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The development and applications of solar pond: a review

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ABSTRACT

Solar energy is a substantial source of clean and renewable energy. Recently, solar pond technology has made a great progress due to the fact that solar ponds can collect and store heat in the same time which has reduced the cost significantly thus making it an area of interest for the industry and researchers. Several salt gradient solar ponds have been constructed in many regions around the world. This paper reviews the various schemes of solar ponds, in addition to their performance, optimization, heat extraction mode and applications as reported in the literature. The maintenance and cost effect on solar pond have also been discussed.

Keywords: Solar pond; Convection; Non-convection; Heat extraction

1. Introduction

Solar pond was first discovered by von Kalecsinsky in Medve Lake in Transylvania in the early 1900. A maximum temperature of 70˚C was recorded at a depth of 1.32 m at the end of summer. Consequently, a minimum temperature of 26˚C was observed at the beginning of spring, while the concentration of NaCl was 26% at the bottom [1]. Other similar solar ponds in the form of natural lakes were discovered afterwards in other parts of the world such as: Orovilve in Washington [2], Vanda in Antarctic [3] and Eilat in Israel [4].

A solar pond extensively collects and stores solar energy. The solar energy will heat a body of water exposed to the sun, but the water gives up its heat unless some procedures are employed to trap it [5]. Water heated by the solar energy becomes less dense, therefore expands and rises up and immediately it reaches the surface, then, the water give up its heat to the air by convection, or rather evaporates, absorbing the heat in it. On the other hand, the colder water, which is more dense, moves down to replace the heated water thereby, creating a natural convective circulation which mixes the water and releases the heat [6]. Therefore, solar ponds were constructed artificially using salt gradient water in order to block the convection. Solar pond can store heat much more efficiently than a body of water of the same size because the salinity gradient prevents convection currents. Solar radiation entering the pond penetrates through to the lower layer, which contains concentrated salt solution. The temperature in this layer rises since it absorbs heat and is unable to move upwards to the surface by convection [7].

In 1948, Block proposed the implementation of a density gradient to reduce the solar pond convection. In the 1950s, Tabor et al. [8,10,11] initiated an extensive research by conducting studies on many

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small-scale ponds. They achieved a collection efficiency of 15% with recorded temperature as high as 103°C. Further, researchers such as Weinberger [12], Elata and Lavin [13], Tabor and Matz [14] and Hirschmann [15] have carried out experimental and theoretical studies on laboratory-scale solar ponds in order to understand the behaviour and the physics of the solar pond. In addition, numerical methods for predicting temperature dispersals within the solar pond have been developed by Stolzenbach et al. [16]. Because improving the conventional salinity gradient solar ponds (SGSPs) performance is important, Osdor [17] has proposed a new concept, the advanced solar pond (ASP). Two advantages of the ASP over the conventional SGSPs are the increased salinity of the solar pond, and heat stability maintenance due to a stratified layer usually set in the lower portion of the gradient zone.

The interest in solar pond research afterwards spread to other countries such as USA, Canada, Australia, India, China, U.A.E, etc. [18]. Nowadays, solar ponds are used in variety of applications such as thermal applications, desalination, salt extraction and power generation. The aim of this paper was to review the various schemes of solar pond, in addition to performance and optimization, heat extraction and applications.

2. Types of solar ponds

Solar ponds are primarily grouped into two types: the convective solar ponds and the non-convective solar ponds.

2.1. Convective solar pond

The shallow solar pond and the deep salt less pond are the examples of convective type.

2.1.1. Shallow solar pond

The shallow solar pond uses fresh water and does not need any addition of salt. They comprise of a black insulation and generally a concrete-made frame with a plastic tube attached. This plastic tube is filled with fresh water and its black bottom absorbs as much solar radiation as possible to heat up the water. Mostly, the plastic tube is covered by another glaze to reduce convection losses to the ambient air [19]. This type of pond has the ability to heat huge amount of water and its simplicity made it one of the promising cheapest methods of taking advantage of the solar energy. Its potential usefulness for solar energy conversion has been a subject of research and investigation for years, particularly Solar Energy Group [20].

Basically, the shallow solar pond is a huge bag of water fitted inside an enclosure with a clear plastic film on top and black plastic film at the bottom (Fig. 1(a) and (b)). The water has typically a depth of 4–15 cm. The water depth increase is proportional to the solar energy collection efficiency and inversely proportional to water temperature. Thermal energy is transformed by heating the water from solar energy during the day, and the water has to be removed from the pond before the night for storage or utilization [19]. In addition, the heat loss from the pond's top surface has to be reduced to increase the pond thermal performance. This is normally achieved using a multilayer semi-transparent insulation system on the top of the pond, which will efficiently decrease the heat loss from flat-plate solar collectors and convective solar ponds [21]. More also, it was found out that increasing the number of surface insulation films will improve the heat storage performance and worsen the performance of radiation collection [21].

Therefore, the ideal surface insulation films number depends on the time of removing the water from the solar tank. If this time is delayed, more surface insulation films need to be added to maintain the water temperature high; this is because the insulation is usually handled manually or rather, the contact between the glass cover and the insulations is not well maintained [21]. Upon that, Rani [22] and Van [23] has proposed the use of a baffle plate inside the system. The system was then analysed by Tiwari and Dhiman [24]. They incorporated the change in vent area, effect of the baffle plate, in addition to the upper and lower masses ratio. A water heater with the baffle plate has been proposed by Dutt et al. [25]. This method makes the design easier and lowers the construction cost.

2.1.2. Saturated solar pond (SSP)

These types of pond are saturated with salt at any depth of the pond. The amount of salt differs simply because of the varying density and the subsequent higher solubility due to the change in temperature. This implies that by heating up the water at the bottom of the pond, its solubility increases and the water cannot rise to the surface and lose its heat content [19].

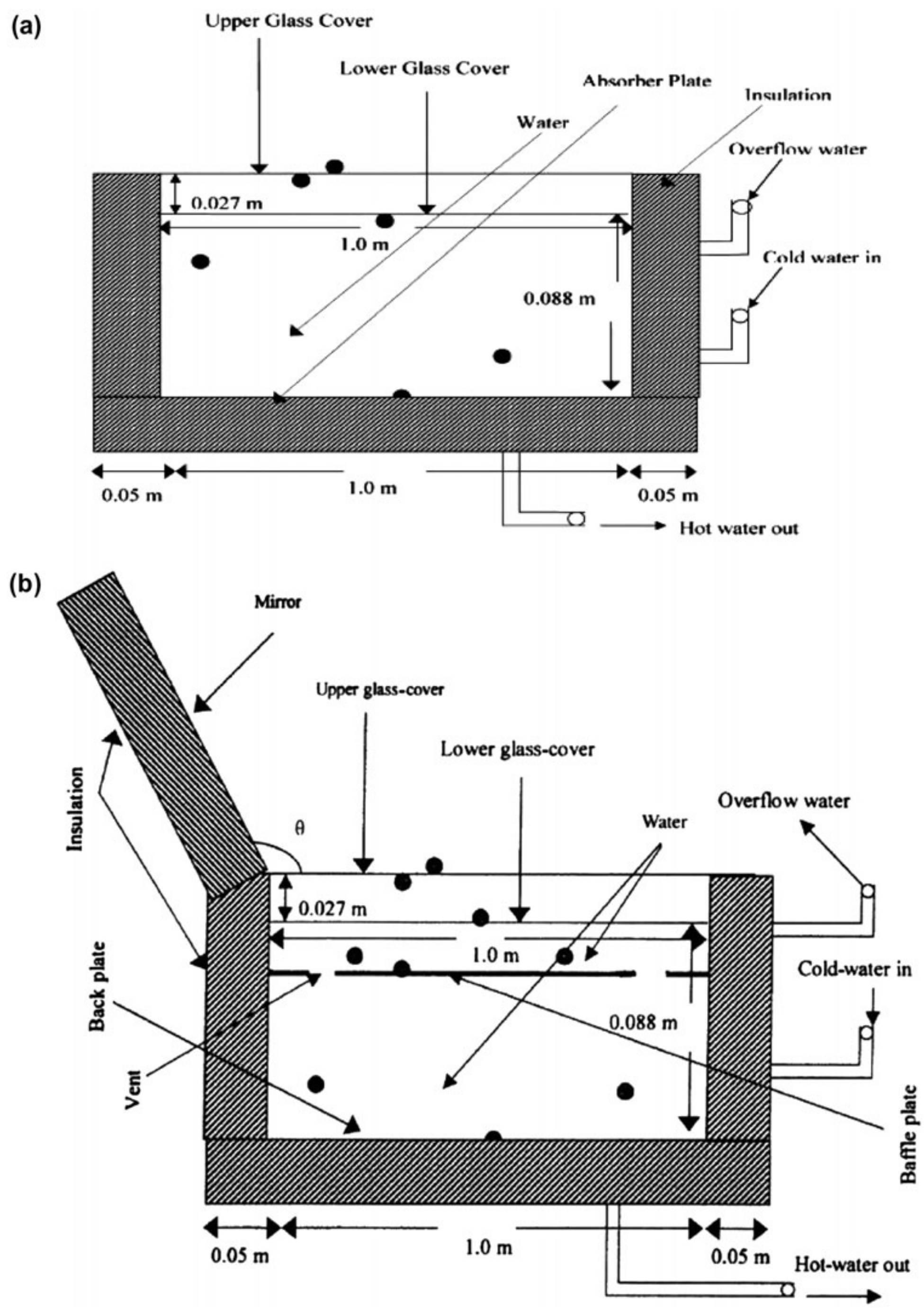

Fig. 1. (a) Shallow solar pond with double glass cover, adapted from: Aboul-Enein et al. [42]. (b) Shallow solar pond with baffle plate, adapted from El-Sebaii [75].

2.2. Non-convective solar ponds

There are four types of non-convective solar ponds: SGSP, partitioned solar pond (PSP), membrane solar pond and polymer gel layers solar pond [18].

2.2.1. SGSP

The SGSP collects and stores solar energy and its stability is usually maintained by the salt. The SGSP is a pool of water approximately 1–5 m deep, which

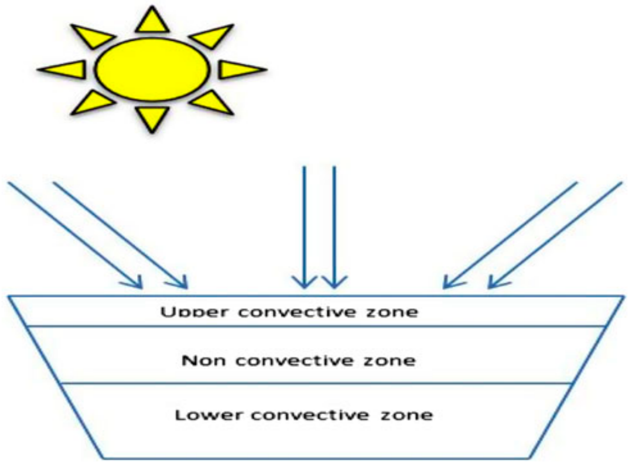

Fig. 2. SGSP, adapted from Hull [65].

contains dissolved salts to create a stable density gradient (Fig. 2). There are three layers in a SGSP: upper convective zone (UCZ), lower convective zone (LCZ) and salinity gradient non-convective zone (NCZ) in the middle. Incident solar energy is collected and stored, which may be delivered at temperature near 100˚C [26]. In the solar pond both UCZ and LCZ have uniform and constant temperature and salt concentrations, while the temperature and the salt concentration increase with depth in the NCZ [27]. The SGSP is the most eco-friendly and environment-friendly among all the solar energy systems for electricity generation, desalination, hot water applications in agriculture, green house heating, domestic hot water production and space heating and cooling of buildings [18].

For proper usage of the solar pond, the following characteristics should be met [19]. The solubility needs to be very high in order to get solution with high density, and it must not vary significantly with temperature. Furthermore, the solution needs to be sufficiently transparent to solar radiation, it should be environmentally soothing and safely handled and significantly available close to site in order to lower the cost of delivery.

Tundee et al. [28] have conducted a study to investigate the use of heat pipe heat exchanger in the solar pond for the heat extraction process. The results show that the LCZ temperature dropped from 39 to 40˚C in 3 h of operation. Preheating brine water of solar stills using mini solar ponds had been investigated [29,30]. The optimum salinity value in the mini SP was found to be 80 g/kg. The effect of heat extraction on the stability and performance of a mini SP has been studied by Ould Dah et al. [31]. It was found that the efficiency of the pond could be enhanced significantly when heat is extracted from gradient zone. However, this method decreases the stability of the LCZ.

2.2.2. PSPs

PSPs use a physical separation of at least the heat storage zone (HSZ) to avoid interactions with the NCZ, this is so as to increase the temperature in the HSZ and hence increase the performance of the solar pond [32]. Usually, solar pond faces many complications such as the biological growth of bacteria and algae, reduced transparency due to dirt and dust falling into the pond, disturbance of the concentration gradient during heat extraction and evaporation [33]. The solutions to the biological problem are by adding chemicals, whereas two transparent partitions can be installed on the top or fairly close to the surface. The role of lower partitions is to isolate the convective layer from the insulating layer [34]. It is important that such a separation has to be a high transmitter to solar radiation; else the benefits from physically separating the HSZ could be equal to the losses through less irradiation into the HSZ [19]. This technique improves the pond stability and makes the heat extraction easy.

2.2.3. Polymer gel layer/viscosity-stabilized solar ponds (VSSPs)

In this type of pond, a gel is used to make the water thicker which obstructs convection losses. The necessities for such a gel are relatively high as it should be thick enough to avoid convection. Also, it must retain its temperature resistance, have a good physical resistance to withstand precipitation and ensure a satisfying transmittance for solar radiation [19]. Gum arabic, starch, locust beam gum and gelatine were found to be potential polymer candidates that can be used. Although the concept of viscosity-stabilized solar pond is very promising; however, economically speaking it is still not competitive as SGSP [19]. A study was conducted by Shaffer [35] utilizing a transparent polymer gel to play the role of the convective layer. The polymer gel is used at a close solid state in order to prevent convection. VSSPs require suitable material with high transmittance to facilitate the diffusion of solar radiation; hence a material with proper thickness should be chosen which would be able to operate at temperature up to 60˚C [36].

Another option of great importance in a solar pond is the double-diffusive convection, which is induced by temperature and concentration differences or by concentration differences of two species is of great importance as it originates due to the opposing gradient in a solar pond [37].

2.2.4. Membrane-stratified solar pond (MSSP)

MSSP is a non-convective solar pond that uses thin transparent membranes to separate layers and suppress convection instead of using salt gradient layers as illustrated in Fig. 3. The transparent membrane thickness has to be small and should have many high transparency films [36]. The weight of water balances the buoyancy effect in order to convert solar radiation into sensible heat [38]. Three membrane types were proposed for the MSSP, which are horizontal sheets, vertical tubes and vertical sheets.

2.3. General overview on the uses of solar ponds

Solar ponds were reported to be used for various applications with several advantages and disadvantages. A summary concerning the experiences of the applications of solar ponds were extracted from the published literature and are summarized in Table 1.

2.3.1. Heat extraction

The use of solar ponds for various thermal applications like greenhouse heating, process heat in dairy plants, desalination and power production has been reported [27]. More also, in the mining industry solar pond has been applied for mineral extraction [39].

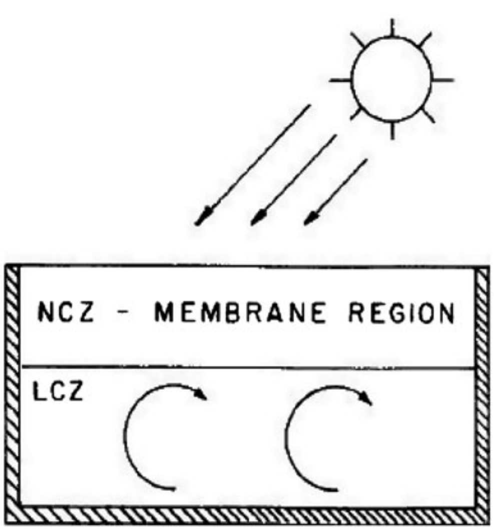

Fig. 3. MSSP, adapted from Hull [65].

Hence, a summary of the application of solar pond for heat and mineral extraction by various researchers is presented.

Generally heat is extracted from the storage zone of a typical solar pond by two methods. The first method is by circulating hot brine from the LCZ through an external heat exchanger, this method is used for instance in El Paso solar pond. The second method is using a heat exchanger that goes through the LCZ with a heat transfer fluid that flows through it in a closed loop; the Pyramid Hill SP in Australia is an example [40]. In NCZ, no natural convection occurs and salinity increases with the depth. The solar radiation transmits into the zone and increases the temperature equally for heat extraction [27]. In addition, Al-Jamal and Khashan [41] demonstrated that the thickness of the NCZ was subject to the amount of heat extracted from solar pond.

The thermal performance of a shallow solar pond was investigated under the batch mode of heat extraction. They found out that the pond could provide 88 litres of hot water at a maximum temperature of 60°C at sunset. More also, the pond can hold hot water till 7.00 a.m. the following day at a temperature of 47°C [42]. In another study, Leblanc et al. [40] determine the thermal performance of solar pond under continuous mode of heat extraction. They established that the continuous mode of heat extraction is more effective than the batch mode of heat extraction.A new approach of heat extraction in solar ponds is to obtain the heat from the gradient layer [40]. The heat is extracted for over two months by an in-pond heat exchanger built of polyethylene pipe. The results show that extracting heat from the gradient layer raises the solar pond energy efficiency up to 55%, compared to extracting only from LCZ. The results from the experimental and the theoretical analysis show a close agreement. From the experimental study, it has been found that convection currents are localized only but not affecting the density profiles. However, more investigation on the effect of heat extraction from the storage zone on the solar pond stability (horizontal and vertical) has to be done. Thus, future work experiments using an external heat exchanger for brine extraction at different levels within the gradient is needed to determine the heat extraction effect of NCZ on the stability of the SGSPs. In addition, an economic analysis needs to be done in order to determine the cost gains from increased thermal efficiency.

In another study, Jaefarzadeh [43] has investigated the process of extracting thermal energy from SGSP using a small-scaled SP with an area and depth of 4 m^2 and 1.1 m, respectively. A polyethylene pipe located at the storage zone was utilized as an internal

Table 1
Comparison of solar ponds

Solar pond type	Advantages	Disadvantages
SGSP	• Low cost of operation • Simple construction • Large thermal storage capacity	• Require regular maintenance • Potential risk of contaminating the ground when there is saltwater leakage • Wind disturbance causing evaporation and instability • The evaporated water surface needs to be constantly checked
PSP	• Improved stability • Less maintenance	• Wind disturbance in most cases • The evaporated water surface needs to be constantly renewed
MSSP	• It is environmentally friendly • Improved stability • Less maintenance	• The evaporated water surface needs to be constantly renewed
VSSP	• It is environmentally friendly • Improved thermal efficiency • Less maintenance	• Higher cost comparing to other types • The evaporated water surface needs to be constantly renewed
SSP	• Large amount of heat production • Improved thermal performance • Simple design • Considerably low cost • Not disturbed by wind or turbidity • Less evaporation	• Requires more pumping equipment • Needs separate night time thermal storage

SGSP; salinity gradient solar pond, PSP; partitioned solar pond, MSSP; membrane stratified solar pond, VSSP; viscosity-stabilized solar pond, SSP; saturated solar pond.

heat exchanger. Fresh water was circulated in a closed path which helps to transfer thermal energy in the bottom layer to the external heat exchanger. The temperature rate of the storage zone was decreasing rapidly in the heat extraction process. However, the temperature then becomes constant progressively. Thus, the solar pond can be used as a reserve energy source for a large load in a short amount of time.

Lesino et al. [39] reported the use of solar pond for the production of industrial grade sodium sulfate from a mineral consisting in a mixture of sulfate decahydrate, sodium chloride and clay. The process uses the solar pond as a basin where the mineral is dissolved at temperatures around 40°C. Further, the sodium sulfate is separated from the concentrated hot solution by fractional crystallization during the night, at low temperature. Results demonstrated an excellent performance of the prototype, with a yield of 100 tons of sodium sulphate decahaydrate achieved after 50 days with a temperature increased up to 56°C and a density of 1,320 kg/m^3. The result obtained compares well with the results determined with a conventional plant because of lower initial investments and operational costs. A SGSP was constructed by Nie et al. [44] using the natural brine of Zabuye salt lake in the Tibet plateau with a square surface area of 2,500 m^2 and is 1.9 m deep. The solar pond started operation in February, when the ambient temperature was very low. The solar pond started operation in spring, when the ambient temperature was very low and has operated steadily for 105 days, with the LCZ temperature varying between 20 and 40°C. Results from the study showed that the LCZ of the pond reached a maximum temperature of 39.1°C. They concluded that the solar ponds can be operated successfully at the Qinghai-Tibet plateau and can be applied for minerals production. In another study, Wu et al. [45] illustrated that Tibetan Plateau is a perfect location for the construction and operation of solar pond. In addition, they described the advantage of solar pond crystallization as compared with the natural evaporation crystallization in the mineral resource exploitation of the salt lake in Tibet. They found out that the crystallization rate of the high-added-value saline minerals, particularly lithium carbonate, can be speeded up in the solar pond, thus increasing the production efficiency. Also, they concluded that the grade of lithium carbonate in the mixed salt can also be improved considerably and the salt product achieved from the solar pond can be used for the final fine processing directly.

Caruso et al. [46] set up an experimental plant consisting of a full titanium desalinator coupled with a small solar pond to investigate the design, optimization, construction, assembling, start-up and extensive monitoring of the system. The data collected during the start-up and operation of the plant under various conditions such as the temperature and salinity have been used for improving the capability on heat recovery with highly corrosive fluid media, on co-generation plants aimed at producing electricity and fresh water and on desalination fed by solar energy. During the experiment, the temperature and the salinity have reached 65℃ and 24%, respectively. In addition, with reference to a 30 m^3/d desalination unit, it was found out that the thermal power savings with a full titanium desalination plant and a conventional has been estimated at about 72 kW. The system achieved an enhanced performance with better heat transmission through tube bundles, reduced requirement of chemicals and improved plant reliability and duration. The design criterion for an in-pond heat exchanger made by a reinforced polyethylene pipe was proposed by Sabetta et al. [47]. The performances and the reliability of the proposed in-pond heat extraction systems were tested in a 2000 m^2 pond. This was achieved by setting up a simple monitoring system, including a flow meter and a thermocouple. The measurement of the flow rate, the inlet and outlet temperatures and the temperature of the lower convective layer allow the computation of the actual value of the overall heat transfer coefficient. The comparison with the overall cost of the in-pond heat extraction system shows that it is about half the cost of an equivalent external heat extraction system. The advantages of the system with respect to generally used external heat exchangers are the absence of corrosion and maintenance problems, the reduction of the danger of erosion of the salt gradient region, the simple installation and finally the low cost of the pipe heat exchanger used make this proposal very attractive for heat extraction from solar ponds of any size.

One major application of solar pond is to be utilized as a continuous energy spare. In steady-state condition, the small pond efficiency was reported to be approximately 10%. However, on the basis of calculations done for a large-scale ponds; there will be 22% increase in efficiency [48]. In order to evaluate the performance of the solar pond heat exchanger, the overall coefficient of the heat transfer has to be estimated [48].

Tundee et al. [28] have carried out studies on the use of heat pipe heat exchanger in the solar pond for the heat extraction process. A small-scale solar pond was used with an area and depth of 7.0 m^2 and 1.5 m, respectively; the pond was constructed at KhonKaen in north-eastern Thailand. They use a heat pipe exchanger consisting of 60 copper tubes with 21 mm inner diameter and 22 mm outer diameter; the heat from the storage zone was successfully extracted. The condenser section length is 200 mm and the evaporator section length is 800 mm. The theoretical model of the heat extraction was formulated based on the equations of energy conservation and from the data of the solar radiation for the location mentioned above. In the analysis, the heat exchanger performance is evaluated by applying various velocities of the inlet air. They found out that the air velocity has great impact on the heat pipe heat exchanger efficiency and the efficiency increases by 43% when velocity drops from 5 to 1 m/s.

In a similar study, Andrews and Akbarzadeh [49] had investigated a different technique of extracting heat from SGSP such that the heat is obtained from the NCZ instead of the LCZ to improve the overall energy efficiency of collecting solar rays. The overall energy efficiency of the pond depends on the gradient-layer thickness, different gradient layer and LCZ heat extraction proportions combinations and heat temperature. They found that extracting heat from the gradient zone has a great impact on improving the overall energy efficiency, producing relatively high temperature by 50% as compared with the conventional technique of extraction. Further, experimental investigations were carried out in order to evaluate the theoretical analysis.

Generally, this technique was discovered to be very promising; however, further investigations need to be done so as to evaluate the sensitivity of the theoretical efficiency of the heat extracted from gradient-layer, and perform more practical experiments in this area. Also, further evaluation on the economic ability and cost estimate has to be carried out.

2.4. Applications of solar ponds

Solar ponds can be used in variety of applications such as heating/cooling of buildings, industrial process heat, power production, heating animal housing and drying crops in farms, desalination, etc.

2.4.1. Heating of building

Studies for the use of solar ponds for house heating were carried out by Tabor [9]. Further, the prospective application of solar ponds to house as well as food and paper process heating was discussed by Styris et al. [50]. The large heat storage capacity found in LCZ of a typical solar pond makes it perfect for usage in heating of buildings applications [19]. The facades of buildings can be important solar collectors and, therefore, become multifunctional. Therefore, installation of collectors on the tilted roofs, south walls, balconies or awnings of buildings is the feasible approaches for integration of solar collectors into buildings. For example, in China's cities, over the last twenty years, solar cooling systems were largely used in public buildings for either absorption or adsorption. In addition, nearly all solar cooling systems are multifunctional. This is because they have been used to supply heating and hot water in other seasons for the purpose of high solar fraction [51].

2.4.2. Industrial heat process

The thermal energy extracted from a solar pond can be used in the heat process or the treatment of materials in manufacturing industries. The solar pond can be a potential process heat supplier for many industries, optimizing the cost of energy and saving gas, oil and electricity [19]. The heat generated is normally at medium temperatures of 50–90˚C. In addition, the unit cost of supplying industrial process heat from a SGSP is less costly than either natural gas or coal for even smaller pond sizes [52].

2.4.3. Power production

Solar ponds could be used as heat source for many applications, one of which is electricity generation. Some of the striking advantages of solar pond power generation plants were described by Chel and Kaushik [53], such as no necessity for fossil fuels, they have low running cost, use local resources and do not litter the environment. The idea of using the solar pond for power production can be very potential for those regions where there are conditions such as insulation and suitable soil that allows the building and operating of large solar ponds [54]. Hence, these can be used to generate considerable electrical energy from the heat extracted. However, because of the low temperature of operation, typically (70–100˚C) the conversion efficiency is limited. Thus, it is required to use organic fluids which have low boiling point, for instance hydrocarbons (e.g. propane) and halocarbons (e.g. freon), to aid in the electric generation [19].

2.4.4. Desalination

A solar pond in conjunction with a desalination plant can be very beneficial. The thermal energy extracted from a solar pond can be used to desalt or purify water that can be used for drinking or irrigation [55]. The desalination plant can obtain energy from a solar pond for heating a body of saline water; which will enhance the heating process in desalination. Furthermore, it has been found that the production of distilled water from this sort of desalination plant can be five times more than the conventional basin type solar still [56].

3. Recent research works to improve performance

Recent reviews of research carried out in a variety of work have attempted to add other benefits to the solar pond general applicability. The prospects in the work done on solar pond to improve its performance and applicability are reviewed and presented.

Straatman [57] proposed a new design of a 50 MW scale production hybrid ocean thermal energy conversion offshore solar pond (OTEC–OSP). The aim of their design is to achieve a system with low levelised electricity costs (LEC) as well as low maintenance cost. Computed LECs indicated that the proposed system (hybrid OTEC–OSP) has the lowest value of LEC around 0.04 /kWh. On the other hand, the combination of an OTEC system to an OSP raises the difference in temperature, which results in 12% efficiency, whereas normal OTEC has an efficiency of 3%.

Silva and Almanza [58] carried out experiments to investigate different soil physical, hydraulic and chemical properties, generally as clay liner. This is majorly due to the wide variations in materials used in the lining of solar pond. Hence, studies have to be carried to determine their long-term performance in case of hot brines in order to eliminate the potential drawbacks in solar pond operations. It was found out that using clay soil as a hydraulic barrier is an alternative of using synthetic materials in solar pond in order to reduce the construction cost and contamination risks. Bezir et al. [59] have conducted a study to investigate the performance of SGSP with or without reflective covered surface. They constructed a SGSP with an area of 12.25 m^2 and 2 m depth. Two collapsible covers were used to lower the thermal energy loses from the surface at night and increasing the thermal efficiency during the daytime. Further, they developed a mathematical model to calculate the harvested solar energy amount by the cover, which gives the variation of temporal temperature inside or outside the pond at any given time. Results showed an increased performance by 25% when reflectors were used. They concluded that reflectors are essential for enhancing the performance of a salinity gradient pond.

Karakilcik et al. [60] built an experimental solar pond with an area of $4\,m^2$ and 1.5 m depth in Cukurova University in Adana, Turkey. The solar pond was filled with salty water of various concentrations to form the three zones and data were collected during January, May and August at various locations using data acquisition device. In addition, a performance model has been developed in order to determine the pond's thermal efficiency. The results indicated that the maximum temperature was recorded in August as follows: 4.5% in UCZ, 13.8% in NCZ and 28.1% for the LCZ (storage zone). They concluded that the thermal performance was strongly affected by the LCZ temperature and the temperature profile with pond depth. An experimental study was conducted by Shi et al. [61] both in the field and in the laboratory to investigate the effect of porous media on salt and thermal diffusion present in the solar pond. The lab experiment shows that adding a porous media in the base of the solar pond could be very beneficial in improving the heat insulation and reduction of salt upward diffusion. On the other hand, the field experiment was conducted using two small-scale solar ponds. They observed a temperature increase in the LCZ when adding porous media. In addition, it was found that the porous media suppressed the increase of turbidity when renewing the salt of the LCZ. Results of the numerical simulations of the thermal properties show that a better result was obtained when a brine layer with porous media such as pebble or slug has a high ground thermal conductivity. Inversely, when the ground's thermal conductivity is small; the solar pond performance decreases, thus reducing the quantity of the heat storage in the solar pond. Moreover, simulation results show that that maximum of LCZ temperature increases proportionally with the thickness of brine layer. Hence, to reach maximum heat storage, it is required to use an optimum thickness of brine layer.

A study conducted by Agha [62] investigated the optimization of pond's size and the stages number for temperature of different storage taking into consideration the change of the energy supply during the summer and the winter. Results show that oversizing of solar ponds leads to certain rejection in the collected heat throughout the summer. The sensitivity analysis of the different factors that affect the water costs indicated that the capital costs involve about two-third of the total desalinated water costs. They concluded that more number of peak clipping days lead to lower quantity of useful energy delivered by the solar pond with a higher thermal energy cost. In addition, Saxena et al. [63] conducted simulation analysis to investigate the significance of water table depth for the heat storage performance. They found out that the deeper the water table, the lesser the heat loses and the higher the temperature achieved by the solar pond. The solar pond has a dimension of $20\,m \times 20\,m$ and the UCZ, NCZ and STZ are taken as 0.2, 1 and 2 m, respectively. Radiation flux in pond's liquid was based on Bryant and Colbeck [64] method assuming clear water. Depth of the water table is considered to vary from 5 to 25 m at an interval of 5 m and then 50 m. Losses through bottom are estimated by the method of Hull et al. [65]. The simulation analysis uses a model of SGSP to analyse its thermal performance under various depths of water table, keeping other parameters as constant. They concluded that increasing the depth of water table increases the maturation temperature and raises the pond's temperature as well. Hence, it should be noted that there is a significant depth of water table, below which further depression does not have a significant impact on thermal performance of the pond.

It was reported by Nelsen [66] that the cost involved to establish solar pond systems for the storage of solar energy is basically determined by the cost of the salt. Also, the stability conditions for the solar pond are measured with the objective to minimize the salt requirements. Therefore, efficient operation of the solar pond depends on the stability with respect to respect to vertical motion of the saltwater solution that insulates the incident solar radiation. An experimental study on the development of the salinity and temperature profiles in a SGSP was performed by utilizing a small model of cylindrical plastic tank pond [67]. The tank was 1 m high, with a diameter of 0.9 m and an insulation layer (polyurethane) of 150 mm. They employed a salinity redistribution technique to implement the salinity gradient. A projector of 2000 W was used to simulate the sunrays and measurements were taken in 29 days period. This time duration will help to show the presence of salt diffusion from the LCZ up to the surface. Results indicated that the temperature profile was achieved inside the pond after five days of heating. Also, the highest temperature achieved a the bottom layer was about 45℃, causing a variance in temperature of 23℃ in the lower and the upper layer.

They concluded that the temperature and salinity profiles acquired experimentally agreed well with those obtained by the empirical relations of Newell [68].

Angeli and Leonardi [69] have used a finite difference method to solve numerically a one-dimensional mathematical model taking into account the thermo-diffusion effect in the salt diffusion equation. The solar pond used has similar dimensions and seasonal temperature variations of the LCZ and UCZ with the same as those measured at El Paso solar pond USA. The model results show that the thermo-diffusion travels in the same direction of molecular process. Whereas, introducing concentrated brine required preserving the salinity-gradient constantly steady producing an additional flux, and consequently lowers the thermo-diffusion impact. It was found out that the thermo-diffusion can reach an average percentage of 10% of the total flux yearly, and sometimes it reaches picks around 15% in summer.

Karim et al. [70] carried out a series of studies to investigate the linear salt-stratified system stability. They use particle image velocimetry and shadowgraph techniques for flow visualization thereby providing a phenomenological description of flow convection. They categorized the experiment into three phases. The first phase corresponds to the onset of a non-periodic fluctuation in space and time of the lower flow, while in the second phase, a well-mixed layer is created and a fluctuating movement developed on the free surface. Lastly, the stratification was transformed from linear to non-linear. Unlike other studies, the author considered heating the free surface system from beneath at constant temperature. Then, focused on the development and the onset of the first mixed layer using minimal stability parameter values that is the values found in a real typical solar pond. Also, Karim et al. [71] investigated the dynamic processes in solar ponds and the behaviour of the gradient zone using small-scale solar pond. For the laboratory-scale experiment, two tanks fabricated from galvanized steel were used with an area of 3.6 m^2 each. The tank walls were insulated using polystyrene foam and thermocouples connected to a multiplexer were installed along the pond in order to measure the temperature time and space variation. It was observed that by introducing a porous medium in the lower layer a reduction in the release of convection in the layer was achieved. The porous medium helps reducing the effect of vortices created in the lower layer of the stratification without affecting the structure of the top layer. They concluded that the instability of solar pond could be limited when using porous media in the bottom layer of the stratification.

Mansour et al. [72] had conducted numerical studies on the transient heat, mass transfer and long-term stability of an SGSP. They employed a two-dimensional transient-variable properties model and finite control volume numerical method. Field experiments were conducted on a pond subjected to real weather condition and the numerical model has been evaluated with real measured data. Results show that the solar heating effect is less during winter and autumn than summer and spring. It was also observed that, two critical zones one underneath the upper surface and one near the bottom had developed in very quickly during the operation. They concluded that the heating effect, water transparency and heat loss can affect the pond's stability as well as its temporal evolution significantly. Also, pond with good limpidity water is more likely to have instabilities than a pond with poor limpidity; this effect is more significant in the lower critical zone.

4. Maintenance and cost

The Maintenance of the solar pond operation is expected to dramatically improve the thermal efficiency and other activities. Li et al. [73] have conducted a series of experimental studies on the turbidity reduction efficiency in the solar ponds using salt from the seawater. The experiments on the turbidity reduction using chemicals shows that alum ($KAl(SO_4)_2.12\ H_2O$) has a better turbidity control due to its strong flocculation as well as preventing the developing of bacteria and algae in seawater. Their results show that desalinated residual brine was able to keep limpidity for a prolonged time even without using any chemical. Also, they observed that subsiding soil in the saline and bittern with similar salinity is faster. However, it subsided quite slowly in the bittern. They concluded that the proposed method is a cost-effective scheme to keep the solar pond from the rain damage.

Therefore it should be noted that when injecting water in the UCZ, the salinity gradient maintains stability. However, the salinity of the UCZ increases rapidly if the surface of the solar pond was not flushed, thus affecting the salinity gradient stability. There are various forms of complexity and limitations associated with the performance of solar ponds, and in some cases limit their use were documented and different alternative methods have been proposed to solve these effect. These problems consist of wind mixing, evaporation, dust and dirt falling on pond surface and the major one is the double diffusion phenomena of the temperature and salinity gradient. The performance of a SGSP depends in the stability of its NCZ and the storage zone. However, instabilities due to double diffusion may occur which will cause steady convective motions, consequently decreasing the insulation properties of the layer [74]. The maintaining of the non-convective gradient zone and its stability is one of the alternatives to solve the problem of double diffusion in a solar pond.

Generally, maintaining the limpidity of a solar pond is very important so that a high LCZ temperature is achieved. Further research has to be done for a better thermal performance and improved maintenance of solar pond.

5. Conclusion

Solar pond has made great progress recently; based on this review the following conclusions were illustrated:

(1) Solar pond is a method for accumulating and preserving the solar energy.
(2) The SGSP was found to give a great performance among the non-convective solar pond with a relatively low technology and low cost approach for harvesting solar energy.
(3) Solar pond is a unique energy trap with a number of potential applications, such as process heating, refrigeration, drying, water desalination and power generation.
(4) The performance of a solar pond reduces due to the effect of water turbidity, growth of algae and wall shading.
(5) To improve the performance of solar pond plane mirror, mobile cover and baffle's plates surface insulation system were used.
(6) The result of the experimental and theoretical investigation of temperature distribution in solar ponds showed that it is a great source of heat, hence presenting a significant potential for energy savings and storage.

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