Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 2253–2263
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Prospects and scopes of solar pond: A detailed review

V. Velmurugan[a], K. Srithar[b,*]

[a]Department of Mechanical Engineering, Infant Jesus College of Engineering, Thoothukudi, Tamil Nadu 628 851, India
[b]Department of Mechanical Engineering, Thiagarajar College of Engineering, Madurai, Tamil Nadu 625 015, India

Received 2 March 2007; accepted 22 March 2007

Abstract

Solar pond is an artificially constructed pond in which significant temperature rises are caused to occur in the lower regions by preventing convection. To prevent convection, salt water is used in the pond. Those ponds are called "salt gradient solar pond". In the last 15 years, many salt gradient solar ponds varying in size from a few hundred to a few thousand square meters of surface area have been built in a number of countries. Nowadays, mini solar ponds are also being constructed for various thermal applications. In this work, various design of solar pond, prospects to improve performance, factors affecting performance, mode of heat extraction, theoretical simulation, measurement of parameters, economic analysis and its applications are reviewed.

Keywords: Solar pond; Heat extraction; Review

Contents

*Corresponding author. Tel.: +91 452 2482240; fax: +91 452 2483427.
E-mail address: ponsathya@hotmail.com (K. Srithar).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.03.011

1. Introduction

Solar ponds are used for collection and storage of solar energy. Thereby the energy can be extracted for any suitable thermal application. Working of a solar pond is very simple. Salts like magnesium chloride, sodium chloride or sodium nitrate are dissolved in the water with the concentration varying from 20% to 30% at the bottom to almost zero at the top. In order to maintain the salt gradient, fresh water is added at the top of the pond, while slightly saline water is run off, at the same time, concentrated brine is added at the bottom of the pond. Three zones, namely upper convective zone (UCZ), non-convective zone (NCZ) and lower convective zone (LCZ) are being maintained in the solar pond. Salinity in UCZ is very less and close to fresh water. In NCZ, salinity increases with the depth. As there is no natural convection in this zone, it is called as NCZ. The solar radiation transmits this zone and increases the temperature uniformly with the depth. LCZ is dense and has a uniform and high density of salt (close to saturated brine). This zone is acting as a storage zone. Maintenance of depth of the gradient zone is essential for the efficient use of solar ponds. The inner surfaces of the pond were painted with black color to increase rate of the solar radiation absorption. The pond can retain hot water till next day morning at a temperature of around 50 °C. This work reviews the different types of solar pond designed for different applications by various researchers and theoretical simulation.

2. Theoretical analysis

A salt gradient solar pond collects and stores solar energy. The stability of the solar pond is maintained by the salt. As shown in Fig. 1, both UCZ and LCZ have uniform and constant temperature and salt concentrations, whereas the temperature and the salt concentration increase with depth in the NCZ. The energy balance for the solar pond can be written as [1] follows. In steady state:

$$\begin{aligned}\text{rate of heat input} &= \text{rate of heat stored in the lower convective zone}\\ &\quad + \text{rate of heat losses to side and bottom of the pond.}\end{aligned}$$

In UCZ approximately 45% of the incoming solar radiation is absorbed and the remaining is lost by evaporation, convection and re-radiation.

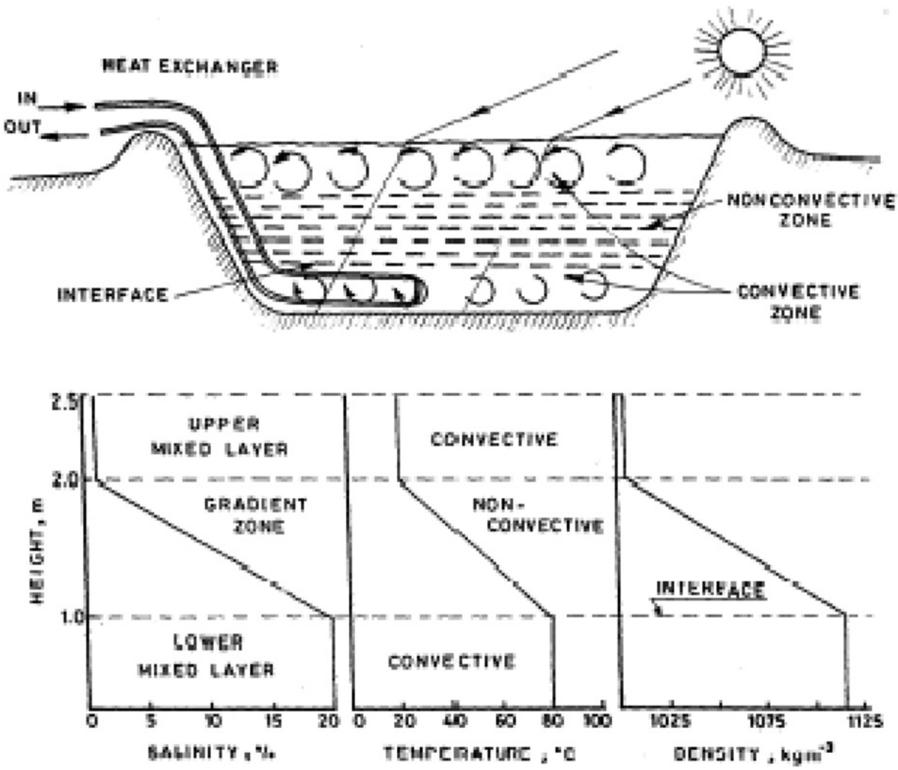

Fig. 1. Variation of salinity, temperature and density with depth.

In NCZ, due to the increasing density, convection currents are suppressed with the effect that warmer water cannot rise to the surface and cool down as in an ordinary pond. Therefore heat losses are only due to heat conduction. Hence, this layer is acting as a good transparent insulation. Depending upon the thickness of the NCZ, around 15–25% of the incoming radiation is absorbed under clear water conditions.

By a blackened bottom in the pond, in LCZ, up to 40% of the total received solar energy can be absorbed. The temperature of this zone varies between 80 and 90 °C. At the bottom of the pond, proper insulation is made to minimize losses. If sand layer is used as insulation, it will also act as a storage device. The temperature of the storage zone (LCZ) at the end of the period, $T_{t+\Delta t}$ is written as [1] follows:

$$T_{t+\Delta t} = \frac{\{A_{\mathrm{s}}[h(z)I_0 + k_{\mathrm{w}}T_{\mathrm{a}}/d_{\mathrm{ncz}}] + [T_t/\Delta t]\}}{\{[mc_p/\Delta t] + [A_{\mathrm{s}}k_{\mathrm{w}}/d_{\mathrm{ncz}}]\}},$$

where T is the temperature (°C), t the time (s), Δt the time intervals (s), A_{s} the surface area (m^2), $h(z)$ the fraction of solar radiation penetrating to the depth z in the pond, I_0 the hourly insolation incident upon a horizontal surface (W/m^2), k_{w} the stored water's thermal conductivity (W/mK), T_{a} the ambient temperature (°C), d_{ncz} the non-convective zone vertical extent (m), m the mass of water in the store (kg), c_p the specific heat of stored water (J/kg K).

3. Construction of a solar pond

Construction of a solar pond is very easy. At the base of the pond, the calculated amount of salt is mixed with fresh water until the pond is half full. In order to maintain salinity gradient, brine was injected into the LCZ and fresh water is supplied through the UCZ. Jaefarzadeh [2] studied various methods of salt injection in the LCZ. The author discussed and verified experimentally the 'dynamic stability' and 'equilibrium boundary criterion' for the lower and upper gradient interfaces. A salt gradient solar pond coupled with evaporation pond was studied by Agha et al. [3,4]. They proved that salt re-concentration by evaporation was an effective method of providing salt to the main solar ponds. Similar model was presented by Ouni et al. [5] and Alagao [6]. They proved that the efficiency of the solar pond was 10–30%, if the storage zone temperature is 40–80 °C.

3.1. Size

In the last 20 years, many salt gradient solar ponds varying in size from a few hundred to a few thousand square meters [7] of surface area have been built in a number of countries. A truncated conical shaped, portable mini solar pond, with cross-sectional area of 1 m^2 was designed by Tahat et al. [1] to study thermal behavior. They attained a maximum temperature of 100 °C, when the depth of NCZ is 300 mm. Aboul-Enein et al. [8] designed a rectangular-shaped mini solar pond of area 1 m^2. Mirror and baffle plates [9] are also used to increase the performance of the pond. Taga et al. [10] used transparent double film at the roof of the solar pond. Tiwari et al. [11] studied the effect on thermal trap on the performance of an underground shallow solar pond water heater.

3.2. Salt used

Normally sodium chloride salt is used in the solar pond. Hassairi et al. [12] used natural brine. But the maximum temperature obtained in the natural brine solar pond is less than sodium chloride used solar pond. Murthy and Pandey [13] used fertilizer salts for operating solar ponds.

4. Applications

Solar pond is used for various thermal applications like green house heating, process heat in dairy plants, desalination and power production. As shown in Fig. 2, Al Hawaj and Darwish [14] designed a solar pond assisted multi-effect desalting system. The author proved that the multi-effect boiling (MEB) solar pond system is viable for desalination of seawater in an arid environment with performance ratio more than twice the amount than a conventional system. Ahmed et al. [15] used solar pond for generating power, water and salt. This work was done to utilize the saline effluent from desalination plants. A comparative study was done by Badran and Hamdan [16] for under-floor heating using solar collectors and solar ponds. As shown in Fig. 3, the solar collector system is 7% more efficient than the solar pond system. The warm water stored in the solar pond was utilized as a heat source for a gas engine powered heat pump used to heat a greenhouse by Taga et al. [10]. Murthy and Pandey [13] studied the usage of solar pond for agriculture applications. A solar pond assisted auto flash multi-stage desalination system was

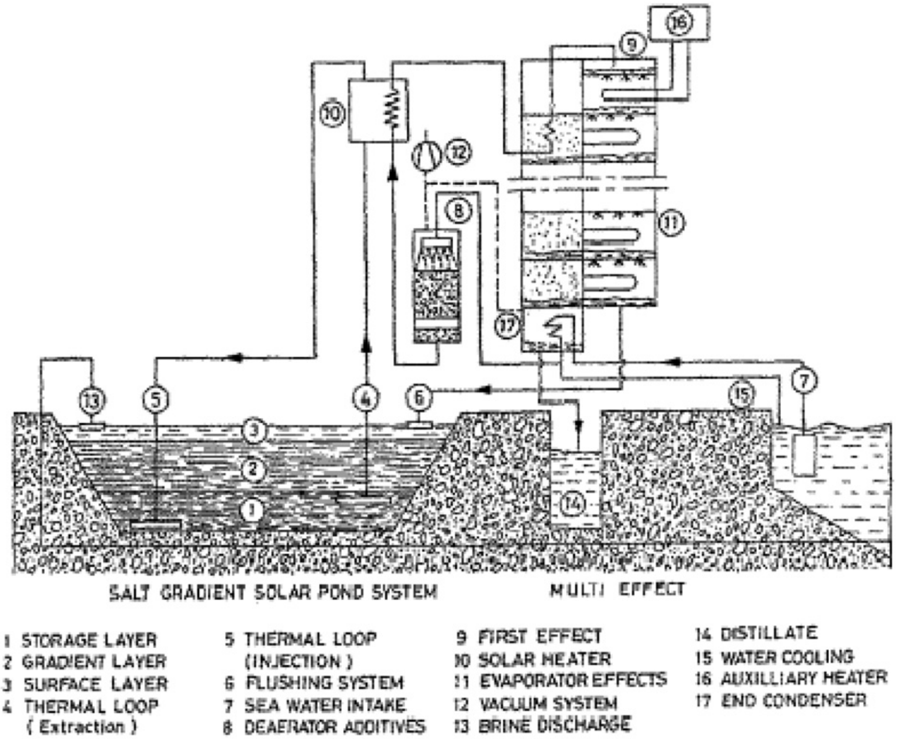

Fig. 2. Solar pond assisted multi-effect desalting system.

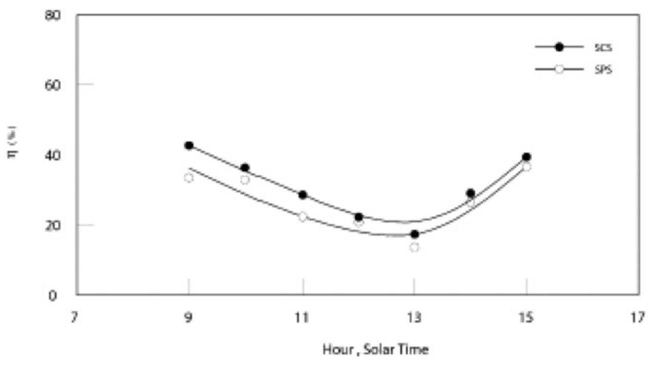

Fig. 3. Overall efficiencies of collector system and pond system.

developed by Szacsvay et al. [17]. A solar pond assisted titanium desalinator was designed by Caruso and Naviglio [18] to resist the chemical corrosion by salt water. Huanmin et al. [19] presented a solar pond assisted multi-effect, multi-stage flash distillation, membrane distillation and a brine concentration and recovery system (BCRS) for desalting impure water. Badran et al. [20] presented a numerical model for the behavior of a salt gradient solar pond greenhouse heating system. Velmurugan et al. [21,22] enhanced the productivity of potable water in a single basin still by integrating a mini solar pond. Fig. 4 shows a

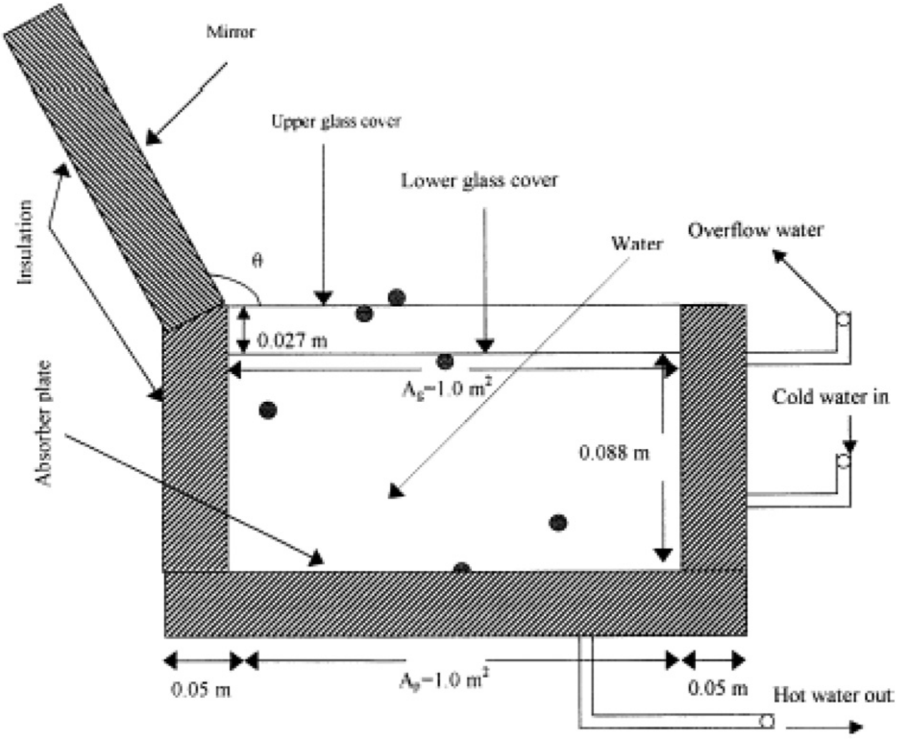

Fig. 4. A schematic diagram of mini solar pond integrated with solar still.

schematic diagram of a single basin solar still integrated with a mini solar pond. They proved that the average distillate water productivity increases by 59% when sponged type solar still is integrated with a mini solar pond.

5. Mode of heat extraction

Aboul-Enein et al. [8] investigated the thermal performance of a shallow solar-pond under the batch mode of heat extraction. They proved that the pond could provide 88 l of hot water at a maximum temperature of 60 °C at sunset. Also the pond can retain hot water till 7.00 a.m. next day at a temperature of 47 °C. Ramadan et al. [23] studied the thermal performance of solar pond under continuous mode of heat extraction. They proved that the continuous mode of heat extraction is more efficient than the batch mode of heat extraction. Fig. 5 shows a schematic diagram of a mini solar pond, used for batch and continuous mode of heat extraction.

6. Methods to improve performance

To increase the temperature of the LCZ, Aboul-Enein et al. [8] used plane mirror at the top portion of the mini solar pond. To minimize the shadow effect, Ibrahim and El-Reidy [24] used mobile covered shallow salt less solar pond. Higher water temperature was obtained when the reflector is adjusted than the adjusting the orientation angle of the

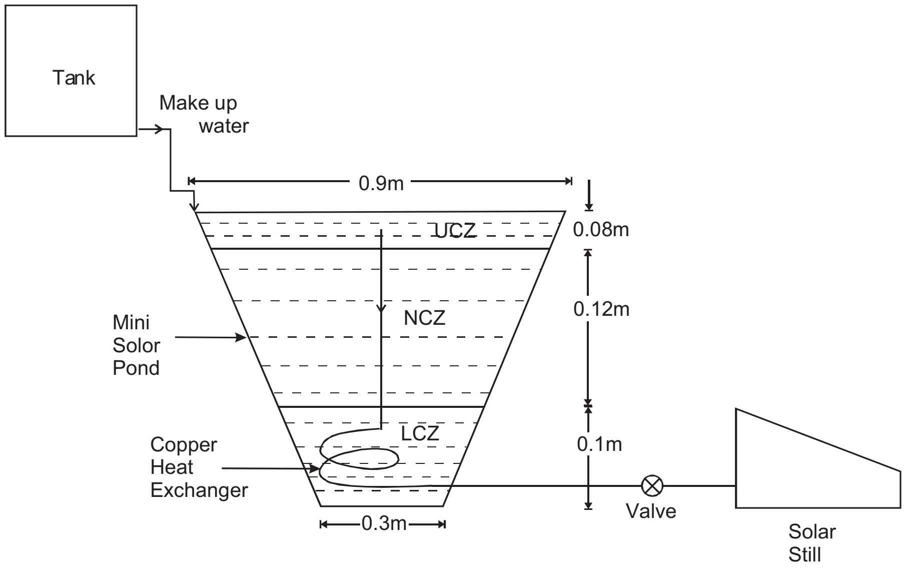

Fig. 5. A schematic diagram of constructed solar pond with double glass cover.

pond. A baffle plate was used and thermal performance was studied by El-Sebaii [9] and proved that the performance of the pond with the baffle plate is better than that of the pond without the plate and the thermal conductivity of the baffle plate has no effect on the pond performance. A solar pond with honeycomb surface insulation system was designed by Arulanantham et al. [25] to minimize the losses. They also proved that efficiency of the pond is around two times greater than ordinary conventional salt gradient solar ponds. In solar ponds, the LCZ plays a dual role. Heat is extracted from solar pond from this zone only. Also it is acting as a storage zone. A method was suggested by Prasad and Rao [26] to estimate the thickness of the LCZ of the solar ponds. Rivera and Romero [27] used a single stage heat transformer operating with the water/lithium bromide mixture to demonstrate the feasibility of the systems to increase the temperature of the heat obtained from solar ponds.

7. Factors affecting performance

The thermal efficiency of the pond depends on the thickness of the various zones in the solar pond. An increase in thickness of the UCZ reduces the amount of solar energy reaching the storage zone. Therefore the thickness of the UCZ should be very less. The various factors, affecting thermal performance of the solar pond are discussed under. Xiang et al. [28] did the thermal calculation by changing the incident rays from a Xe-lamp into natural ray and halogen lamp. As a result, it was found that the temperature distributions in the solar pond were notably different due to spectral characteristics of the incident ray. Therefore, the spectroscopic consideration for thermal performance of any solar pond was necessary to obtain a correct solution under the spectral incidence with special wavelength distribution.

7.1. Water turbidity and bottom reflectivity

The suspended matter in solar pond salt water, which prevents the penetration of light inside water, is called turbidity. Jackson turbid meter is used to measure turbidity. The unit for turbidity is helometric turbidity units. Wang and Yagoobi [29] studied the effect of turbidity on the thermal performance of a salt gradient solar pond. They found that high turbidity levels could prevent ponds from storing energy in the LCZ. Husain et al. [30] proved that reflective bottom and turbidity with certain limits improve the efficiency of pond. Giestas et al. [31] studied the gravitational stability of a salty layer of a fluid subject to an adverse temperature gradient as a result of heat absorption.

7.2. Wall shading effect

The thermal performance of a solar pond is a function of solar irradiation, heat losses from the sides to the surroundings and from the LCZ towards the upper layers, ultimate storage capacity, and the effectiveness of the heat exchanger system. In small vertical wall solar ponds, the shading of walls plays an important role on reducing the sunny area of the pond and its thermal performance. Jaefarzadeh [32] analyzed the effect of wall shading on the LCZ temperature. A numerical investigation was conducted by Jubran et al. [33]. They developed a model to predict the generation of convective layers on the solar pond walls.

7.3. Effect of energy extraction

The temperature of the UCZ and LCZ are almost uniform. The temperature of the NCZ increases, when the depth increases. When the thickness of the NCZ increases, the temperature of the UCZ also increases. Al-Jamal and Khashan [34] proved that the thickness of the NCZ was dependent on the amount of heat extracted from solar pond.

8. Economic analysis

A cost analysis was done by Glueckstern [35] for various desalting technology like solar pond, concentrator collector and seawater reverse osmosis process. The author concluded that the salt-gradient solar ponds to power hybrid MED/SWRO systems are currently the preferred technology for large-scale desalination.

9. Parameter measurement

It is very important to measure the various parameters like salinity, thermal conductivity and specific heat of the solar pond water. Various methods are being used by different authors. Some are discussed as follows. Thermocouples were normally used to measure temperature along the pond layers. Sreenivas et al. [36] presented a new model, which indicates the dependence of the equilibrium condition on the mixed layer depth, apart from the salinity and temperature gradients in the gradient zone. Husain et al. [37] proposed two formulations for estimation of available radiation at a depth in solar pond. It provided a 20–25% saving in computational time as compared to Hull's method with comparable accuracy.

9.1. Salinity measurement

To measure the density profile in the pond, known volume samples were taken from the three different zones and weighed. Tahat et al. [1] followed this method for measuring the salinity. During this investigation, the water salinity was maintained by recycling the salty water removed from the pond's surface and injecting it into the solar pond, near its base. Angeli and Leonardi [38] presented a one-dimensional numerical study of the salt diffusion in a salinity-gradient solar pond. A cylindrical-electroconductivity-temperature (CET) sensor and its special circuit were developed on the basis of the electro-conductivity-temperature measurement method by Li et al. [39] by which they measured the salt-gradient quickly at any experimental site.

9.2. Thermal conductivity and specific heat measurement

Al-Jamal and Khashan [34] used a correlation to find thermal conductivity and specific heat of pond water. Thermal conductivity of pond water is a function of temperature and salinity. Specific heat is a function of salinity and density.

10. Conclusion

Prospects in the works done on solar pond to improve its performance and their applications are reviewed. The important points are highlighted below:

- Solar pond is a device used for collecting and storing the solar energy.
- The temperature, salinity and density of UCZ and LCZ are almost constant. Whereas, in NCZ they are increasing with depth.
- Mini solar pond can also be used for various thermal applications.
- Heat can be extracted either batch mode or continuous mode from LCZ of the solar pond.
- Natural brine and fertilizer salts are used in the solar pond instead of sodium chloride. But sodium chloride used solar pond gives better results.
- The solar pond is used for green house heating, process heat in dairy plants, desalination, agriculture applications and power production.
- Plane mirror, mobile cover, baffle plates and honeycomb surface insulation system are used to improve the performance of the solar pond.
- Water turbidity and wall shading effect reduces the performance of the solar pond.
- Various methods, used to measure the parameters like salinity, thermal conductivity and specific heat of the saline water are also reviewed.
- A mini solar pond can also be used for enhancing productivity of a solar still. Around 59% solar still productivity increases when it is integrated with a mini solar pond.

References

[1] Tahat MA, Kodah ZH, Probert SD, Al-Tahaineh H. Performance of portable mini solar pond. Appl Energy 2000;66:299–310.
[2] Jaefarzadeh MR. On the performance of salt gradient solar pond. Appl Therm Eng 2000;20:243–52.

[3] Agha KR, Abughres SM, Ramadan AM. Design methodology for a salt gradient solar pond coupled with an evaporation pond. Sol Energy 2002;72(5):447–54.
[4] Agha KR, Abughres SM, Ramadan AM. Maintenance strategy for a salt gradient solar pond coupled with an evaporation pond. Sol Energy 2004;77:95–104.
[5] Ouni M, Guizani A, Lu H, Belghith A. Simulation of the control of a salt gradient solar pond in the south of Tunisia. Sol Energy 2003;75:95–101.
[6] Alagao FB. Simulation of the transient behavior of a closed-cycle salt-gradient solar pond. Sol Energy 1996;56(3):245–60.
[7] Kumar A, Kishore VVN. Construction and operational experience of a 6000 m^2 solar pond at Kutch, India. Sol Energy 1999;65(4):237–49.
[8] Aboul-Enein S, El-Sebaii AA, Ramadan MRI, Khallaf AM. Parametric study of a shallow solar-pond under the batch mode of heat extraction. Appl Energy 2004;78:159–77.
[9] El-Sebaii AA. Thermal performance of a shallow solar-pond integrated with baffle plate. Appl Energy 2005;81:33–53.
[10] Taga M, Fujimoto K, Ochi T. Field testing on non salt solar ponds. Sol Energy 1996;56(3):267–77.
[11] Tiwari GN, Garg HP, Madhuri. Effect of thermal trap on the performance of an underground shallow solar pond water heater. Energy Convers Manage 1985;25:127–33.
[12] Hassairi M, Safi MJ, Chibani S. Natural brine solar pond: an experimental study. Sol Energy 2001;70(1):45–50.
[13] Murthy GRR, Pandey KP. Scope of fertilizer solar ponds in Indian agriculture. Energy 2002;27:117–26.
[14] Al Hawaj O, Darwish MA. A solar pond assisted multi-effect desalting system. Desalination 1994;99:119–35.
[15] Ahmed M, Arakel A, Hoey D, Coleman M. Integrated power, water and salt generation: a discussion paper. Desalination 2001;134:37–45.
[16] Badran AA, Hamdan MA. Comparative study for under floor heating using solar collectors or solar ponds. Appl Energy 2004;77:107–17.
[17] Szacsvay T, Holfer-Noser P, Posnansky M. Technical and economic aspects of small-scale solar-pond powered seawater desalination systems. Desalination 1999;122:185–93.
[18] Caruso G, Naviglio A. A desalination plant using solar heat as a heat supply not affecting the environment with chemicals. Desalination 1999;22:225–34.
[19] Huanmin H, Walton JC, Andrew HPS. Desalination coupled with salinity-gradient solar ponds. Desalination 2001;136:13–23.
[20] Badran AA, Jubran BA, Qasem EM, Hamdan MA. Numerical model for the behaviour of a salt-gradient solar-pond greenhouse-heating systems. Appl Energy 1997;58(1):57–72.
[21] Velmurugan V, Mugundhan K, Srithar K. Experimental studies on solar stills integrated with a mini solar pond. In: Proceedings of the third BSME-ASME international conference on thermal engineering, Dhaka, Bangladesh; 2006 [in CD].
[22] Velmurugan V, Srithar K. Solar stills integrated with a mini solar pond—analytical simulation and experimental validation. Desalination 2007;216:232–41.
[23] Ramadan MRI, El-Sebaii AA, Aboul-Enein S, Khallaf AM. Experimental testing of a shallow solar pond with continuous heat extraction. Energy Build 2004;36:955–64.
[24] Ibrahim SMA, El-Reidy MK. Performance of a mobile covered shallow solar pond. Renew Energy 1995;6(2):89–100.
[25] Arulanantham M, Avanti P, Kaushika ND. Solar pond with honeycomb surface insulation system, Technical Note. Renew Energy 1997;12(4):435–43.
[26] Prasad R, Rao DP. Estimation of the thickness of the lower convective layer of solar ponds. Renew Energy 1996;7(4):401–7.
[27] Rivera W, Romero RJ. Evaluation of a heat transformer powered by a solar pond. Sol Energy Mater Sol Cells 2000;63:413–22.
[28] Xiang YL, Kanayama K, Baba H. Spectral calculation of the thermal performance of a solar pond and comparison of the results with experiments. Renew Energy 2000;20:371–87.
[29] Wang J, Yagoobi S. Effect of water turbidity on thermal performance of a salt gradient solar pond. Sol Energy 1995;54(5):301–8.
[30] Husain M, Patil PS, Patil SR, Samdarshi SK. Combined effect of bottom reflectivity and water turbidity on steady state thermal efficiency of salt gradient solar pond. Energy Convers Manage 2004;45:73–81.
[31] Giestas M, Pina H, Joyce A. The influence of radiation absorption on solar pond stability. Int J Heat Mass Transfer 1996;39(18):3873–85.

[32] Jaefarzadeh. Thermal behavior of a small salinity-gradient solar pond with wall shading effect. Sol Energy 2004;77:281–90.
[33] Jubran BA, Al-Abdali H, Al-Hiddabi S, Al-Hinai H, Zurigat Y. Numerical modeling of convective layers in solar ponds. Sol Energy 2004;77:339–45.
[34] Al-Jamal K, Khashan S. Effect of energy extraction on solar pond performance. Energy Convers Manage 1998;39(7):559–66.
[35] Glueckstern P. Potential uses of solar energy for seawater desalination. Desalination 1995;101:11–20.
[36] Sreenivas KR, Arakeri JH, Srinivasan J. Modeling the dynamics of the mixed layer in solar ponds. Sol Energy 1995;54(3):193–202.
[37] Husain M, Patil SR, Patil PS, Samdarshi SK. Simple methods for estimation of radiation flux in solar ponds. Energy Convers Manage 2004;45:303–14.
[38] Angeli C, Leonardi E. A one-dimensional numerical study of the salt diffusion in a salinity-gradient solar pond. Int J Heat Mass Transfer 2004;47:1–10.
[39] Li XY, Baba H, Kanayama K. Development of electrolyte solution concentration measurement system and application in solar pond. Renew Energy 2003;23:195–206.