Chapter 18
Investigation of Heat Storage Performance of a Solar Pond with Potassium Chloride

Mehmet Karakilcik, Ismail Bozkurt, Ilker Balkaya, and Ibrahim Dincer

Abstract This chapter concerns an experimental investigation of heat storage performance of a solar pond saturated with potassium chloride. The solar pond consists of potassium chloride water zones. The heat storage zone (HSZ) is formed as saturated brine with potassium chloride to collect and storage reaching the solar radiation. The gradient zone (GZ) is called non-convective zone (NCZ) with various density layers prepared with potassium chloride brine decreasing from HSZ to upper convective zone (UCZ). The layers consist of five different concentrations with a thickness of 10 cm each. These layers form a brine gradient to prevent heat transfer by convection from HSZ and brine layers to UCZ. The brine gradient layers act as an insulator between HSZ and UCZ. UCZ is a clean water layer. Solar radiation is especially absorbed by saturated brine zone through UCZ and NCZ. The mass capacity of the HSZ is approximately 430 kg. The measurements of the temperatures and densities of the layers are obtained by using thermocouples and hydrometers from August to November. The exergy efficiency of saturated potassium chloride brine is defined in terms of heat storage capacity of saturated brine and average representative solar energy. As a result, the maximum and minimum exergy efficiencies of the HSZ are obtained as 25.33 % in August and 9.77 % in November, respectively.

Keywords Energy • Exergy • Efficiency • Potassium chloride solar pond

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M. Karakilcik (✉) • I. Balkaya
Department of Physics, Faculty of Sciences and Letters, University of Cukurova, Adana 01330, Turkey
e-mail: kkilcik@cu.edu.tr

I. Bozkurt
Department of Mechanical Engineering, Faculty of Engineering, University of Adiyaman, Adiyaman 02040, Turkey

I. Dincer
Clean Energy Research Laboratory (CERL), Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (UOIT), 2000 Simcoe Street, North Oshawa, ON, Canada L1H 7K4

I. Dincer et al. (eds.), *Progress in Clean Energy, Volume 2*,
DOI 10.1007/978-3-319-17031-2_18

Nomenclature

A	Surface area, m^2
C	Specific heat, J/kg K
E	Total solar energy reaching to the pond, MJ/m^2
Ex	Exergy, J
F	Absorbed energy fraction at a region of δ-thickness
h	Solar radiation ratio
HSZ	Heat storage zone
m	Mass, kg
NCZ	Non-convective zone
S	Entropy, J/K
s	Salinity
T	Temperature, °C
UCZ	Upper convective zone
V	Volume, m^3

Greek Letters

δ	Thickness where long-wave solar energy is absorbed, m
β	Incident beam entering rate into water
θ	Angle
ρ	Density, kg/m^3
ψ	Exergy efficiency

Subscripts

d	Destruction
g	Gain
i	Incident
l	Loss
r	Refraction
rec	Recovered
side	Side wall
surr	Surrounding
sys	System

18.1 Introduction

Solar energy is the most important source of renewable energy in Turkey. There are many potential applications of solar energy, including solar ponds. A solar pond is an integral device for collecting and storing solar energy; by virtue of having built in thermal energy storage, it can be used irrespective of time and season [1]. Recently, there has been increasing interest in environmentally solar energy. In this regard, solar ponds receive some increasing attention for implementation. Bozkurt and Karakilcik [2] investigated heat storage performance of integrated solar pond and collector system. The integrated solar pond efficiencies were calculated experimentally and theoretically according to the number of collectors. Karakilcik et al. [3] presented an experimental investigation of the exergetic performance of a solar pond integrated with solar collectors. The energy efficiencies are compared with the corresponding exergy efficiencies. Karakilcik et al. [4] investigated an experimental investigation of energy distribution, energy efficiency, and ratios of the energy efficiency with respect to shading effect on each zone of a small rectangular solar pond. Bozkurt et al. [5] studied the effect of the transparent covers (glass, polycarbonate, and mica) on the small cylindrical solar pond performance. Sodium chloride salt has been used in most of these studies. In few studies, however, magnesium chloride salt has been used [e.g., 6–8]. The performance of the solar ponds is changed with its construction parameters. So, many parameters such as dimensions, materials (e.g., NaCl, MgCl) for concentration and transmission of the layers, inner and outer insulations, collection and storing capacity, material climatic conditions, and location of the pond effect on the performance. Therefore, many studied are conducted on the better parameters in order to improve the performance of the solar pond. Hence, some experimental and theoretical studies dealing with solar ponds for different salty waters were done [9].

In this study, a new experimental work is carried out with a small potassium chloride solar pond. The exergy analysis of potassium chloride solar pond has not yet been studied anywhere. Therefore, this study is the first work in the area dealing with the investigation of exergetic performance analysis of saturated potassium chloride brine solar pond. For this purpose, the small solar pond was filled with potassium chloride salty water in order to build the HSZ and layers from bottom to up. Some thermophysical properties of potassium chloride salt water (e.g., thermal conductivity, concentration, and heat capacity) are investigated and calculated to use in performing exergy analysis.

18.2 Experimental Apparatus and Procedure

A solar pond generally consists of three zones. The surface zone is called as upper convective zone (UCZ). UCZ is the freshwater layer at the top of the pond. The middle zone is called as non-convective zone (NCZ). NCZ is composed of

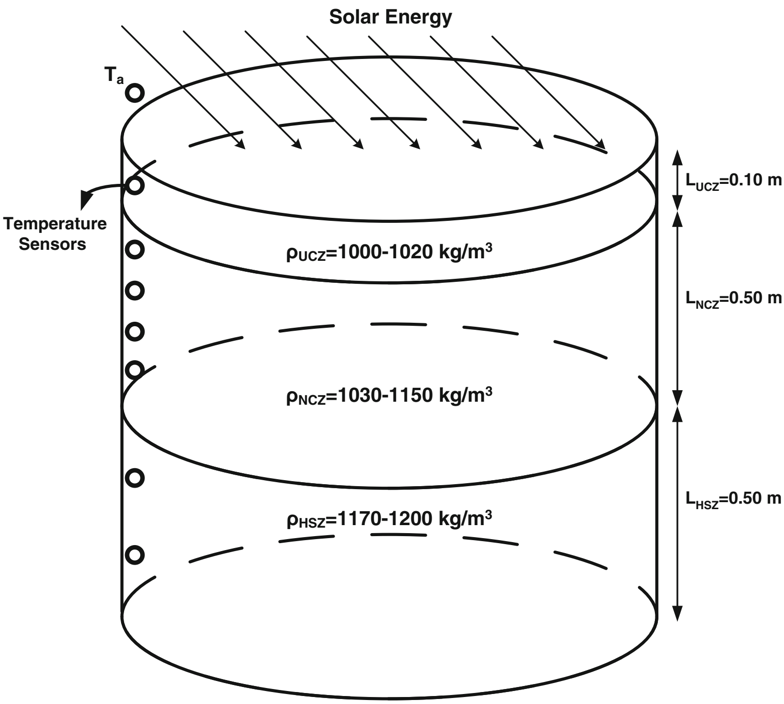

Fig. 18.1 A schematic representation of the potassium chloride solar pond

salty water layers whose brine density gradually increases toward the bottom of the pond. This zone plays a key role in the solar pond because this zone constitutes a transparent insulating layer to prevent convection heat losses. Solar radiation that reaches the bottom of the pond is absorbed by heat storage zone (HSZ) which is composed of salty water with highest density. An experimental model solar pond with the area of 0.72 m^2 and a depth of 1.10 m was built in Cukurova University in Adana, Turkey (i.e., 35°18′ E longitude, 37°05′ N latitude). Figure 18.1 shows a schematic representation of the experimental solar pond system by using potassium chloride salt.

The pond's bottom and side wall was insulated by using 0.10 m thickness glass wool. The pond temperature was measured at 7 points, starting from the bottom, at 0.25, 0.40, 0.55, 0.65, 0.75, 0.85, and 1.05 m heights by using thermocouples with an accuracy of about ±1 °C. The density distributions are also measured and analyzed by taking samples from the same point of the temperature sensors. The pond was filled in August 2013 and worked. The thicknesses of the UCZ, NCZ, and HSZ are 0.10 m, 0.50 m, and 0.50 m, respectively. The range of salt density in the zones is 1,000–1,020 kg/m^3 in UCZ, 1,030–1,150 kg/m^3 in NCZ, and 1,170–1,200 kg/m^3 in HSZ.

18.3 Exergy Analysis

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of systems and processes [10]. The exergy analysis of solar thermal energy systems is usually used to determine exergy efficiencies and identify and quantify exergy destructions so that directions for improved efficiency can be determined. One of these thermal energy systems is solar pond. It describes solar pond system and their components (e.g., size and construction material and its thermophysics and thermodynamic properties of the pond) and discusses the use of exergy analysis to assess and improve solar pond systems. Exergy methods provide a physical basis for understanding, refining, and predicting the variations in solar pond's zone behavior.

This study describes a method of exergy analyzing the quality work of the solar ponds on the basis of exergy dynamics that is related to the efficiency with which a system performance itself, and if steady, maintains its complexity. Once the exergy ratio has been calculated, it would then be possible to understand what the performance of the system is. Thus the exergy ratio can indicate the role of the performance in time. Furthermore, valuations of the exergy ratio at different times can give further indications on the behavior of the system. If the value of the ratio is increasing the system will move toward forms with lower thermodynamic efficiency, due to environmental factors like reference temperature and climatic changes. In contrast, if it is decreasing, the system is moving toward an efficient use of the available resources [11].

In this study, we focus on to improve the capacity of HSZ by using saturated brine with potassium chloride because of useful heat energy to be stored in this zone of the pond.

The exergy balance equation for HSZ of the pond can be written as

$$\begin{aligned}\Delta \mathrm{Ex}_{\mathrm{stored}} &= \mathrm{Ex}_{\mathrm{rec,NCZ}} - (\mathrm{Ex}_{\mathrm{d,HSZ}} + \mathrm{Ex}_{\mathrm{l,HSZ}} + \mathrm{Ex}_{\mathrm{side,HSZ}} + \mathrm{Ex}_{\mathrm{down,HSZ}}) \\ &= \beta \mathrm{Ex}_{\mathrm{solar}} A_{\mathrm{HSZ}}[(1-F)h(x-\delta)] - \\ &\left\{ \begin{array}{c} T_0(\Delta S_{\mathrm{net,HSZ}}) + m_{\mathrm{HSZ}} C_{\mathrm{p,HSZ}} \left[(T_{\mathrm{HSZ}} - T_{\mathrm{m,NCZ}}) - T_0 \ln\left(\dfrac{T_{\mathrm{HSZ}}}{T_{\mathrm{m,NCZ}}} \right) \right] \\ + m_{\mathrm{HSZ}} C_{\mathrm{p,HSZ}} \left[(T_{\mathrm{HSZ}} - T_{\mathrm{side,HSZ}}) - T_0 \ln\left(\dfrac{T_{\mathrm{HSZ}}}{T_{\mathrm{side,HSZ}}} \right) \right] \\ + m_{\mathrm{HSZ}} C_{\mathrm{p,HSZ}} \left[(T_{\mathrm{HSZ}} - T_{\mathrm{down,HSZ}}) - T_0 \ln\left(\dfrac{T_{\mathrm{HSZ}}}{T_{\mathrm{down,HSZ}}} \right) \right] \end{array} \right\}\end{aligned} \tag{18.1}$$

where $\Delta \mathrm{Ex}_{\mathrm{stored}}$ is the exergy stored in HSZ, $\mathrm{Ex}_{\mathrm{rec,NCZ}}$ is the recovered exergy from NCZ to HSZ, $\mathrm{Ex}_{\mathrm{d,HSZ}}$ is the exergy destruction in HSZ, $\mathrm{Ex}_{\mathrm{l,HSZ}}$ is the exergy loss from HSZ to NCZ, and $\mathrm{Ex}_{\mathrm{side,HSZ}}$ is the exergy loss through side walls. $\mathrm{Ex}_{\mathrm{down,HSZ}}$

is the exergy loss through bottom wall, and ΔEx_{stored} is the exergy stored in HSZ. β is the fraction of the incident solar radiation that actually enters the pond and is given by Hawlader [12] as follows:

$$\beta = 1 - 0.6\left[\frac{\sin\theta_i - \sin\theta_r}{\sin\theta_i + \sin\theta_r}\right]^2 - 0.4\left[\frac{\tan\theta_i - \tan\theta_r}{\tan\theta_i + \tan\theta_r}\right]^2 \tag{18.2}$$

Here, θ_i and θ_r are the incidence and refraction angles. h represents the ratio of the solar energy reaching the depth in the layer I to the total solar incident falling on to the surface of the pond and is given by Bryant and Colbeck [13] as

$$h = 0.727 - 0.056\ln\left[\frac{(x_I - \delta)}{\cos\theta_r}\right] \tag{18.3}$$

where x_I is the thickness of the layer, and δ thickness of the layer in the UCZ where long-wave solar energy is absorbed. The exergy of solar radiation can be expressed by Petela [14]:

$$Ex_{solar} = E_{net}\left\{1 - \frac{4T_0}{3T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4\right\} \tag{18.4}$$

where E_{net} is the net incident solar radiation reaching the surface of HSZ. As seen in Eq. (18.1), $\Delta S_{net,HSZ}$ is the net entropy change for HSZ of the pond which is defined as $\Delta S_{net,HSZ} = \Delta S_{sys} + \Delta S_{surr}$. The exergy destruction within HSZ can be written as

$$Ex_{d,HSZ} = T_0\left[m_{HSZ}C_{p,HSZ}\ln\left(\frac{T_{HSZ}}{T_0}\right) - \left(\frac{Q_{g,HSZ}}{T_{HSZ}} + \frac{Q_{side,HSZ}}{T_0}\right) + \left(\frac{Q_{down}}{T_0}\right)\right] \tag{18.5}$$

where $m_{HSZ} = \rho_{HSZ}V_{HSZ}$ is the mass of potassium chloride salty water in HSZ, ρ_{HSZ} is the averaged density of HSZ, and V_{HSZ} is the volume of HSZ. T_0 is the reference air temperature; T_{HSZ} is the temperature of HSZ. $Q_{g,HSZ}$, $Q_{side,HSZ}$, and Q_{down} are the gain and heat losses from side and bottom wall, respectively. $C_{p,HSZ}$ is the specific heat capacity of potassium chloride salt water in HSZ. The specific heat capacity is calculated by using an empirical equation [15]:

$$C_{p,HSZ} = (-0.0044s_{HSZ} + 4.1569)10^3 \tag{18.6}$$

where s_{HSZ} is the salinity of potassium chloride salty water. The density difference at low temperature takes place approximately in linear relationship between the density and salinity. We use an empirical correlation as given below to determine the salinity of the saturated brine zones:

$$s_{HSZ} = \frac{(\rho_{HSZ} - 998.24)}{0.756} \tag{18.7}$$

The exergy efficiency is written for HSZ as follows:

$$\psi_{HSZ} = \frac{\Delta Ex_{stored}}{Ex_{r,NCZ}} = 1 - \frac{(Ex_{d,HSZ} + Ex_{l,HSZ} + Ex_{side,HSZ} + Ex_{down,HSZ})}{Ex_{r,NCZ}} \tag{18.8}$$

18.4 Results and Discussion

The performance of the solar pond depends not only on thermal energy flows (e.g., heat losses and/or heat gains in the zones), but also on incoming solar radiation (e.g., accounting for reflection, transmission, and absorption) and insulating by better insulator material, both inner gradient layer and side walls [4]. Moreover, properties of the saturated brine with potassium chloride can affect the performance of small solar ponds (Fig. 18.1). In this study, we present the results of the experimental calculations for exergy efficiencies of HSZ of an experimental potassium chloride solar pond. These results show how thermophysical properties are crucial for absorbing and storing capacity of the performance effect of HSZ of the pond.

Here we now present the results of the exergy efficiency of potassium chloride solar pond. It has been demonstrated that the stability of the salt density distributions in a solar pond is of great significance. Figure 18.2 shows the variation of the experimental salty solution densities with height from bottom to surface of the pond, throughout the 4 months. As seen in Fig. 18.2, the density distribution is kept approximately.

The average experimental temperature distributions are shown in Fig. 18.3. As seen here, the average temperature of HSZ is observed to be a maximum of 53.21 °C in August, and a minimum of 27.17 °C in November. The temperature of the solar pond increases toward the bottom like the density distribution. The average temperature of UCZ closes to the ambient temperature because this zone is surface zone.

Figure 18.4 shows both average energy and exergy distribution during 4 months. As seen in Fig. 18.4, the minimum energy and exergy content were observed as 298.11 MJ/m^2 and 279.03 MJ/m^2 in November, respectively. The maximum energy and exergy content were observed as 629.95 MJ/m^2 and 587.71 MJ/m^2 in August, respectively.

Figure 18.5 shows the variation of the exergy input, exergy stored, and destruction and losses taking place in the HSZ of potassium chloride solar pond during 4 months. As obviously seen here, the exergy inputs are equivalent to the summation of exergy stored and exergy destruction and losses. The exergy stored in HSZ appears to be maximum as 27.08 MJ in August and minimum as 5.02 MJ in November.

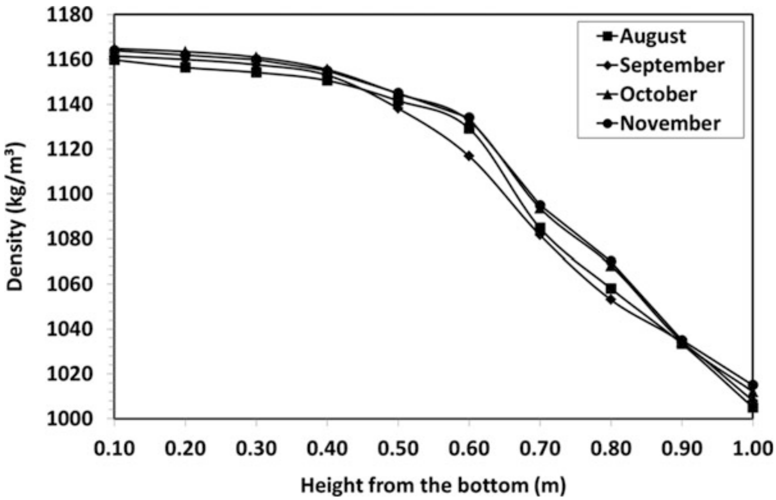

Fig. 18.2 Density distributions of potassium chloride in the solar pond

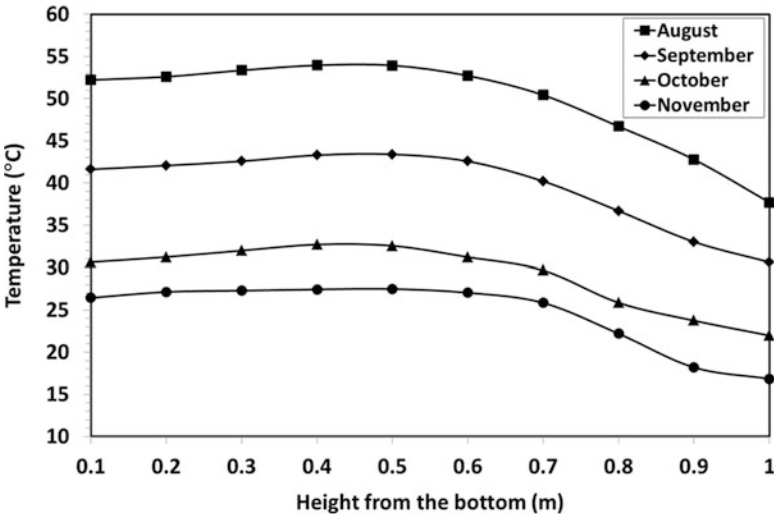

Fig. 18.3 Temperature distributions of potassium chloride in the solar pond

The exergy efficiency variations are given in Fig. 18.6 and the maximum and the minimum exergy efficiencies of HSZ are observed in August as 25.33 % and 9.77 % in November, respectively. The exergy analysis takes into account the true magnitudes of the destructions and losses and these should be minimized for performance improvement of the solar pond.

The results have been found for the potassium chloride solar pond for August, September, October, and November. The exergy efficiency is determined for HSZ

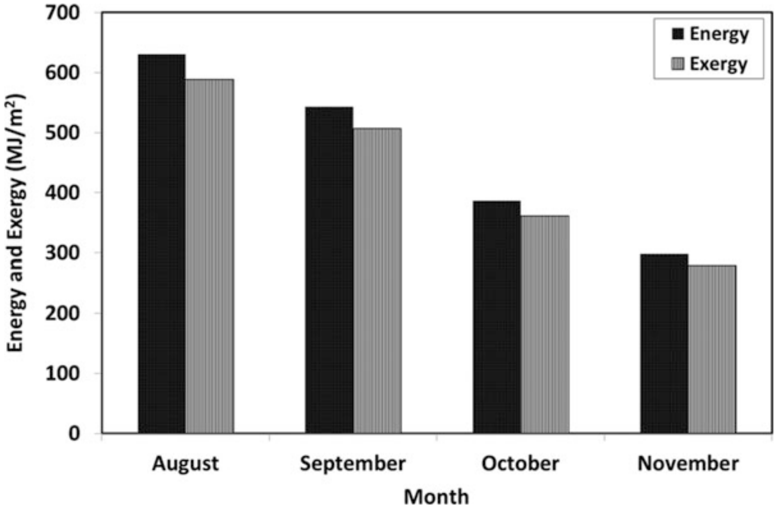

Fig. 18.4 Energy and exergy variations of the solar energy in Adana, Turkey

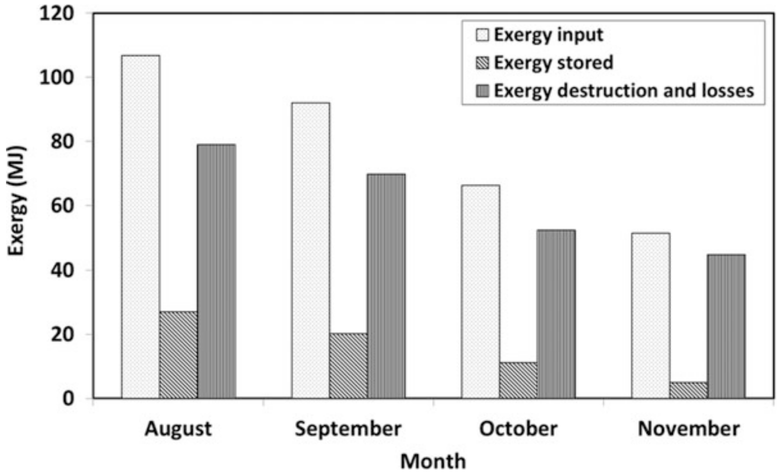

Fig. 18.5 Variations of the exergy input, storage, destruction, and losses of HSZ of the solar pond

of the pond. As seen in Fig. 18.6, the maximum exergetic efficiencies are obtained in August, and the minimum efficiencies in November although the greatest amount of thermal energy has been stored in August than in November. This is because of the decreasing incident radiation to per square meter of the pond's surface and the fact that it is responsible for the largest heat losses from HSZ by decreasing the environment temperature in November.

The temperature distribution profiles (in Fig. 18.3) for the inner zones are usually different, causing the zone's exergy efficiencies to also differ. The temperature

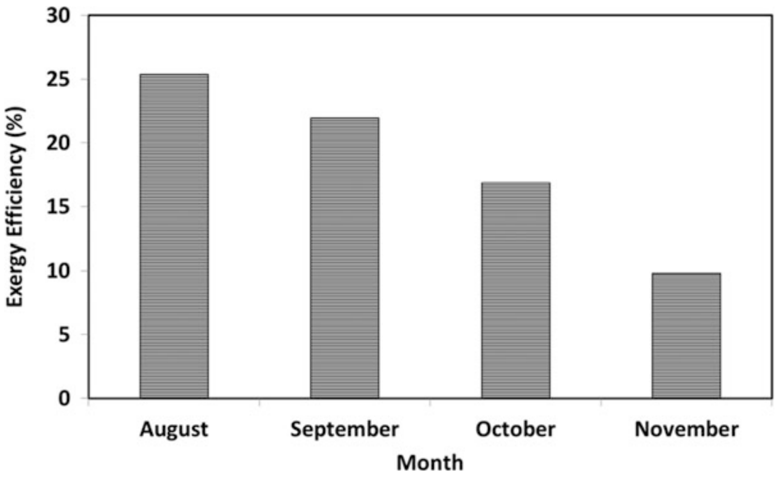

Fig. 18.6 Exergy efficiencies of HSZ in the solar pond

distributions, thus, have an important effect on the performance of the pond. The energy efficiency of the pond is decreased because of thermal energy losses due to heat transfer from the surface of the pond to air. The gradient zone's efficiency consequently has a greater effect on the performance of the HSZ. Most of the energy is stored in the HSZ of the pond. As seen in Fig. 18.5, HSZ has higher capacity to store thermal energy since this zone is insulated by gradient zone and insulated side walls. This zone plays a key role in the improvement of storage performance of the solar pond. As a result, the inner regions of the pond store more thermal energy in August than in November due to the considerable temperature differences between the zones. Not only heat losses affect the exergy efficiencies of the HSZ but also shading areas in the zones by side walls affect the storage performance. We thus suggest that heat storage, heat losses, shading areas, and solar radiation absorption should be carefully considered when determining the thermal performance of solar ponds. In the future studies, if the tilt angle of the side walls and better thermodynamic properties of the salty water of the solar ponds are selected appropriately, it can obtain much more efficiency by eliminating the shading effect of the walls and increasing the heat capacity and protecting the heat energy in the HSZ.

18.5 Conclusions

In this study, we carried out experiment in potassium chloride solar pond to see its effect on the exergy efficiency of the gradient zone in order to demonstrate the effect of saturated brine HSZ on the thermal performance of the solar pond. The temperature of each zone depends on the incident radiation, concentration, conduction and zone thicknesses, shaded surface area of the zones, and heat losses from upper surface area, bottom wall, and side walls. So, to increase the performance of the pond, the zone thicknesses should be modified to achieve higher efficiency and stability of the pond. Through careful design and thermodynamic parameter modifications, pond performance can be maintained even if the incoming solar radiation reaching and storing in the HSZ. Experimental data are used to determine the efficiency for HSZ for a real insulated solar pond. Several parameters of the pond having influences on the thermal performance are discussed. It is shown that the introduction of the other two zones (upper and non-convective zones) provides many conveniences in calculating the storage efficiency in the HSZ, and in determining the relations between heat loads and a best operating state. Therefore, the exergy efficiency of the HSZ of a solar pond is an important parameter in practical applications. Exergy efficiencies of the HSZ decreased from August to November due to the decreasing ratio of solar radiation reaching the pond. Also, while environmental temperature decreases surrounding the pond, the heat losses increase from HSZ to the air. It is important to determine the true magnitudes of these losses for performance improvement studies of HSZ. The results demonstrate the effect of the potassium gradient layers (gradient zone) as an insulation zone and materials and ambient temperature on the efficiency of the pond. It is important that exergy is a potential to help achieve better efficiency of the pond.

Acknowledgement The authors are thankful to University of Cukurova for financial support of this work (Grant No. FEF2012YL12).

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