Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Thermal Analysis of Salt Gradient Solar Ponds with Theoretical and Experimental Concepts

M.H.Shojaeefard, K.Tafazzoli Aghvami*

*School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran. *Email: k_tafazoli@mecheng.iust.ac.ir*

ARTICLE INFO

Received: 20 Oct 2017
Received in revised form: 04 Nov 2017
Accepted: 08 Novt 2017
Available online: 13 Nov 2017

Keywords:
Renewable energy; Solar ponds; Thermal energy; Mathematical model; Thermodynamic analysis

A B S T R A C T

Renewable energy is a promising alternative to fossil fuel-based energy and is on the rise, largely to reduce dependency on limited reserves of fossil fuels and to mitigate impacts of climate change. Solar energy is an important source of renewable energy. The development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. Among such technologies, solar ponds are considered as reliable and economical means of solar energy application. A solar pond is a body of water which collects solar radiation and stores it as thermal energy for a long period of time in the form of a simple and low cost solar energy system. 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 have 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. The present article introduces solar ponds theory and applications with emphasis on salt gradient solar ponds including mathematical models describing their behavior.

1. Introduction

Renewable energy is on the rise, largely to reduce dependency on limited reserves of fossil fuels and to mitigate impacts of climate change [1]. Renewable energy replaces conventional fuels in four areas: electricity generation, hot water supply or space heating, engine fuels and off-grid energy services. The rapid deployment of renewable energy is resulting in significant energy security, climate change mitigation and economic benefits [1]. 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. It increases energy security through reliance on an indigenous resource, enhances sustainability, reduces pollution, decreases the costs of mitigating global warming. Solar technologies are characterized as either passive or active depending on the way they capture and distribute solar energy or convert it into solar power. Active techniques include the use of concentrated solar power and solar water heating to harness the energy.

Solar thermal energy is a form of energy and a technology for harnessing solar energy to generate thermal energy or electrical energy for use in industry, and in the residential and commercial sectors. Solar thermal technologies can be used for water heating, space heating, space cooling and process heat generation. Among solar thermal technologies, solar ponds are considered as reliable and economical means of solar energy application. A solar pond is a simple and low cost solar energy system which collects solar radiation and stores it as thermal energy in the same medium for a long period of time. For this reason, solar ponds attract the interest of researches in this subject more than some alternative solar energy systems. A solar pond uses a body of still water to collect solar energy and stores it as thermal energy. All lakes, oceans and ponds collect solar energy and convert it to thermal energy, but their heat retention efficiency is poor due to the occurrence of natural convection in that body of water. Therefore, such a system will be more effective and efficient in the collection and storage of solar energy if the thermal losses to the environment are reduced either by preventing the natural convection in the body of water or by covering the pond surface with a partially transparent insulation. The term solar pond as a result is used for a water pool with reduced heat losses. It can collect solar energy, concentrate and store it as heat up to approximately 100°C. The solar pond involves simple technology and uses water as working material for three functions: collection of solar radiant energy and its conversion into heat, storage of heat, and transport of thermal energy out of the system.

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. The thermal conductivity of the salt solution, which is even less than that of stagnant water, decreases with the increase of salinity and thus acts as an insulating layer [2]. The salt gradient solar ponds consist of three layers as shown in Fig. 1 [3]. The top surface layer is known as the convection zone that is a zone of constant temperature and salinity and is referred to as the upper convective zone (UCZ). The thickness of this surface layer varies from 0.1 to 0.4 m and is formed due to upward salt transport, surface heating and cooling and wave-action. The second layer is the non-convective zone (NCZ) with thickness ranges from 0.6 to 1.0 m, which acts as an insulating layer of the pond. The density in the NCZ increases with increasing depth of the gradient layer. The thickness of the gradient layer depends on the desired temperature, solar transmission properties and thermal conductance of water. The bottom or the third layer is a high temperature layer known as the lower convective zone (LCZ) and acts as the storage layer. This layer has a constant temperature and salinity as illustrated in Fig. 2 [3]. Useful heat is usually extracted from this layer; its thickness depends on the temperature and the amount of the thermal energy to be stored. A suitable salt used in the solar ponds must meet these characteristics; it must have a high value of solubility to allow high solution densities, the solubility should not vary appreciably with temperature, its solution must be environmentally benign and safe to handle and it must be available in abundance near site; so that its total delivered cost is low.

Thermal insulation in the pond bottom and sides may be used to reduce heat losses; it may speed up pond heating but at excessive cost. Pond shape is also an important consideration. Circular surface shapes provide a minimum perimeter for a given pond surface area, involve minimum heat losses to ground, and hence are thermally the most efficient. Rectangular shapes do not have this advantage but are usually less expensive to construct.

There are several types of solar ponds other than salt gradient solar ponds, such as partitioned solar ponds, viscosity stabilized solar ponds, membrane stratified solar ponds, saturated solar ponds, membrane viscosity stabilized solar ponds, and shallow solar ponds which are constructed and utilized for different purposes and applications in various regions.

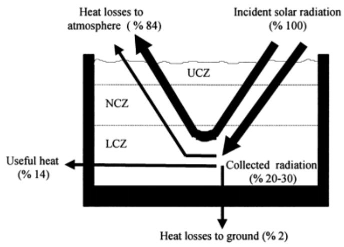

Figure 1. The salt gradient solar pond configuration [3]

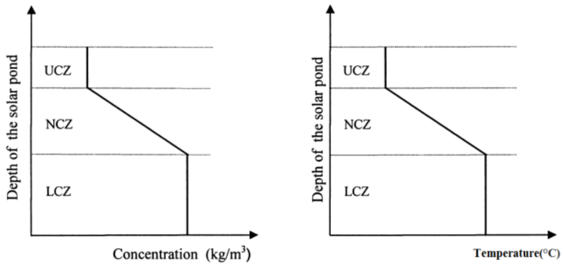

Figure 2. Schematic diagram of concentration and temperature profiles of a solar pond [3]

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 [4].

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.

Angeli and Leonardi [5] studied numerically the salt diffusion and stability of the density gradient in a solar pond using a one–dimensional transient model. They calculated the optimum thickness of gradient zone and its transient behavior, taking into account the seasonal solar radiation and the temperature of solar pond. Husain et al. [6] studied numerically the thermal behavior of solar pond. In their research, the temperature of UCZ is estimated by three different approaches. The approaches of Weinberger and Kaushik yield the same temperature while the approach of Joshi and Kishore yielded a smaller temperature. Kurt et al. [7] studied experimentally the performance of a small solar pond under simulated solar radiation from two halogen-lamps. Also, they studied numerically the transient thermal and solute behavior in one-dimensional solar pond. In their experimental results, the use of salt (sodium-carbonate) in the density gradient zone permits the storage of a great quantity of solar energy as thermal energy in the LCZ for a long period of time. Jaefarzadeh [8] studied the thermal behavior of a salinity gradient solar pond. In this research work, the sensitivity analysis shows the importance of the wall shading effect to reduce the sunny area and the temperature of the LCZ. Mansour et al. [9] studied numerically the temporal evolution of thermal and solute transfer in a three-dimensional solar pond considering the influence of the external factors (solar radiation, wind velocity, ambient temperature, etc.) on its stability characteristics. In their research work, the solar radiation has an important effect on the internal temperature and the stability of the solar pond. Husain et al. [10] proposed two simple formulations to estimate the solar radiation in a depth of a solar pond and took the universal functions of Hull as a baseline for comparison of accuracy in the estimation of solar radiation.

3. Mathematical Model for Solar Ponds

Since a solar pond is not considered as a homogenous system, the heat diffusion equations developed for homogenous systems cannot be used for a solar pond in the analysis of heat and mass transfer. For this reason, in order to understand how a pond works, mathematical modeling is required.

3.1. Heat Transfer Mathematical Model

The mathematical model developed here is based upon an energy balance over a horizontal fluid layer. Incoming energy to the layer and radiant energy absorbed by the layer equals the loss of energy from the layer and energy accumulation in the layer with time. Based upon energy conservation, the energy balance over a horizontal fluid layer of thickness *dx* is expressed as follows:

[Heat conducted in] + [Heat convecting in by fluid movement] + [Radiant energy absorbed in]

= [Heat conducted out] + [Heat convecting out by fluid movement] +

[Energy accumulation in fluid layer with time]

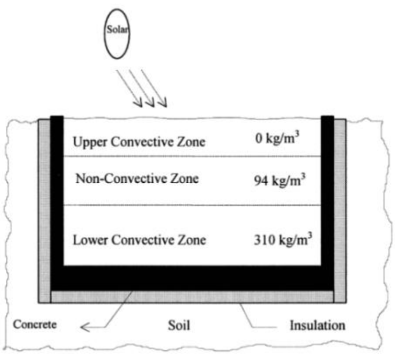

Figure 3. The physical structure of the model solar pond [3]

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 of 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., [11]

$$\eta_e = \frac{Q_{net}}{Q_{in}} \qquad (1)$$

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:

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

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

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

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, $Q_{absorbed,UCZ}$ is the amount of net incident solar radiation absorbed by the UCZ, and $Q_{down,NCZ}$ 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:

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

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

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

4.1.3. Energy Balance Equation for the HSZ

A fraction of the incident solar radiation on the solar pond which 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:

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

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

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

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 [12].

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.

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 [13]:

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., [14]

$$\eta_{ex} = \frac{Ex_{out,desired}}{Ex_{in}} \tag{9}$$

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 [15]:

$$Ex_q = q(1 - \frac{T_0}{T}) \tag{10}$$

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 efficiency of the UCZ may be written as:

$$\eta_{ex,UCZ} = \left[\frac{Ex_{out,desired}}{Ex_{in}}\right]_{UCZ} = 1 - \frac{\left[\left(Ex_{a,UCZ} + Ex_{sw,UCZ}\right) + Ex_{d,UCZ}\right]}{\left(Ex_{solar} + Ex_{g,NCZ}\right)} \tag{11}$$

4.2.2. Exergy Balance Equation for the NCZ

Input exergy to the NCZ = the exergy coming from the UCZ to the NCZ + 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.

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.

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., $Ex_{stored,HSZ}$.

Thus, the exergy balance equation for the HSZ may be written as:

$$\left[Ex_{out,desired}\right]_{HSZ} = \left[Ex_{stored,HSZ}\right] = [(Ex_{out,desired})_{NCZ} - (Ex_{l,HSZ} + Ex_{sw,HSZ} + Ex_{b,HSZ}) - Ex_{d,HSZ}] \tag{12}$$

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.

References

[1] Velmurugan, V. and Srithar, K. (2008). Prospects and scopes of solar pond: A detailed review. Renewable and Sustainable Energy Reviews, 12, 2253-2263.

[2] Bernad, F., Casas, S., Gibert, O., Akbarzadeh, A., Cortina, J. and Valderrama, C. (2013). Salinity gradient solar pond: Validation and simulation model. Journal of Solar Energy, 98, 366-374.

[3] El-Sebaii, A., Ramadan, M., Aboul-Enein, S. and Khallaf, A. (2011). History of the solar ponds: A review study. Renewable and Sustainable Energy Reviews, 15, 3319-3325.

[4] Leblanc, J., Akbarzadeh, A., Andrews, J., Lu, H. and Golding, P. (2011). Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency. Journal of Solar Energy, 85, 3103-3142.

[5] Angeli, C. and Leonardi, E. (2004). A one-dimensional study of the salt diffusion in a salinity gradient solar pond. International Journal of Heat and Mass Transfer, 47, 1–10.

[6] Husain, M., Patil, P.S., Patil, S.R. and Samdarshi, S.K. (2003). Computer simulation of salt gradient solar pond's thermal behaviour. Renewable Energy, 28, 769–802.

[7] Kurt, H., Ozkaymak, M. and Binark, A.K. (2006). Experimental and numerical analysis of sodium-carbonate salt-gradient solar pond performance under simulated solar radiation. Applied Energy, 83, 324–342.

[8] Jaefarzadeh, M.R. (2004). Thermal behavior of a small salinity-gradient solar pond with wall shading effect. Solar Energy, 77, 281–290.

[9] Mansour, R.B., Nguyen, C.T. and Galanis, N. (2004). Numerical study of transient heat and mass transfer and stability in a salt-gradient solar pond. International Journal of Thermal Sciences, 43, 779–790.

[10] Husain, M., Patil, P.S., Patil, S.R. and Samdarshi, S.K. (2004). Simple methods for estimation of radiation flux in solar ponds. Energy Conversion and Management, 45, 303–314.

[11] Bejan, A. (2006). Advanced engineering thermodynamics. (New Jersey: John Wiley & Sons)

[12] Karakilcik, M., Dincer, I. and Rosen, M. (2006). Performance investigation of a solar pond. Applied thermal engineering, 26. 727-735.

[13] Dincer, I. and Rosen, M. (2007). Exergy: energy, environment and sustainable development. (UK: Elsevier LTD)

[14] Petela, R. (2010). Engineering thermodynamics of th ermal radiation: for solar power utilization. (New York: McGraw-Hill Companies)

[15] Karakilcik, M. and Dincer, I. (2008). Exergetic performance analysis of a solar pond. International journal of thermal science, 47, 93–102.