Investigation of Thermal Performance of a Solar Pond With External Heat Addition

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This study addresses the method of adding heat to a salt gradient solar pond (SGSP) from external sources and investigates the thermal performance of the pond. In this case, the external heat source is solar heat collected by evacuated tube solar collectors (ETSC), and collected heat is transferred to the lower-convective zone (LCZ) of the SGSP by circulating fluid from the LCZ. Results show that heat addition from the external source enhances the thermal performance of the SGSP in terms of heat recovery and thermal efficiency but with certain constraints. The heat addition efficiency reduces with increase in aperture area of the ETSC. Also with increasing heat addition, the heat removal from the SGSP has to be increased; otherwise, the SGSP efficiency reduces rapidly. Heat removal from SGSP has to be performed keeping in mind the heat demand and the quality of heat. The latter reduces with an increase of heat extraction beyond a certain limit. Hence, optimizing the range of parameters in case of adding heat from external sources is very important for the best performance of a SGSP. [DOI: 10.1115/1.4038788]

1 Introduction

Salt gradient solar ponds (SGSPs) consist of a large but shallow body of saline water with a salinity gradient, built with a purpose to capture and store solar thermal energy. The solar insolation that penetrates through the surface of the pond is absorbed by different layers of the pond and is converted to heat. The natural convection in the pond due to temperature variation is suppressed by the existing salinity gradient in the nonconvective zone (NCZ), and solar thermal energy which reaches the bottom or lower-convective zone (LCZ) is stored for a long time.

The main reason which hinders the use of SGSP in the industry is the limited efficiency of them as solar collectors. This is evident as only a fraction of the solar insolation reaches the bottom of SGSP due to rapid attenuation as it passes through water. Researchers in the past have investigated ways to improve the efficiency of SGSP. Methods proposed by them include increasing the thickness of the LCZ and reducing the upper-convective zone (UCZ) thickness [1], introducing an additional upper NCZ [2], improving water clarity [3], using a solar reflector to reflect additional solar energy to the pond [4], recovering the thermal energy from the ground underneath SGSPs [5], etc. The main advantage of SGSP is the capacity of long-term storage of thermal energy. Evacuated tube solar collector (ETSC) as collectors of solar thermal energy have much higher efficiency than SGSP, but they need a separate heat storage device. Nonpressurized insulated tanks can store hot water at about 90 °C for a very limited period of time with a drop of about 8 °C of temperature within 2 days [6,7], whereas a SGSP can store heat for weeks without significant drop in temperature [7].

The present note investigates the transient thermal performance of a hybrid system of SGSP coupled with ETSC. The solar thermal energy collected by ETSC is transferred to the LCZ of SGSP by circulating fluid through them. Heat is extracted from the LCZ by passing fluid through the in-pond heat exchangers. Thus, the best way to control the heat extraction is to control the heat extraction fluid flux (HEFF) through the heat exchangers in LCZ.

2 Heat Addition From External Source

The mathematical model for the SGSP without any external heat addition is based on the energy balance equation given by [8]

$$\Delta E_n^{\tau+\Delta\tau} = h_n^\tau \times \Delta\tau + q_{n-1}^\tau \times \Delta\tau + q_{n+1}^\tau \times \Delta\tau - q_e^\tau \times \Delta\tau \quad (1)$$

where $\Delta E_n^{\tau+\Delta\tau}$ represents the change in the energy content of nth layer (i.e., layer under investigation) in solar pond after time $\Delta\tau$, h_n^τ represents the solar radiation energy absorbed by nth layer in solar pond at time τ, q_{n-1}^τ represents the conductive heat transfer to or from the division above the nth layer in solar pond at time τ, q_{n+1}^τ represents the conductive heat transfer to or from the division below the nth layer in solar pond at time τ, and q_e^τ represents the heat extracted from the LCZ at time τ.

Here, the total energy (q_a) added to the LCZ of the solar pond from ETSC is calculated using the following equation:

$$q_a = \frac{\eta_{\rm et}}{100} \times R \times H_{\rm et} \quad (2)$$

where $\eta_{\rm et}$ is the efficiency of the ETSC, R is the ratio of the aperture area of ETSC to the SGSP floor area, and $H_{\rm et}$ is the incident solar radiation on the ETSC. According to Ref. [9], $\eta_{\rm et}$ is a function of incident solar radiation and the difference between LCZ temperature and ambient temperature, given by

$$\eta_{\rm et} = \left\{0.536 - 0.8240\frac{(T_{\rm lcz} - T_{\rm atm})}{H_{\rm et}} - 0.0069\frac{(T_{\rm lcz} - T_{\rm atm})^2}{H_{\rm et}}\right\} \times 100 \quad (3)$$

where $T_{\rm lcz}$ is the instantaneous LCZ temperature and $T_{\rm atm}$ is the atmospheric temperature. The heat added to the SGSP is also proportional to the ratio (R)

$$R = \frac{A_{\rm et}}{A_{\rm sp}} \quad (4)$$

where $A_{\rm et}$ is the aperture area of the ETSC and $A_{\rm sp}$ is the SGSP floor area. With the heat addition, the new energy balance equation for SGSP becomes

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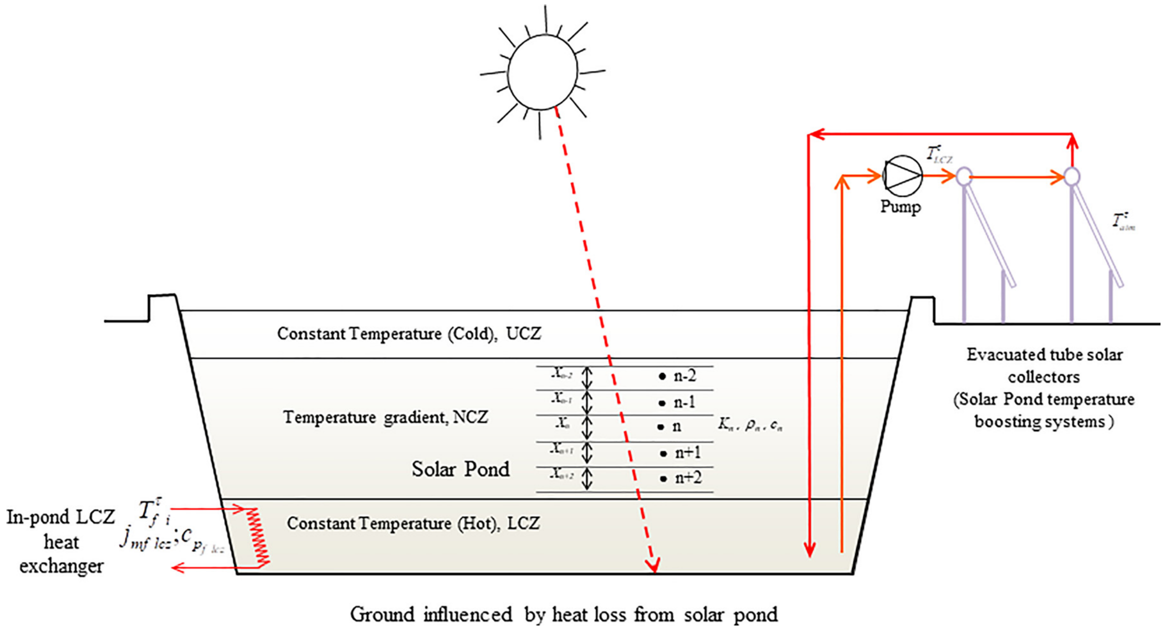

Fig. 1 Schematic diagram of the hybrid system of salinity gradient solar pond coupled with ETSCs

$$\Delta E_n^{\tau+\Delta\tau} = h_n^\tau \times \Delta\tau + q_{n-1}^\tau \times \Delta\tau + q_{n+1}^\tau \times \Delta\tau - q_e^\tau \times \Delta\tau + q_a^\tau \times \Delta\tau \quad (5)$$

The present SGSP coupled with ETSC is located at Melbourne, Australia, and is schematically shown in Fig. 1. The depth of the SGSP is 3 m in which the thicknesses of the UCZ, NCZ, and LCZ are equal to 0.3 m, 1.2 m, and 1.5 m, respectively. The operation of the SGSP in Melbourne starts on 1st October, which is early spring in the southern hemisphere and heat removal starts 60 days after that [8,10]. The different zones and boundaries of SGSP considered for numerical modeling are shown here schematically in Fig. 2. The statistical data of monthly average values of temperature and solar radiation on a horizontal surface in Melbourne are adequately approximated here using sinusoidal functions [8] and is shown in Fig. 3. To study the thermal performance of the hybrid system of SGSP coupled with ETSC, the finite difference numerical model similar to that discussed by Date et al. [8] has further been developed with heat addition component. In this study, the heat transfer here is treated as one-dimensional unsteady conduction, with heat generation from incoming solar radiation as done by many researchers [1,4,5,8]. Solar radiation that is incident on the SGSP is absorbed by different layers and is converted to heat. A part of the absorbed heat is lost to the atmosphere and the ground and the rest is available for recovery. The heat loss from the sides of the solar pond here is considered to be negligible compared to the heat loss from top and the bottom, as the solar pond surface area is assumed to be large enough compared to the side walls. The initial temperature of the heat extraction fluid is assumed to be equal to the daily average ambient temperature of Melbourne which again is assumed to be equal to the UCZ temperature. The ground temperature at 5 m below the SGSP bottom is assumed equal to the yearly average ambient temperature of the location [1] which is treated as a boundary condition. For numerical modeling, the LCZ and UCZ are assumed to be single layers with uniform temperature. The NCZ and the ground up to a thickness of 5 m below SGSP are divided in 8 and 20 sublayers,

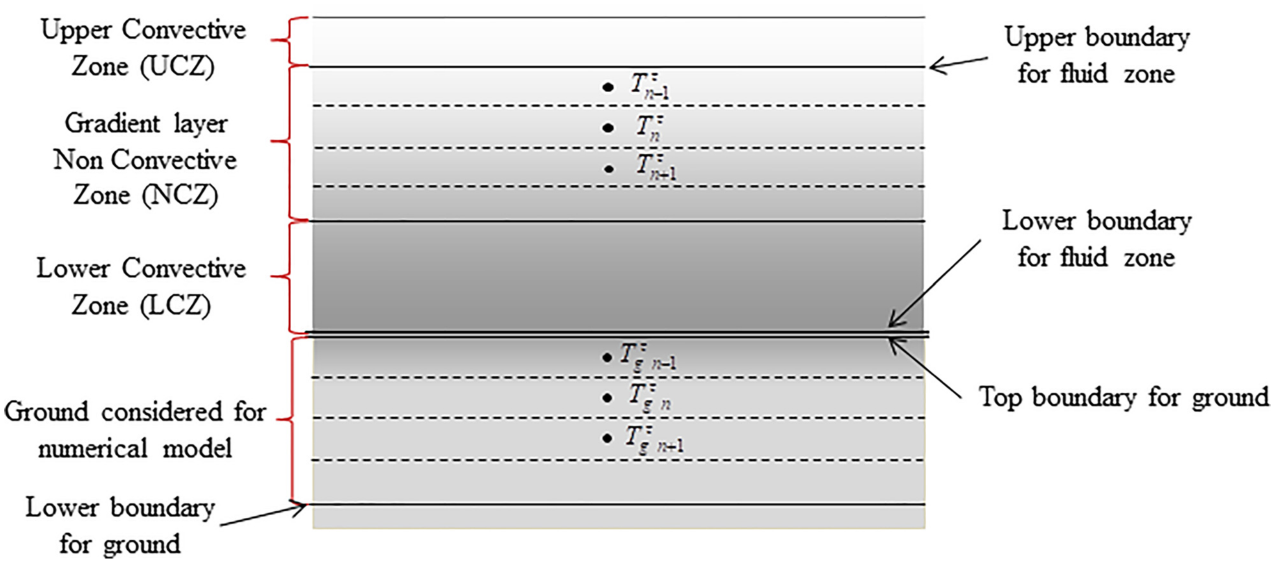

Fig. 2 Schematic diagram showing the different zones and boundaries of SGSP with the numerical grid

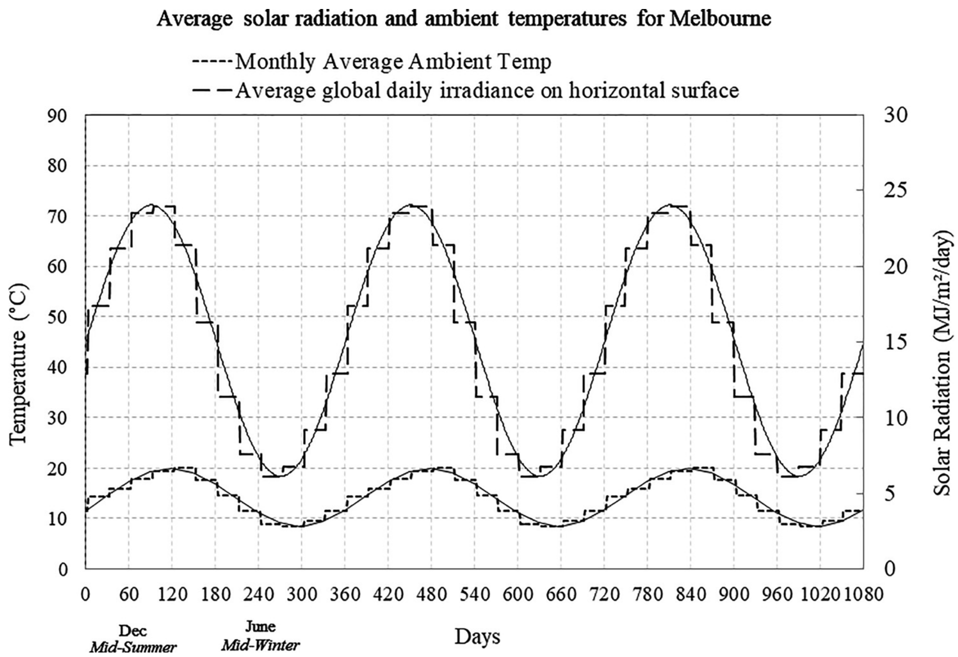

Fig. 3 Monthly average of daily solar radiation on a horizontal surface and monthly average temperature in Melbourne

respectively. The temperatures are estimated at the center of each sublayer by the finite difference model.

3 Results and Discussion

The temperature development of the SGSP over 3 years is shown in Fig. 4 for four different values of R and three different HEFF from the LCZ. Note here that increase in R value implies increase of the ETSC aperture area which in turn indicates the increase in amount of heat added to the SGSP. Increase of HEFF on the other hand means increase in heat recovery from the LCZ.

A recent paper [10] mentions that the heat addition to the SGSP from ETSC should be performed carefully because when the HEFF is kept low for low heat demand, during the end of winter the temperature of fluid from ETSC falls below the instantaneous LCZ temperature and that instead of adding heat, results in loss of heat from LCZ to the heat transfer fluid from ETSC. Hence, the minimum HEFF value here is fixed to a slightly high value of 0.0002 kg/m^2/s. Also, for any meaningful use of the SGSP heat, the difference ($\Delta T_{\min}$) between the extracted fluid temperature and ambient temperature should be a minimum of 20 °C [8,10] and fixing the HEFF is vital keeping this in mind. Figure 4 indicates that when the HEFF is >0.00025 kg/m^2/s during end of the winter, $\Delta T_{\min}$ falls below this limit and hence the limiting value of HEFF in this case should be kept to 0.00025 kg/m^2/s.

From Fig. 4 it is evident that the addition of heat from external sources has increased the SGSP temperature over the years. The yearly average LCZ temperature when no heat is added from outside ($R=0$) and at the limiting HEFF of 0.00025 kg/m^2/s is 44 °C whereas the same for $R=0.5$ is 59 °C. Also, the addition of heat facilitates increased heat removal from LCZ by increasing HEFF, as it can be seen from Fig. 4(*c*) that for $R=0.1$ and HEFF = 0.0003 kg/m^2/s, $\Delta T_{\min} > 20^0$C at the end of winter whereas $\Delta T_{\min}$ falls below 20 °C for $R=0$. From the analysis related to Fig. 5 (shown later), it can be seen that when no heat is added ($R=0$) the amount of heat extracted at HEFF of 0.00025 kg/m^2/s (which is the limiting HEFF for $R=0$) is 1059.6 MJ/m^2/year at annual SGSP efficiency ($\eta_{\text{sp an}}$) of 15.6% whereas with heat addition from outside with $R=0.1$ at an HEFF of 0.00030 kg/m^2/s which is the limiting HEFF for $R=0.1$), 1277.2 MJ/m^2/year amount of heat can be extracted at a rate of 40.5 W/m^2 from LCZ at an $\eta_{\text{sp an}}$ of 19.8%. Hence, when heat is added from outside keeping the ETSC area only 10% of the SGSP surface area, 21% [(1277.2 − 1059.6)/1059.6 × 100] more heat can be extracted from the SGSP with 27% [(19.8 − 15.6)/15.6 × 100] higher efficiency.

Figure 6 represents the efficiency of the ETSC (η_{et}) coupled with SGSP given by Eq. (3), for different R values, and different HEFF, over 3 years. The figure shows that η_{et} reaches its highest during mid-summer and lowest during mid-winter, due to the obvious reason of maximum and minimum values of H_{et} during these times, respectively. Note that strangely η_{et} value decreases on increasing ETSC aperture area. The annual efficiency of ETSC ($\eta_{\text{et an}}$) for an HEFF of 0.00025 kg/m^2/s reduces from 34% to 26% on increasing R value from 0.1 to 0.5, which implies a decrease of 24%. This reduction of efficiency is attributed to the increase in heat loss from the ETSC with increasing aperture area. Also note that η_{et} increases for the same R value with increasing HEFF. The $\eta_{\text{et an}}$ for $R=0.5$ increases from 22% to 26% on increasing HEFF from 0.00020 kg/m^2/s to 0.00025 kg/m^2/s. The reason behind this is the slight decrease in the LCZ temperature due to increase of HEFF. From the definition of η_{et} in Eq. (3), it is evident that a decrease of LCZ temperature will result in an increase in η_{et}. The heat addition from ETSC to the SGSP on the other hand increases on increasing R value. The heat addition from ETSC to the LCZ is also plotted in Fig. 6 which shows that an increase of R value from 0.1 to 0.5 at a HEFF of 0.00025 kg/m^2/s results in an increase of heat addition from 185 MJ/m^2/year to 213 MJ/m^2/year, which is an increase of only 15%. This analysis proves that the increase in the aperture area of ETSC, although it enhances the heat addition to SGSP, also lead to the efficiency reduction of ETSC, which limits the heat addition in turn. Hence, the number of ETSC or the aperture area of the ETSC tubes has to be fixed carefully taking in account the efficiency of the ETSC. Increase in the number of tubes significantly may result in very small or practically no significant increase in heat addition, which is economically not profitable.

The heat extraction from the LCZ of the SGSP and the efficiency of the SGSP (as defined in Ref. [8]) over 3 years is shown in Fig. 5 for two sets of R values and HEFF. Just as expected, the heat extraction from SGSP increases with the R value and HEFF. As more heat is added to the SGSP with increasing number of

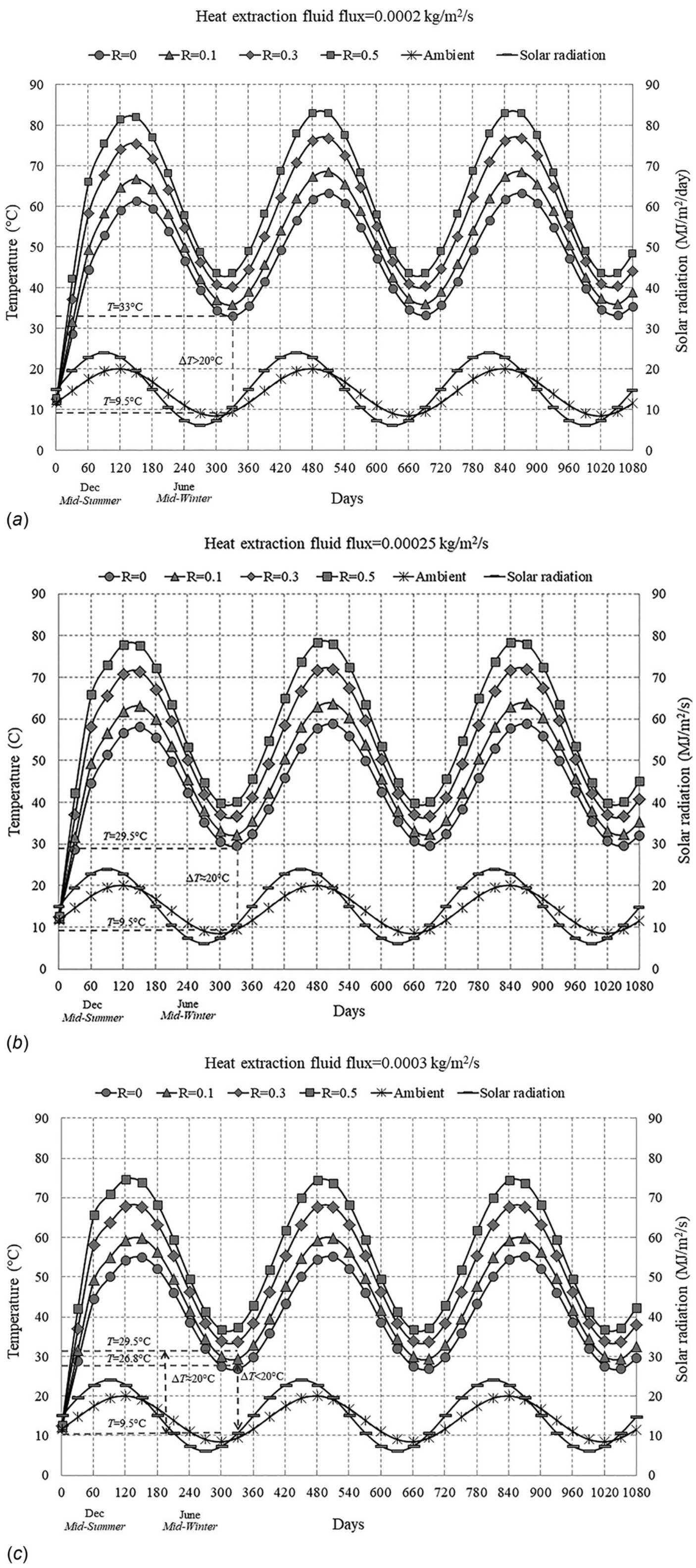

Fig. 4 Temperature development of the solar pond in Melbourne for different R values and for HEFF equal to (*a*) 0.0002 kg/m^2/s, (*b*) 0.00025 kg/m^2/s, and (*c*) 0.0003 kg/m^2/s

ETSC, the heat reserve in the SGSP increases, which facilitates higher amount of heat removal. The amount of heat removal can also be enhanced by increasing the HEFF through the LCZ as mentioned before. But again this has to be fixed carefully, as increasing HEFF results in decrease of LCZ temperature. For example, $R = 0.1$ if HEFF is fixed more than 0.0003 kg/m^2/s, $\Delta T_{\min}$ falls below 20 °C during the end of winter, which means extraction of higher amount of heat would cause fall of the quality of heat. For a HEFF of 0.00025 kg/m^2/s when $R = 0.1$, the average heat removal from SGSP is 37.5 W/m^2, which amounts to an annual heat removal of 1182.6 MJ/m^2/year. The average heat removal and annual total heat removal for $R = 0.5$ are 48.6 W/m^2

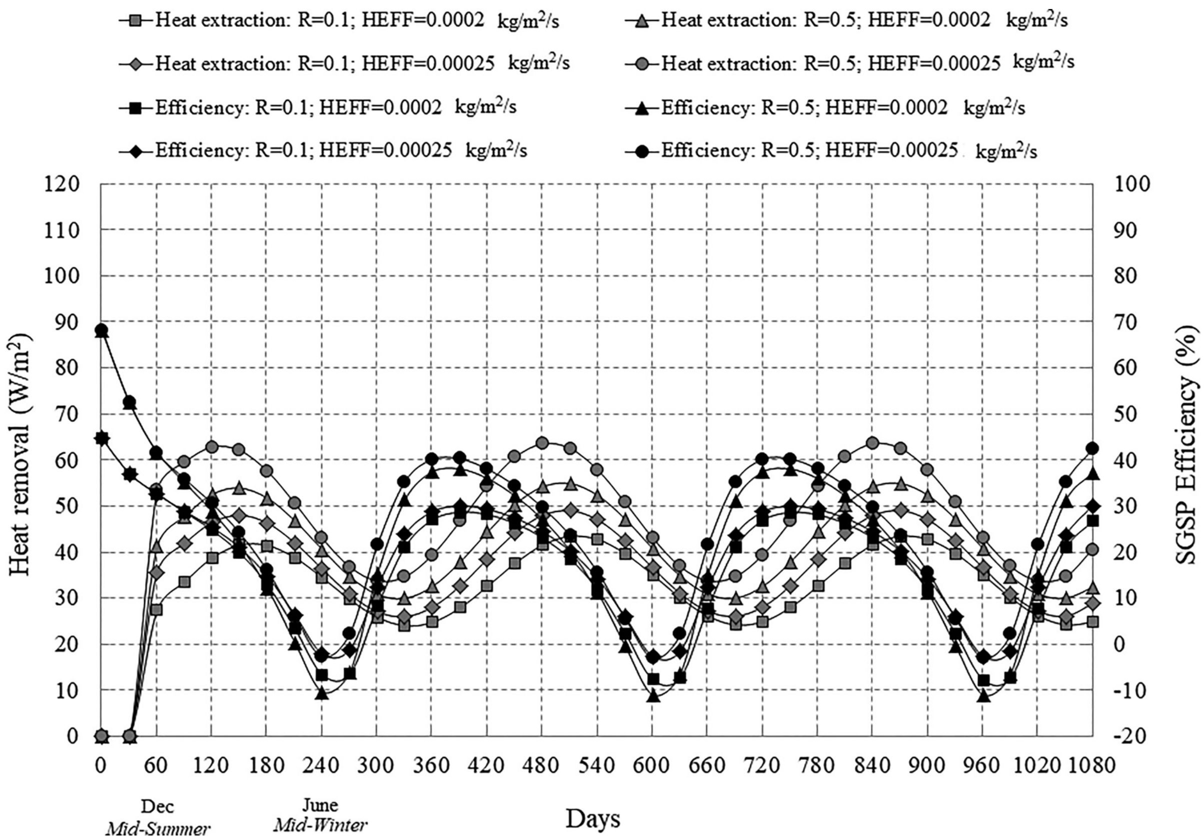

Fig. 5 Heat removal from LCZ and instantaneous efficiency of the SGSP for different *R* values and different HEFF through LCZ

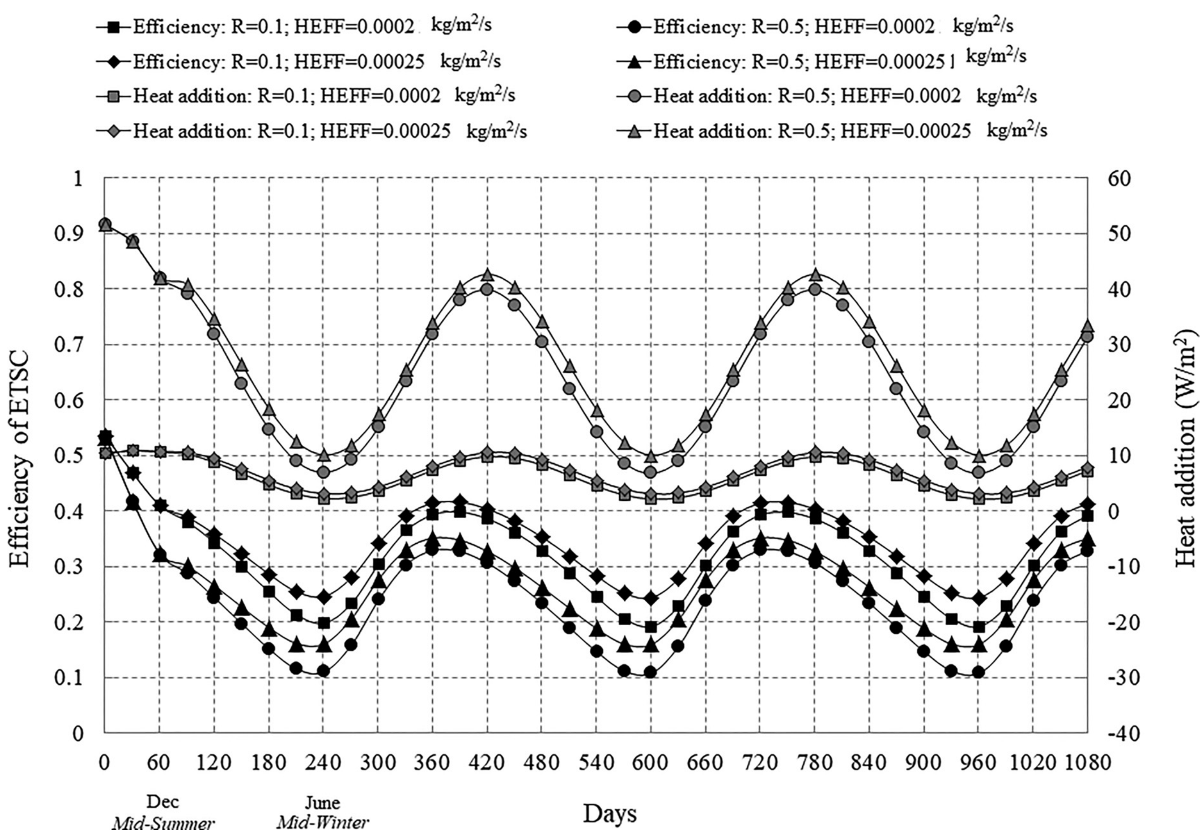

Fig. 6 The thermal efficiency of the ETSC and the heat addition from the ETSC to LCZ for different *R* values and different heat extraction from LCZ

and 1532.6 MJ/m^2/year, which implies an increase of 30% in heat recovery from $R = 0.1$. The $\eta_{sp\,an}$ for the same HEFF of 0.00025 kg/m^2/s for $R = 0.1$ and 0.5 is 17.6% and 23.5%, respectively, compared to an efficiency of 15.6% for no heat addition ($R = 0$) case, which implies an increase of 13% and 50.6%, respectively. Also note that for the same R value, or in other words the same amount of external heat addition, SGSP efficiency increases with the increase of amount of heat extracted from LCZ. For instance for $R = 0.5$, average $\eta_{sp\,an}$ equals to 19% when HEFF = 0.0002 kg/m^2/s, whereas the same equals to 23.5% when HEFF = 0.00025 kg/m^2/s, which implies heat storage efficiency of the SGSP increases by 24% by increasing the HEFF by 25%. The reason for this is the utilization of the heat with heat addition which otherwise will get stored in LCZ rising its temperature and leading to loss of heat. But again, HEFF cannot be increased without a limit to increase SGSP efficiency; $\Delta T_{min} > 20^0$C has to be maintained to maintain the quality of heat extracted.

4 Conclusions

The present note analyses the thermal performance of a SGSP coupled with an external heat source (ETSC). Addition of heat from outside is proved to enhance the heat extraction from SGSP and thermal efficiency of a SGSP but with certain constraints. The efficiency of ETSC & SGSP and HEFF are important parameters which should be analyzed and optimized prior to the start of operation of a SGSP to harvest the best performance of it. The efficiency of ETSC for instance reduces on increasing the aperture area of ETSC which limits the heat addition. So increasing the number of ETSC significantly (which increases the project expenses) will not necessary mean a considerable increase of heat addition which may turn out to be unprofitable. HEFF on the other hand is to be limited to such a value that ΔT_{min} is kept above 20 °C value. SGSP efficiency increases significantly by addition of heat, but with increasing heat addition from ETSC heat removal from SGSP has to be increased in order to maintain the SGSP efficiency, which otherwise reduces rapidly. Hence, optimizing all the parameters are needed keeping in mind all the analysis performed here to harvest the best performance of a SGSP coupled with ETSC.

The findings of the present study can be further validated by conducting some experimental analysis. This work can also be extended toward investigation of the thermal performance of a SGSP, for other locations which receive huge amount of solar radiation and need a low cost and efficient storage device to store the solar thermal energy. The hybrid system of the SGSP coupled with the ETSC provides an efficient solution to the problem of solar thermal energy capture and storage.

Nomenclature

A = area (m^2)
E = energy content (J/m^2)
h = solar radiation flux absorbed by SGSP layers (W/m^2)
H = incident solar radiation on ETSC (W/m^2)
q = conductive heat flux (W/m^2)
q_a = total energy added to the LCZ from ETSC (W/m^2)
q_e = heat flux extracted by heat transfer fluid (W/m^2)
R = ratio of aperture area of ETSC to the SGSP floor area
T = temperature (°C)

Greek Symbols

η = efficiency
τ = present time (s)
Δ = difference
$\Delta\tau$ = time increment (s)

Subscripts

a = addition
atm = atmospheric
e = extraction
et = evacuated tubes
et an = evacuated tube annual
lcz = lower convective zone
min = minimum
n = nth layer/node in solar pond and ground
sp = solar pond
sp an = solar pond annual

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