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Energy analysis and shadow modeling of a rectangular type salt gradient solar pond

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ABSTRACT

In calculating the total solar energy input into a salt gradient solar pond, the current method is insufficient mainly caused by two problems. Firstly, the existing equations of solar pond energy analysis can be only used for momentary calculations but it is very time-consuming for long time periods. Secondly, the shading effect inside the pond affects significantly the energy storage performance of the pond, especially in small ones. To solve the first problem, the mean values of variable parameters during the concerned time period is proposed in this work and the 'first mean value theorem for definite integrals' is used to derive the average values. For the second problem, a rectangular pond with vertical walls is investigated as an example, and the exact sunny areas in different depths of the pond are calculated at different time conditions. The experimental data of a published study is used for the validation. The energy efficiency of the low convective zone of the experimental pond is calculated theoretically, which shows a good agreement with the experimental value. The experimental data and theoretical results for the energy efficiency are 9.68% and 11.38% for January, 17.54% and 18.92% for May, and 28.11% and 30.94% for August, respectively. The modified equations can be used to predict a pond performance before its construction.

1. Introduction

With increasing concerns of carbon emission and global warming, there is an urgent need to develop alternative energy sources to replace fossil fuels in the long term (Vandani et al., 2015). Developing renewable energy technologies, especially solar-based, has received intensive interest in the last a few decades (Boudhiaf and Baccar, 2014; Sakhrieh and Al-Salaymeh, 2013). Solar energy is one of the foremost types of renewable energies and its technologies are ideal choices for thermal applications of renewable energies (Aramesh et al., 2017). Many technologies like desalination, electricity production, thermal applications of nanofluids and solar ponds have been applied as the hybrid items with the solar energy conversion systems (Kasaeian et al., 2015, 2016). Among present technologies for various applications of solar energy, salt gradient solar pond is a promising option for solar energy storage due to its unique characteristics such as low cost and high capability for long-term energy storage (Hongfei et al., 2002; Husain et al., 2004a; Kurt et al., 2000). Many studies have been conducted on the energy analysis of solar pond in different conditions for the purpose of optimization (Husain et al., 2004b), which is briefly reviewed below.

Jaefarzadeh (2004) studied the thermal behavior of a small salt gradient solar pond with wall shading effect in 2004. The effect of vertical walls of a square pond on the reduction of the sunny area was included in the model, and the result reported an overall efficiency of 10% for the pond. In 2006 Karakilcik et al. (2006a, 2006b) presented an experimental and theoretical investigation of temperature distributions in an insulated solar pond during both daytime and night time. Theoretical temperature distributions were compared with various cases, such as inside the pond, underneath the pond and in the side walls.

In 2008 Karakilcik and Dincer (2008) presented an experimental and theoretical investigation of exergy performance of a solar pond. The exergy efficiencies were less than the energy efficiencies for each zone of the pond due to the exergy destructions in the zones and losses to the surroundings. Bozkurt and Karakilcik (2012) presented a heat storage performance investigation of an integrated solar pond with a collector system in 2012. It was concluded that to increase the system performance, the zone

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Nomenclature

A	ponds' cross section (m^2), shaded area (m^2)
$\bar{A}$	average cross section (m^2)
B	day angle (°)
C	integral constant
E	irradiance (MJ/m^2), equation of time (min)
$h(X)$	ratio of solar energy reaching to X depth
$\bar{h}(X_i)$	average of $h(X)$
L	longitude (°), pond length (m)
n	refraction index, day number
Q	entering thermal energy (MJ)
t	local solar time (s)
W	pond width (m)
X	depth (m)
x	incident beam vector component along x direction
y	incident beam vector component along y direction
z	incident beam vector component along z direction

Greek symbols

β	ratio of solar energy entering
$\bar{\beta}$	average of β
δ	declination angle (°)
θ	angle (°)
ϕ	latitude (°)
ω	hour angle (°)
γ_S	solar azimuth angle (°)

Subscripts and superscripts

i	a specific depth, incident
LCZ	lower convective zone
r	refraction
$solar, tot$	total solar energy during a time interval
$stored, LCZ$	stored heat in LCZ
$solar, LCZ$	total solar energy entering LCZ

thicknesses, sunny areas of the pond, number of the collectors and salt gradient system should be modified to achieve higher efficiency and stability of the pond. In the same year, Bozkurt et al. (2012) compared the performance of an integrated and a nonintegrated solar pond experimentally, and revealed a higher energy efficiency for the integrated system.

In 2013 Karakilcik et al. (2013) presented an experimental investigation of the energy distribution and energy efficiency of a small rectangular solar pond due to shading effect on each zone, and found that the efficiency of the solar pond was decreased by increasing the shading area. Atiz et al. (2014) in 2014 studied the turbidity effect on the exergy performance of solar ponds under various weather conditions and concentrations. The results showed that the exergy efficiency was significantly decreased by increasing the turbidities of the zones. In the same year, Bozkurt et al. (2014) presented a theoretical analysis for a solar pond at different geometries for the Adiyaman region in Turkey. The energy efficiency of the solar pond was increased by an increase in the size of the pond. In 2015, Bozkurt et al. (2015b) presented a new performance model to determine the energy storage efficiency of a solar pond. The heat losses of the solar pond were determined by using the Heat 2 software. The experimental and the theoretical heat storage performance of the lower convective zone of the solar pond were determined, and the results showed that the presented model could predict the efficiency of the pond with a good accuracy. In 2015, Bozkurt and Karakilcik (2015) investigated the effect of the sunny area ratios on the thermal efficiency of a solar pond model. The results showed that with an increase of sunny area ratio, the performance of the solar pond was increased. Another research by Bozkurt et al. (2015a) in 2015 studied the performance of a magnesium chloride saturated solar pond. The maximum energy and exergy efficiencies were found to be respectively 27.41% and 26.04% for the heat storage zone in August.

In all previous studies, the existing equations could be used for the momentary time intervals, but a massive amount of calculations was needed to analyze the energy behavior of solar ponds during a specific period. Moreover, in the previous works, the walls' shading effect was either neglected or was not considered precisely. In this study, the energy analysis of solar ponds is modified for the first time, to eliminate the mentioned drawbacks of previously used methods. The average value of variable parameters are implemented in the modified method, which can be used to calculate the pond performance for a much longer period, yet with much less calculations. In addition, accurate correlations are presented for rectangular ponds to obtain the exact sunny areas inside the pond in different time and locations. The presented energy analysis method shows better accuracy than the former methods in predicting the behavior of a pond.

2. Energy analysis

In the correlations for calculating the amount of solar energy entering the pond at different pond depths, various parameters are dependent on the sun incident angle. It is very time consuming in considering the changes of this angle during a day and different seasons in order to find the total amount of the entered energy. A simplification of these correlations can lead to less amount of calculations. In next sections, the principles of this study will be described and then modification of the relations will be discussed.

2.1. Principles

The equation that is being used widely to calculate the energy entering the pond in any depth is given by (Bozkurt, 2016; Khalilian, 2016):

$$Q_{solar} = \beta E A_i h(X_i) \tag{1}$$

where E is the total solar energy flux reaching pond surface $(\frac{W}{m^2})$, β is the fraction of the incident solar radiation that enters the pond, A_i is the sunny area of solar pond at the desired depth of X_i (m^2), and $h(X_i)$ is the ratio of the solar energy reaching to that depth. The value of E can be measured during the desired period or can be inquired from meteorological stations.

The parameters of β, A and h are dependent on the incident angle of solar irradiance to the pond. Therefore Eq. (1) can calculate entering energy to the pond only in short periods of time in which the incident angle can be considered as a constant. On the other hand, for rectangular solar ponds, the azimuth angle can also affect the sunny areas inside the pond, as a change in azimuth angle changes the walls shading. In the previous studies, which considered the shading effect, solar pond direction is assumed to be in a way that the azimuth angle become equal to zero and the shading is limited to only one of the walls (Bozkurt and Karakilcik, 2015; Dincer and Rosen, 2012; Karakilcik et al., 2013). By considering the changes in the azimuth angle during the day, this assumption is valid only for short periods of time. In order to solve the mentioned problems, the equations of those three parameters