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Energetic performance analysis of solar pond with and without shading effect

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ABSTRACT

Solar ponds are one of the innovative technologies in the field of utilizing solar energy and have attracted much attention as storage for the thermal energy, in recent years. In this paper, numerical and experimental studies have been conducted for investigating the energy distributions and also efficiencies in the inner zones of a square solar pond. For this purpose, a small scale solar pond with a square cross-section was built and tested in Urmia University in Urmia-Iran. The height and area of the solar pond were equal to 1.1 m and 4 m^2, respectively. In the small solar ponds, the shading by the side walls affects the accumulation of solar energy and thermal energy storage. Therefore, for achieving a complete understanding of the energy performance in the small solar ponds, a shading model is also used for square solar ponds. Therefore, by using the proper relations, energy efficiencies of the inner zones with and without the shading effect were analyzed. For lower convective zone, the highest energy efficiencies for the cases with and without shading area are in July and were equal to 9.32% and 6.57%, respectively. The results confirm that applying the correct format of equations in calculating the energy efficiency of the ponds would lead to reasonable results.

1. Introduction

According to the shortage of fossil energy resources and increasing demand for power generation due to population growth and economical development of many countries, using renewable energy sources is seem to be the only solution (Sukhatme, 1996). Solar energy can be controlled to satisfy the energy needs for a sustainable future.

Several technologies have been proposed for converting the solar thermal energy to the useful energy. However, it should be noted that solar energy is a discrete and time-dependent source of energy; therefore, storing and using this source of energy are the important challenges (Mekhilef et al., 2011). So it is required to construct and use combined low-cost systems that collect and store the thermal solar energy. Solar pond is a low-cost thermal collector, which is able to store the solar thermal energy for a long time (Swift et al., 1987).

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 in pond. The most important type of non-convecting ponds is the salinity gradient solar pond (SGSP).

The salt gradient solar pond (SGSP) is a stable artificial pond of salt water, in which the salt concentration gradient increases through the depth of the pond (Munoz and Almanza, 1992). The solar radiation is absorbed as heat energy and stored for a long time. The salt gradient solar pond is comprised of three layers (Fig. 1); upper convective zone (UCZ), non-convective middle zone (NCZ) and lower convective zone (LCZ). In the UCZ layer, the salt concentration is homogeneous and convective heat transfer is occurred, the temperature is approximately equal to the ambient temperature and the salinity is about the sea water salinity (3.3 wt%). NCZ layer is a gradient type layer with conductive heat transfer. The saline density and temperature increase quasi-linearly to achieve the maximum level, hence the convection is not possible and the heat transfer is done through conduction. LCZ layer is the storage layer with the densest and uniform salinity close to saline saturation. The thickness of the LCZ layer is variable and can be up to 2 meters. The LCZ temperature is dependent on various factors such as the thickness of the LCZ, radiation intensity, NCZ thickness, ambient temperature and stability of salt gradient.

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,

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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/kgK)
k	thermal conductivity of water (W/mK)
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	energy efficiency
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

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). A number of studies focused on the energy performance analysis of solar 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 layers 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 efficiency (Khalilian, 2016a, 2016b).

Although the wall shading effects could be neglected in analyzing the large solar ponds, in the small solar ponds, wall shading 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).

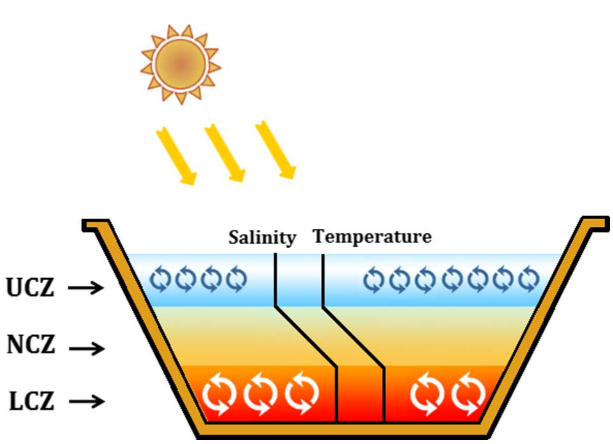

Fig. 1. Schematic view of the solar pond showing the distribution of the three zones.

As mentioned before, no paper presented the proper relations and the correct definitions of pond's energy efficiency. Therefore, in this paper, we aim to introduce and apply the proper relations for analyzing the energy efficiency of solar ponds to prevent further mistakes in this field. Also, it should be noted that the shading effect is considered in analyzing the energy efficiency.

2. Experimental apparatus and testing procedure

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. Inside of the pond was painted black to ensure absorption of the radiation and sunlight, while the outside was insulated with 0.20 m thick glass-wool to reduce the rate of heat loss. 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 middle zone, NCZ, with a thickness of 0.50 m, was filled with salt water having increasing densities toward LCZ. The surface layer, UCZ, was filled with fresh water with a thickness of 0.20 m. To measure the temperature of each pond, several thermocouples with measuring accuracy ranges of ± 1 °C were installed at 5, 10 to 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. Experiments were performed in the city of Urmia, Iran at 45°E longitude and 37.5°N latitude. Data and measurement of the ponds were collected in one year period. The climatic conditions for Urmia City are listed in Table 1 (NASA, 2016).

3. Solar radiation in solar pond

Once the solar radiation, I, reaches the pond surface, a part of it is immediately reflected back into the sky. The remainder of the solar radiation in pond, I_0, is obtained from

$$I_0 = (1-R)I \tag{1}$$