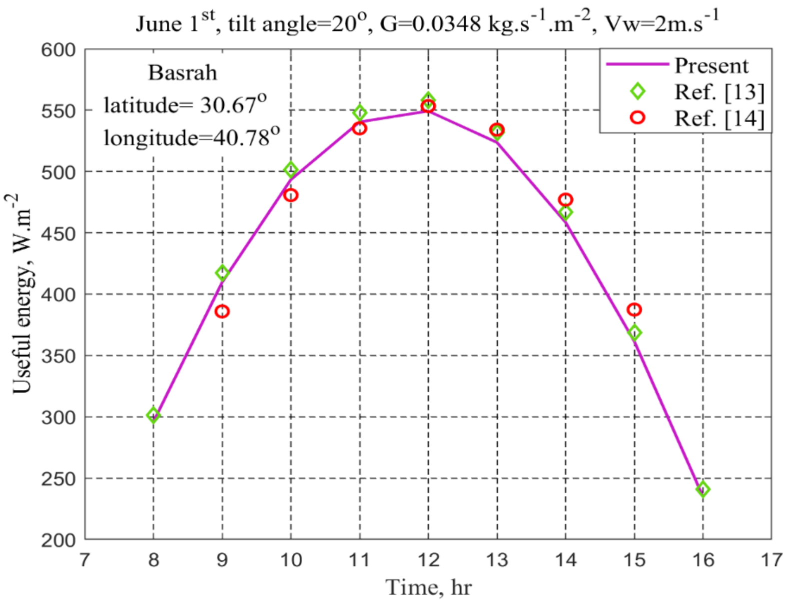

Figure 12. *Comparison between the present simulation results and the results obtained by Refs. (Moneer, 1997; Joudi and Mohammed, 1986) for useful energy gained.*

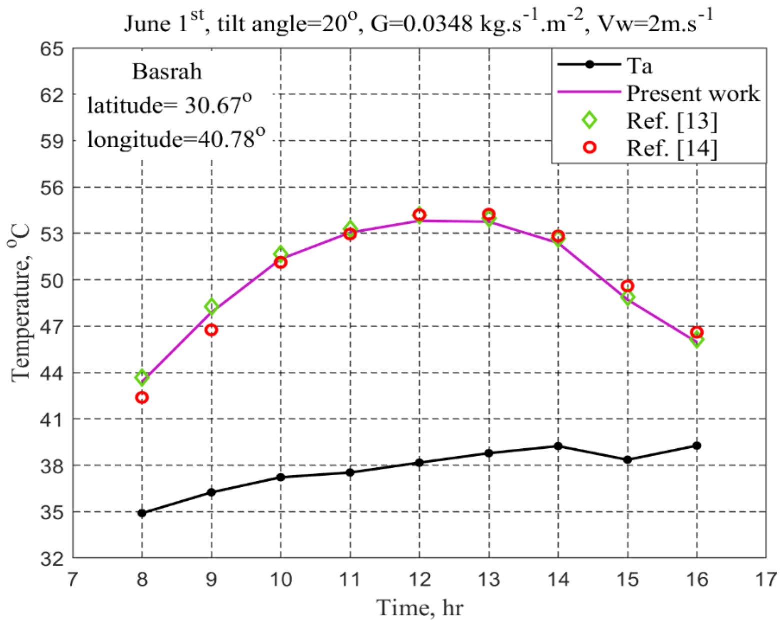

Figure 13. *Comparison between the present simulation results and the results obtained by Refs. (Moneer, 1997; Joudi and Mohammed, 1986) for* air *outlet temperature.*

The agreement with the experimental results is within a maximum diviation of about 5.7% for the useful energy and 2.3% for the air outlet temperature. These comparisons prove that the predictions of the computer model are quite reliable.

4.3. Greenhouse with rock- bed storage

The rock-bed is a popular and economical heat storage material, sensible heat storage placed underground have the advantage of providing a large and cheap heat transfer surface (Gourdo et al., 2019). In this study, two important types of excess heat that can be stored in an efficient storage system are considered. First, the excess free solar heat gain inside the greenhouse during the day when the greenhouse temperature exceeds 20ºC. Second, the useful solar energy collected by the solar air heater that can be used directly to heat the greenhouse or stored in a suitable storage system to be used during times when heat is needed (i.e., at night and during cloudy weather). The heat demand which maintains the greenhouse at the desired temperature can be calculated as:

$$Heat\ demand\ =\ Heat\ load\ -\ Q_u \tag{14}$$

The result for the hourly heat demand on a typical winter clear sky day in January is shown in Table 3. Negative values of the heat demand indicate an excess heat inside the greenhouse that should be extracted from it by ventilation or even cooling.

Table 3. *Heat demand and excess heat sources for the greenhouse.*

Time, (hr)	**Heat load,** (W/m^2)	**Useful solar gain from the collector,** (W/m^2)	**Heat demand,** (W/m^2)	**Excess solar heat gain to be stored,** (W/m^2)	
				from collector	**generated inside greenhouse**
1	477.32	0	477.32	0	0
2	477.32	0	477.32	0	0
3	481.64	0	481.64	0	0
4	494.6	0	494.6	0	0
5	503.24	0	503.24	0	0
6	511.88	0	511.88	0	0
7	490.28	0	490.28	0	0
8	434.13	6.02	428.11	0	0
9	218.14	172.93	45.21	0	0
10	-32.4	314.25	-	314.25	32.4
11	-257.02	400.62	-	400.62	257.02
12	-412.53	434.3	-	434.3	412.53
13	-490.28	419.06	-	419.06	490.28
14	-438.44	351.88	-	351.88	438.44
15	-308.86	232.77	-	232.77	308.86
16	-92.87	70.75	-	70.75	92.87
17	75.59	0	75.59	0	0
18	166.31	0	166.31	0	0
19	209.5	0	209.5	0	0
20	248.38	0	248.38	0	0
21	274.3	0	274.3	0	0
22	308.86	0	308.86	0	0
23	313.17	0	313.17	0	0
24	317.49	0	317.49	0	0
Total			**5823.2**	**2223.63**	**2032.4**

A rock- bed storage system adopted by Ref. (Kürklü et al., 2003) with a recovery efficiency of 80% was assumed to be used in this study. The storage system includes two rock-bed canals excavated in the subsoil of the greenhouse each canal has 3×1.25×0.75 m. The supplied heat to the greenhouse would be;

$$Heat\ supply = Heat\ stored \times 0.8 \quad (15)$$

The total excess heat gained from the collector and generated inside the greenhouse are 2223.63 W/m^2 and 2032.4 W/m^2, respectively. Therefore, the supplied heat related to these two sources are 1778.9 W/m^{2}and 1625.92 W/m^2, respectively. The stored energy which keeps the greenhouse inside air temperature at 20°C during nighttime can be calculated as:

$$Stored\ energy = \frac{Heat\ supply}{Total\ heat\ demand} \quad (16)$$

Therefore, the solar air collector with a mass flux of 0.06 kg.s^{-1}.m^{-2} can cover about 30.5% of the total heat demand whereas, the excess heat inside the greenhouse can cover about 28%. This means that both of the total stored solar energy gained from the collector together with that generated inside the greenhouse can cover about 58.5% of the total heat demand. The remaining (41.5%) can be provided by using an auxiliary heating systems.

5. Summary

The following conclusions can be deduced from the results obtained:

1- The energy balance method used in the present work to estimate the greenhouse heating load is more accurate than the method followed by several authors cited in the literature, since the heat gain of the soil is included.

2- Solar and soil heat gains are the main heat gain components to the interior of the greenhouse that reduce the total heat load.

3- Two rows of collectors give an air temperature of 30°C at noon in January with a mass flux of 0.06 kg.s^{-1}.m^{-2} of collector area.

4- A rock- bed thermal storage system can be used to store the excess heat during the day and recover it at night.

5- The combination of the free solar gain inside the greenhouse and the useful energy from the collectors covers 58.5% of the heating demand of the greenhouse in January.

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