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Investigation of Thermodynamic Performance of Salt Gradient Solar Ponds

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A B S T R A C T

Solar pond is an artificially constructed pool by which the solar energy is collected and stored in a cost-benefit approach compared to conventional solar energy collection methods. Salt gradient solar pond, capable of providing a considerable quantity of hot water, has received wide currency in both research and industrial fields. Heat absorbed in the salt gradient solar pond can be extracted in different ways for various thermal applications, ranging from domestic to industrial uses. Thermal efficiency as a key criterion for evaluation of the performance of the pond, is directly influenced by the method applied to extraction of the heat. Investigation of the performance of a solar pond requires a comprehensive thermodynamic study through energy and exergy analyses based on the first and second laws of thermodynamics. Such observations have been aimed at achieving higher efficiency and effectiveness of the system. The present article presents thermodynamic analysis for performance investigation of salt gradient solar ponds in all three zones including theoretical and experimental results.

1. Introduction

Renewable energy replaces conventional fuels in four distinct areas: electricity generation, air and water heating/cooling, motor fuels, and rural (off-grid) energy services. Renewable energy contributed 19 percent to our global energy consumption and 22 percent to our electricity generation in 2012 and 2013. This energy consumption is divided as 9% coming from traditional biomass, 4.2% as heat energy (non-biomass), 3.8% hydro electricity and 2% is electricity from wind, solar, geothermal, and biomass. Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries.

Solar energy is considered as an important source of renewable energy. The development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Active solar technologies encompass solar thermal energy, using solar collectors for heating, and solar power, converting sunlight into electricity either directly using photovoltaics, or indirectly using concentrated solar power.

Among solar thermal technologies, solar ponds are considered as reliable and economical means of solar energy application. A solar pond, as a passive solar technique, is a pool of saltwater which acts as a large-scale solar thermal energy collector with integral heat storage for supplying thermal energy. Salt gradient solar pond, capable of providing a considerable quantity of hot water, is one of the most efficient and practical types of solar ponds. These ponds are typically 1-2m deep and the bottom is painted black. The convection currents that normally develop due to the presence of hot water at the bottom and cold water at the top are prevented by the presence of strong density gradient from bottom to top. This density gradient is obtained by using a high concentration of suitable salts such as NaCl at the bottom of the pond and negligible concentration at the top [1]. A salt gradient solar pond consists of three distinct zones. The first zone, which is located at the top of the pond and contains the least dense salt/water mixture, is the absorption and transmission region, also known as the upper convective zone (UCZ), which has the function of protecting the salinity gradient layer. Its stability is controlled by addition of water on the solar pond surface and prevention of the naturally induced wind agitation. The second zone, which contains a variation of salt/water densities increasing with depth, is the gradient zone or non-convective zone (NCZ), also called the salinity gradient layer. The main purpose of this zone is to act as an insulator to prevent heat from escaping to the UCZ, maintaining higher temperatures at deeper zones. The last zone is the lower convective zone (LCZ) also called the heat storage zone (HSZ), which consists of saturated brine with almost homogeneous salinity and density [2].

2. Applications of Solar Ponds

Because of large storage of heat and negligible diurnal fluctuation in pond temperature, solar pond has variety of applications like, heating and cooling of buildings, swimming pool and greenhouse heating, industrial process heat, desalination, power production, agricultural crop drying, etc [3].

2.1. Heating of Buildings

Solar ponds have ideal use for house heating even for several cloudy days because of the large heat storage capability in the lower convective zone (LCZ) of the solar pond. The solar pond may be operated in conjunction with a heat pump. The heat pump could serve as an air conditioner in summer, the fresh water layer above the top partition, in the partitioned solar pond, could be designed to serve as a heat sink to increase the coefficient of performance of air conditioner.

2.2. Power Generation

The solar pond is ideal for electricity generation. One remarkable advantage is that its upper surface is cool due to evaporation and can be used for cooling the condenser. The heat available from salt gradient solar ponds is at temperatures of 50-100°C. Therefore, the basic element involved in electricity generation is the low-temperature turbine. Based on the nature of the turbine, two plant types are possible: flashed steam plants and binary (organic) fluid cycle plants. Commercial turbines that operate with flashed steam cycle conditions are not available. However, binary fluid cycle turbines are commercially available [3].

These turbines are similar to steam turbines and are based on the Rankine power cycle. Because of low temperature, the working fluid is an organic fluid that has low boiling point such as Halocarbons like Freon or Hydrocarbons like Propane and as a result the turbine is smaller than the corresponding steam turbine. These turbines obtain 0.4-0.7 Carnot efficiency.

2.3. Industrial Process Heating

In industrial process heating, the thermal energy is used directly in the preparation and/on treatment of materials and goods manufactured by the industry. The solar pond can play a significant role in supplying the process heat to industries, thereby, saving oil, natural gas, electricity, and coal. Any of the following industries and industrial processes may be supplied with heat from a solar pond: salt and mineral production, drying of timber, milk pasteurization, concentration and separation by evaporation, cleaning and washing in the food industry, textile processing, such as wool scouring, industrial laundry, and the paper industry for preheating.

2.4. Desalination

Multi-flash desalination unit along with a solar pond is an attractive proposition for getting distilled water because the multi-flash desalination plant works below 100°C which can be achieved by a solar pond. This system will be suitable at places where potable water is in short supply and brackish water is available. It has been estimated that about 4700 m^3/day distilled water can be obtained from a pond of 0.31 km^2 area with a multi-effect distillation unit.

3. Thermal Performance and Energy Extraction Methods

3.1. Thermal Performance

In practice, a salt gradient solar pond is a three-zone configuration. The temperature gradients are relatively large in the surface region where most of the infrared portion of the solar spectrum is absorbed; the gradient induces instabilities and results in the formation of the surface convective zone. Various processes, including wind mixing, penetrative convection, and diffusive action of salt and heat, also contribute to the formation of this zone. In normal conditions, its depth ranges between 0.2 and 0.5 m. This layer is a liability on solar pond heat collection and storage since in a pond of fixed depth the growth of the mixed surface layer takes place at the expense of the thickness of the insulating gradient layer. The mixed surface layer does not provide thermal insulation to the storage layer and absorbs a considerable portion of incident solar energy. Similarly, the excessive absorption (up to 30%) of radiation by the pond floor induces thermohydrodynamic instabilities in the bottom region and makes it convective and isothermal. The bottom convective zone provides thermal storage. A convective storage layer is therefore placed in the bottom of all modern solar ponds. The minimum depth of this zone should be 0.5m, which is sufficient to level the diurnal fluctuations in the storage zone temperature. Depths of more than 1.25 m are very effective in leveling the seasonal fluctuations, and at a depth of 10m no seasonal variation is observed. A storage layer 1.2 m deep is usually considered appropriate. The optimum depth of the nonconvective zone is a function of collection temperature, which seems to favor a depth of approximately 1.25 m for this zone. The following are typical thermal performance efficiencies of solar ponds:

Predicted: 20–30% at a collection temperature of 70–90°C

Achieved: 9-15%

3.2. Energy Extraction Methods

There are two methods of extracting heat from the lower convective zone of the solar pond. The first, which is the most commonly suggested method, is to extract the bottom layer of heated brine by using appropriate diffuser to prevent excessive velocities of motion within the pond and thereby minimizing the erosion of the gradient zone. The heat of the heated brine is removed by an external heat exchanger and the cooled brine is returned to the pond on the other end. The second method involves a heat exchanger that is placed in the lower convective zone of the pond. Its most appropriate position is just below the gradient zone, so that the heat removal can stimulate convection throughout the lower convective zone and remove heat from its entire volume. This method of heat extraction has several disadvantages. These disadvantages include large quantity of tubes are required, difficulties in locating the heat exchanger, difficult to repair, corrosion problems, etc. [4]. The amount of useful energy extracted from the solar pond depends on the design of the pond as well as on the energy collected in the storage zone of the salt gradient solar pond. The ratio of the amount of extracted heat from the salt gradient solar pond to the total solar insolation reaching the upper surface of the pond is referred to as the thermal efficiency of the pond. These methods of heat extraction are also applicable for the other types of solar ponds.

4. Thermodynamic Analysis of Solar Ponds

The rates of the absorption of the incident solar radiation and heat transfers in the three zones must be determined in order to understand the thermal performance of the solar pond. Thermodynamic models are used for the performance analysis of solar ponds through energy analysis based on the first law of thermodynamics. These works are required to be considered again for the evaluation and revival of the solar pond technology based on the second law of thermodynamics, i.e. through exergy analysis.

Exergy analysis has been found as an effective tool to design a more efficient energy system by reducing the irreversibility and inefficiency in the system as well as processes, in addition to the energy analysis. Therefore, it has become necessary to analyze the performance of solar pond through both energy and exergy analyses to achieve better efficiency and effectiveness of the system. The energy and exergy analyses are complementary thermodynamic tools. They are based on the two laws, i.e. first and second laws thermodynamics.

4.1. Energy Model: Analysis Based on the First Law of Thermodynamics

The energy efficiency of any thermal system is defined as the ratio of net energy transfer to the energy input to the system and the same may be applied to the solar pond system, i.e. [5]

$$\eta_e = \frac{Q_{net}}{Q_{in}} \tag{1}$$

The schematic diagrams of the energy flow in upper convective zone (UCZ), non-convective zone (NCZ) and heat storage zone (HSZ) of an insulated salt-gradient solar pond are illustrated in Figure 1.

4.1.1. Energy Balance Equation for the UCZ

A fraction of incident solar radiation absorbed in the UCZ is converted into heat and the heat transfer from NCZ to UCZ is added amounting to heat stored in the UCZ. The rest of the fractions of incident solar radiation associated with reflection and transmission from UCZ will not be contributing to the heating of UCZ. Therefore, energy balance equation for UCZ may be written as:

$$Q_{net,\ UCZ} = Q_{stored,\ UCZ} = Q_{in} - Q_{out} = (Q_{solar\ absorbed,\ UCZ} + Q_{down,\ from\ NCZ}) - (Q_{side,\ UCZ} + Q_{wa}) \tag{2}$$

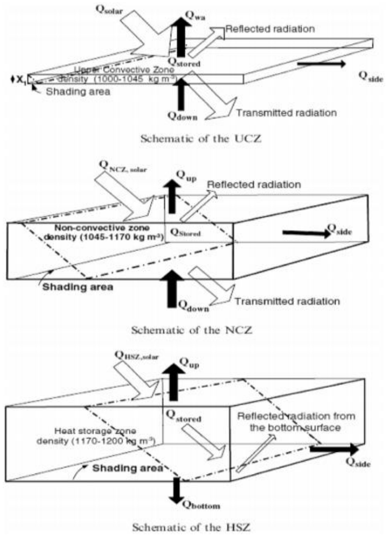

Figure 1: Schematic diagram of the energy flow in UCZ, NCZ and HSZ of an insulated salt gradient solar pond [6]

Here, $Q_{net,\ UCZ}$ is the net heat transfer through UCZ and it is stored in UCZ i.e. $Q_{stored,\ UCZ}$.

The thermal efficiency of the UCZ is written using Eqs. (1) and (2) i.e.

$$\eta_{e,\ UCZ} = \left[\frac{Q_{net}}{Q_{in}}\right]_{UCZ} = \left[1 - \frac{(Q_{side,\ UCZ} + Q_{wa})}{(Q_{solar\ absorbed,\ UCZ} + Q_{down,\ from\ NCZ})}\right] \tag{3}$$

Where, $Q_{side,\ UCZ}$ is the total heat loss to the side walls of the pond, Q_{wa} is the total heat lost to the environment from the upper surface of the UCZ, $Q_{solar\ absorbed,\ UCZ}$ is the amount of net incident solar radiation absorbed by the UCZ, and $Q_{down,\ from\ NCZ}$ is the total heat input to UCZ from NCZ on account of heat transfer from non-convective zone.

4.1.2. Energy Balance Equation for the NCZ

A fraction of the incident solar radiation on UCZ is transmitted into the NCZ. A portion of it is reflected back to the UCZ and another portion is transmitted to the HSZ. Rest of the incident solar radiation is absorbed in the NCZ due to which NCZ is heated and zone's temperature increases. Heat is also added into the NCZ due to heat transfer from HSZ. Therefore, energy balance equation for NCZ may be written as:

$$Q_{net,\ NCZ} = Q_{stored,\ NCZ} = Q_{in} - Q_{out} = (Q_{solar\ absorbed,\ NCZ} + Q_{down,\ from\ HSZ}) - (Q_{side,\ NCZ} + Q_{up\ to\ UCZ}) \tag{4}$$

The thermal efficiency of the NCZ is written using Eqs. (1) and (4) i.e.

$$\eta_{e,\ NCZ} = \left[\frac{Q_{net}}{Q_{in}}\right]_{NCZ} = \left[1 - \frac{(Q_{side,\ NCZ} + Q_{up\ to\ UCZ})}{(Q_{solar\ absorbed,\ NCZ} + Q_{down,\ from\ HSZ})}\right] \tag{5}$$

Where, $Q_{\text{up to UCZ}}$ is the heat loss from NCZ to the UCZ, $Q_{\text{solar absorbed, NCZ}}$ is the amount of solar radiation entering the NCZ which is transmitted from the UCZ after attenuation of incident solar radiation in the UCZ, and other terms are analogous to terms used in Eq. (4) with reference to NCZ.

4.1.3. Energy Balance Equation for the HSZ:
A fraction of the incident solar radiation on the solar pond is transmitted through the UCZ and NCZ, after attenuation, reaches the HSZ. A part of the transmitted solar radiation from the NCZ to the HSZ is reflected from the bottom and the greater part of the solar radiation is absorbed in the HSZ converting into the stored sensible heat. Hence, the temperature in the HSZ is increased to maximum. Therefore, energy balance equation for HSZ may be written as:

$$Q_{\text{net, HSZ}} = Q_{\text{stored, HSZ}} = Q_{\text{in}} - Q_{\text{out}} = Q_{\text{solar absorbed, HSZ}} - (Q_{\text{bottom}} + Q_{\text{side, HSZ}} + Q_{\text{up to NCZ}}) \quad (6)$$

The thermal efficiency of the HSZ is written using Eqs. (1) and (6) i.e.

$$\eta_{e,\text{ HSZ}} = \left[\frac{Q_{\text{net}}}{Q_{\text{in}}}\right]_{\text{HSZ}} = \left[1 - \frac{(Q_{\text{bottom}} + Q_{\text{side, HSZ}} + Q_{\text{up to NCZ}})}{(Q_{\text{solar absorbed, HSZ}})}\right] \quad (7)$$

Where, Q_{bottom} is the heat loss to the bottom from the heat storage zone, and other terms are analogous to terms used in Eq. (5) with reference to HSZ.

An experimental and theoretical investigation of temperature distributions in an insulated solar pond, particularly during daytime and night time, suggests that during the months of January, May and August, it is found that the total heat losses from the inner surface of the pond and its bottom and side walls, as a function of temperature difference, are determined to account for 227.76 MJ (e.g., 84.94% from the inner surface, 3.93% from the bottom and 11.13% from the side walls, respectively). A performance model developed in order to determine the thermal efficiencies of the pond and its various zones predicted that the highest thermal efficiency was obtained for August as follows: 4.5% for the UCZ, 13.8% for the NCZ and 28.1% for the HSZ, respectively. Figure 2 shows the efficiency variations of all three zones of the solar pond with respect to months.

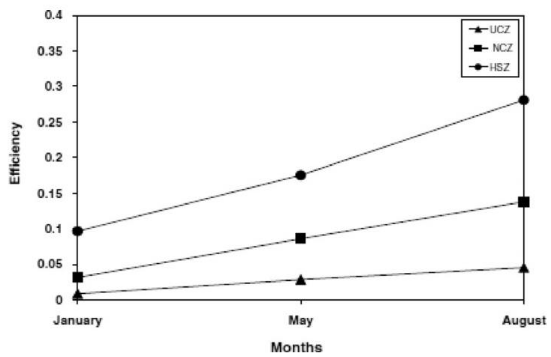

Figure 2: Variations of efficiencies of all three zones of the solar pond with respect to months [6]

4.2. Exergy Model: Analysis Based on the Second Law of Thermodynamics
The second law of thermodynamics asserts that exergy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. Exergy analysis is a technique that uses conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, optimization and improvement of the energy systems. It indicates the association of exergy losses, i.e. loss of available energy, with heat transfer processes. It allows thermodynamic evaluation of energy conservation in the energy systems because it provides the method for a clear distinction between energy losses to the environment and internal irreversibilities (i.e. exergy destruction) in the processes. Combining the conservation of law of energy and non-conservation law of exergy, a general exergy balance is expressed as [7]:

Exergy input - Exergy output (useful and losses) = Exergy accumulation + Exergy consumption or destruction (8)

One of the main objectives of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. Exergy analysis is a potential thermodynamic tool for design, analysis, evaluation, and performance improvement of solar pond systems. The exergy efficiency of a solar pond thermal system or individual zone may be defined as the ratio of desired exergy output, i.e. net exergy transfer (in case of UCZ and NCZ) as useful product or exergy accumulation (in case of heat stored in the HSZ) to the exergy input to the system or individual zone, i.e. [8]

$$\eta_{\text{ex}} = \frac{Ex_{\text{out,desired}}}{Ex_{\text{in}}} \quad (9)$$

The thermal radiation from the sun is relatively rich in exergy. The total incoming solar exergy i.e. the exergy of the solar radiation (Ex_{solar}), on the top surface of solar pond is calculated by multiplying the rate of incident solar radiation, G_s (W/m^2) by the Petela expression (Ψ_s), i.e.

$$\Psi_s = \left[1 + \frac{1}{3}\left(\frac{T_o}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_o}{T_S}\right)\right]$$

And surface area of the solar pond (A). Thus, exergy of the solar radiation in watt (W) on the top surface of solar pond is given as

$$Ex_{\text{solar}} = G_s\left[1 + \frac{1}{3}\left(\frac{T_o}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_o}{T_S}\right)\right]A \quad (10)$$

Where, T_o is the reference temperature of the environment or temperature of the dead state in Kelvin, and T_S is the sun's surface temperature taken as 6000 K.

The exergy (work potential) of heat or rate of exergy transfer accompanying heat connected to internal and external heat transfer of solar pond per unit area may be expressed by a general equation:

$$E_{X_q} = q\left(1-\frac{T_o}{T}\right) \tag{11}$$

Where, q is the rate of heat transfer (W/m^2), T is the temperature of the system in general (Kelvin), but for solar pond, T is the temperature of layers/zones and T_o is the reference temperature of the environment or temperature of te dead state (Kelvin).

In the exergy analysis of solar pond, Eq. (11) can be written as:

$$E_{X_Q} = \left[(qA)\left(1-\frac{T_o}{T}\right)\right] = \left[(Q)\left(1-\frac{T_o}{T}\right)\right] \tag{12}$$

Where E_{X_Q} is the exergy of heat transfer in W.

Exergy efficiencies of the three zones of salt-gradient solar pond can be derived and expressed based on the exergy balance equations.

4.2.1. Exergy Balance Equation for the UCZ

Input exergy to the UCZ = the exergy of solar radiation reaching the UCZ + the exergy gained from the NCZ.

Exergy losses from the UCZ = the exergy loss from UCZ to the environment + the exergy loss through side walls of the UCZ.

Exergy destruction in the UCZ = $E_{X_{Q-d,\ UCZ}}$.

If exergy accumulation in the UCZ is assumed to be negligible, then the exergy balance equation for the UCZ may be written using Eq. (8) as

$$[E_{X_{out,\ desired}}]_{UCZ} = [(E_{X_{solar}} + E_{X_{Q-g,\ NCZ}}) - (E_{X_{Q-a,\ UCZ}} + E_{X_{Q-sw,\ UCZ}}) - E_{X_{Q-d,\ UCZ}}] \tag{13}$$

Exergy efficiency of the UCZ may be written using Eqs. (9) and (13) as

$$\eta_{ex,\ UCZ} = \left[\frac{E_{X_{out,\ desired}}}{E_{X_{in}}}\right]_{UCZ} = 1 - \frac{[(E_{X_{Q-a,\ UCZ}} + E_{X_{Q-sw,\ UCZ}}) + E_{X_{Q-d,\ UCZ}}]}{(E_{X_{solar}} + E_{X_{Q-g,\ NCZ}})} \tag{14}$$

4.2.2. Exergy Balance Equation for the NCZ

Input exergy to the NCZ = the exergy coming from the UCZ to the NCZ, i.e. + the exergy gained from the HSZ.

Exergy losses from the NCZ = the exergy loss from NCZ to UCZ + the exergy loss through side walls of the NCZ.

Exergy destruction in the NCZ = $E_{X_{Q-d,\ NCZ}}$.

If exergy accumulation in the NCZ is assumed to be negligible, then the exergy balance equation for the NCZ may be written using Eq. (8) as

$$[E_{X_{out,\ desired}}]_{NCZ} = [(E_{X_{out,\ desired}})_{UCZ} + E_{X_{Q-g,\ HSZ}} - (E_{X_{Q-l,\ NCZ}} + E_{X_{Q-sw,\ NCZ}}) - E_{X_{Q-d,\ NCZ}}] \tag{15}$$

The exergy efficiency of the NCZ may be written using Eqs. (9) and (15) as

$$\eta_{ex,\ NCZ} = \left[\frac{E_{X_{out,\ desired}}}{E_{X_{in}}}\right]_{NCZ} = 1 - \frac{[(E_{X_{Q-l,\ NCZ}} + E_{X_{Q-sw,\ NCZ}}) + E_{X_{Q-d,\ NCZ}}]}{[(E_{X_{out,\ desired}})_{UCZ} + E_{X_{Q-g,\ HSZ}}]} \tag{16}$$

4.2.3. Exergy Balance Equation for the HSZ

Input exergy to the HSZ = the exergy coming from the NCZ to the HSZ.

Exergy losses from the HSZ = the exergy loss from HSZ to NCZ + the exergy loss through side walls of the HSZ + the exergy loss through bottom of HSZ.

Exergy destruction in the HSZ = $E_{X_{Q-d,\ HSZ}}$.

The exergy accumulation in the HSZ is the desired exergy output of the solar pond in the form of exergy stored in the HSZ, i.e. $(E_{X_{Q-stored,\ HSZ}})$.

Thus, the exergy balance equation for the HSZ may be written using Eq. (8) as

$$[E_{X_{out,\ desired}}]_{HSZ} = [E_{X_{Q-stored,\ HSZ}}] = [(E_{X_{out,\ desired}})_{NCZ} - (E_{X_{Q-l,\ HSZ}} + E_{X_{Q-sw,\ HSZ}} + E_{X_{Q-b,\ HSZ}}) - E_{X_{Q-d,\ HSZ}}] \tag{17}$$

The exergy efficiency of the HSZ may be written using Eqs. (9) and (17) as

$$\eta_{ex,\ HSZ} = \left[\frac{E_{X_{out,\ desired}}}{E_{X_{in}}}\right]_{HSZ} = 1 - \frac{[(E_{X_{Q-l,\ HSZ}} + E_{X_{Q-sw,\ HSZ}} + E_{X_{Q-b,\ HSZ}}) + E_{X_{Q-d,\ HSZ}}]}{[(E_{X_{out,\ desired}})_{NCZ}]} \tag{18}$$

As an example, exergy efficiencies of three zones of the solar ponds have been calculated and compared with the energy efficiencies on the basis of the energy and exergy model developed. The salt gradient solar pond has a surface area of $2 \times 2\ m^2$ and depth of 1.5 m. The highest energy and exergy efficiencies are found to be: 4.22% and 3.02% for the UCZ, 13.80% and 12.64% for the NCZ, and 28.11% and 27.45% for the HSZ, respectively in the month of August as shown in Figure 3.

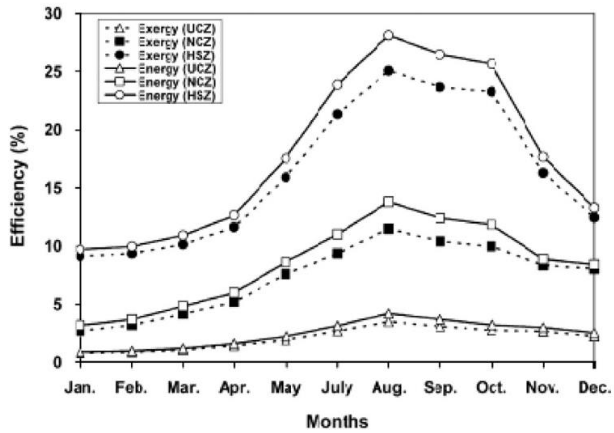

Figure 3: Variations of the energy and exergy efficiencies of the three zones of the solar pond [9]

5. Conclusions

This paper introduces the concept, applications, thermal performance, heat extraction methods and thermodynamic analysis of solar ponds. Salt gradient solar ponds are considered as the most common type of solar ponds whose applications include heating of buildings, power generation, industrial process heating and desalination. The two methods of extracting heat from the lower convective zone of the solar pond were also discussed.

The rates of the absorption of the incident solar radiation and heat transfers in the three zones must be determined in order to understand the thermal performance of the solar pond. Thermodynamic models are used for the performance analysis of solar ponds through energy analysis based on the first law of thermodynamics. These works are required to be considered again for the evaluation and revival of the solar pond technology based on the second law of thermodynamics, i.e. through exergy analysis.

Energy balance equations for the UCZ, NCZ and HSZ of a solar pond were introduced and subsequently the thermal efficiencies of these zones were presented.

Finally, a general exergy balance was introduced for each zone and the corresponding exergy efficiency was presented.

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