Solar Energy 158 (2017) 311–320

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Assessment of the overall energy and exergy efficiencies of the salinity gradient solar pond with shading effect

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ARTICLE INFO

Keywords:
Solar energy
Salinity gradient solar pond
Energy analysis
Exergy analysis
Shading effect

ABSTRACT

In this paper, the energy and exergy distributions and efficiencies in the square solar ponds have been investigated numerically and experimentally. For this purpose, a small scale solar pond with square cross-section was built and tested at Urmia University in Urmia-Iran with a height and area of 1.1 m and 4 m^2, respectively. In the small solar ponds, shading by the side walls affects the accumulation of solar energy and thermal energy storage. Therefore, a shading model is also developed for achieving a complete understanding of the energy performance of the small solar ponds. So, by using the proper relations and considering the shading effect, energy and exergy efficiencies were analyzed in the pond. Maximum energy efficiency of the pond with and without shading effect were 3.27% and 3.65%, respectively, the values for maximum exergy efficiencies were also 0.19% and 0.27%, respectively. The results confirmed that by applying the correct relations for energy and exergy efficiencies, the ponds' performance can be properly investigated.

1. Introduction

Comparing with the commonly used energies, solar energy provides attractive benefits like inexhaustibility, cleanness and inexpensiveness (Sukhatme and Sukhatme, 1996). Solar energy is an important source of renewable energy, which has not yet been commercialized even in industrial countries. A major limitation in using the solar energy is the cyclic nature and time-dependency of the solar energy (Mekhilef et al., 2011). Therefore, solar-based energy systems are required to store energy for no radiation periods. Solar ponds are such storage systems.

Solar pond is a collector that generates low temperature heat at a low cost (Swift et al., 1987). The basic principles and implementation of solar ponds are simple; also the construction and maintenance costs are low. In solar ponds, collecting and storing the heat is done in one unit and the efficiency essentially depends on the storage capacity and thermophysical properties of the pond fluid and its environment.

There are two general types of solar ponds, convecting shallow ponds and non-convecting deep ponds (El-Sebaii et al., 2011). In the first group, the system is consisted of a low depth basin (usually few centimeters). In the second group, the natural convection should be prevented in order to store thermal energy. The most important type of non-convecting ponds is the salinity gradient solar pond (SGSP).

A salinity gradient solar pond (SGSP) simply uses a large body of salty water as a medium for collecting and storing heat from the sun (Munoz and Almanza, 1992). Physically, it is consisted of three different layers as shown in Fig. 1. The cold, thin upper layer is known as the upper convective zone (UCZ) and contains low salinity water (2–3% saline) and its temperature follows the daily average ambient temperature. The second layer is the gradient layer known as the non-convective zone (NCZ), where salinity increases from the top of NCZ to the bottom of the NCZ. The associated density gradient helps to suppress heat loss by natural convection. The bottom layer or lower convective zone (LCZ) has homogenous high salinity water, which absorbs and stores the solar thermal energy in the form of radiation.

In recent decades, in order to understand the functioning mechanism of solar ponds, numerous theoretical and experimental studies have been performed on their performances (Farahbod et al., 2013; Wu et al., 2013; Nie et al., 2011; Sakhrieh and Al-Salaymeh, 2013; Wang et al., 2014; Nakoa et al., 2015). However, many important problems such as the conversion efficiency of solar to thermal energy, heat exchanges between each zone and heat losses from the pond are the most important research areas to be dealt with from the thermodynamic point of view. To assess the thermal performance of the solar ponds, several thermodynamic models were developed based on the energy conservation principle, i.e., first law of thermodynamics (Shah et al., 1981; Ali, 1989, 1986; Chiasson et al., 2000; Sayer et al., 2016; Ding et al., 2016). In this regard, exergy analysis based on the second law of thermodynamics is beneficial, providing a useful tool for the energy analysis, as well as for designing more efficient energy system by minimal irreversibility in the system and processes. Moreover, the energy and exergy analyses are complementary thermodynamic tools. A number of studies focused on the energy performance analysis of solar

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http://dx.doi.org/10.1016/j.solener.2017.09.059
Received 2 April 2017; Received in revised form 31 August 2017; Accepted 26 September 2017

Nomenclature

UCZ	upper convective zone
NCZ	non-convective zone
LCZ	lower convective zone
Q_{solar}	the radiation energy reaching and absorbing in each zone (W/m^2)
Q_{cond}	conductive heat transfer (W/m^2)
A	total surface area of the layer (m^2)
A_e	the sunny or effective radiation area
A_{sh}	the shaded area
C_p	heat capacity of water (kJ/kg K)
k	thermal conductivity of water (W/m K)
m	mass of the pond water (kg)
I	solar radiation reaching the pond surface (W/m^2)
I_0	solar radiation entering to the pond surface (W/m^2)
$h(x)$	fraction of solar radiation that reaches a depth x (W/m^2)
R	reflection coefficient
E	energy (W)
L	length of a rectangular pond
W	width of a rectangular pond
l'	the shade length of a pond (m)
X_{ucz}	thickness of the UCZ layer (m)
X_{ncz}	thickness of the NCZ layer (m)
X_{lcz}	thickness of the LCZ layer (m)
x	depth in solar ponds (m)
T	temperature (K)
T_0	atmospheric temperature (K)
T_{sun}	sun's surface temperature (K)
t	time (s)
n	index of refraction

Greek letters

η_{en}	energy efficiency
η_{ex}	exergy efficiency
Ξ	exergy (W)
θ_i	angle of incidence
θ_r	angle of refraction
θ_v	angle of incidence of beam radiation with normal to a vertical plane
ρ	density (kg/m^3)
$\Delta\tau$	time intervals
ξ	the fraction of beam radiation
δ	the angle of declination
ϕ	the angle of latitude
ω	the hour angle
γ	surface azimuth angle
Ψ	Petela expression

ponds to provide a better understanding of the heat transfer process (Rubin et al., 1984; El-Sebaii et al., 2013; Date et al., 2013).

Several researchers defined pond thermal efficiency as the ratio of energy stored in LCZ layer to the solar energy entered to the pond surface (Tahat et al., 2000; Alcaraz et al., 2016). While some others believed that the pond thermal efficiency can be defined as the ratio of energy stored in LCZ to solar energy entered to the LCZ surface (Kurt and Ozkaymak, 2006). Karakilcik et al. (2006) defined energy efficiency for the various zones of pond and investigated the values in different months of the year. Unfortunately, in reviewing the efficiency of solar ponds, no comprehensive, accurate definition has been found for energy efficiency, also it was figured that sometimes incorrect equations were used for energy and exergy efficiencies (Khalilian, 2016a,b).

Many studies have focused on the exergy analysis of the thermal power plants and other engineering heating systems (Dincer and Rosen, 2011); however applying exergy analysis for solar energy applications, particularly solar ponds, is still in the early stages of research. To the best of our knowledge, only a few cases have been investigated in the exergetic efficiency of solar ponds and, unfortunately, as mentioned before, some improper relations were used in those papers (Dincer and Rosen, 2011). Although the wall shading effects could be neglected in analyzing the large solar ponds, in the small solar ponds, wall shading

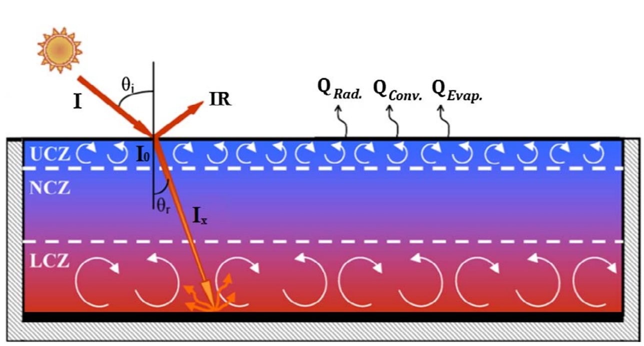

Fig. 1. Schematic view of the solar pond showing the distribution of the three zones (modified from Boudhiaf et al., 2012).

plays an important role in reducing the effective surface of radiation and heat energy storage. Several studies by different researchers have investigated the effect of wall shading on the performance of solar ponds (Jaefarzadeh, 2004; Assari et al., 2015).

Considering the above-mentioned explanations, proper relations and correct definitions for energy and exergy efficiencies should be presented and used. Therefore, in this paper, we aim to introduce and apply the proper relations for analyzing the energy and exergy efficiencies of solar ponds in order to prevent further mistakes in this field. Also, it should be noted that the shading effect is considered in the efficiency analysis.

2. Experimental setup

An experimental, small scale solar pond with square cross-section was built in Urmia University of Iran with a height and area of 1.1 m and 4 m^2, respectively. A scheme of the experimental set-up is shown in Fig. 2. This pond was constructed from 1.5 mm galvanized metal sheet. The inside of the pond was painted black to ensure absorption of radiation, while the outside was insulated with 0.20 m thick glass-wool to reduce the heat loss towards the surrounding environment. The injection filling technique described by Zangrando (1980) was used to establish the salinity gradient. The LCZ was filled with salt water until 0.40 m height having a concentration of 300 g/l. The NCZ with a thickness of 0.50 m, was filled with salt water with increasing densities toward LCZ. The UCZ was filled with fresh water with a thickness of 0.20 m.

The evolving state of the solar pond is measured regularly including specific gravity, pH, turbidity and temperature. Reliable instruments and monitoring procedures are used for successful measuring of these properties. To measure the temperature of pond zones, several thermocouples with measuring accuracy ranges of ± 1 °C were installed at 5, 10–110 cm with 10 cm distance from the lower to upper end of the pond. A data-logger recorded the data of the thermocouples every ten minute in an external memory.

The salinity gradient of the solar pond was measured as a function of depth on a regular basis over a period of one year from Jan 2016 to Jan 2017. Fig. 3 illustrates the salinity distribution along the depth in