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Experimental and numerical investigations of the thermal behavior of small solar ponds with wall shading effect

Morteza Khalilian

Engineering Department, Urmia University, Urmia, Iran

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ABSTRACT

In this study, a combined numerical and experimental investigation of the thermal behaviour of small solar ponds with various shapes, is presented. For this purpose, two prototypes of solar ponds with square and circular cross sections and similar volumes were examined. In the small solar ponds, the side walls shading affects accumulation and storing the solar thermal energy. Therefore, for evaluating the effect of shadow shape and size on the pond performance, a model for temperature distribution in a solar pond was presented, and the thermal behaviour of the pond was investigated considering the shadow effects. Temperature changes in the storage zone were calculated numerically and compared with the experimental results. According to the results, by considering the shadow effect, the maximum temperatures of circular and square ponds were 66.8 °C and 65.8 °C, respectively. Also, the effect of the angular placement of ponds on various geographical directions has been investigated. The maximum temperature was obtained at the placement angle $\gamma = 0°$ for square ponds, whereas the rectangular ponds should have been constructed at $\gamma = 90°$ to achieve the maximum temperature and shadow effect reduction. The results provided a strong perspective for determining the dimensions and angular placement of the solar ponds before construction of a solar pond.

1. Introduction

A salinity-gradient solar pond (SGSP) is a cost-effective and vastly used solar pond; it absorbs and stores solar radiation for a long period of time with an artificial stable salinity distribution (Munoz and Almanza, 1992). It consists of three saltwater layers with different thicknesses, as shown in Fig. 1. The surface layer, namely the upper convective zone (UCZ), is homogeneous and convective, where the density of the saline is close to the fresh water. In the middle layer, namely the non-convective zone (NCZ), the saline density increases with depth and hence natural convection is stopped and the heat transfer occurs only through conduction, so this layer can be considered as a heat insulator. The bottom layer, known as the lower convective zone (LCZ), is dense and convective; it has a relatively uniform density near to saline saturation. A part of the solar irradiation is transmitted to this zone and increases its temperature. The thermal energy collected in LCZ could be utilized later by a heat exchanger (Wang and Akbarzadeh, 1982).

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.

For a solar pond with small surface area, the shadow of the vertical walls plays a key role in reducing the sunny area of the pond, and its thermal energy storage. Therefore, the effect of side walls shading needs to be taken into account in the thermal analysis of small ponds. So far, some studies reported in the literature are concerned with the effect of shading on the thermal performance of small ponds. Lund and Routti (1984) investigated the feasibility of using solar ponds for residential heating in cold climate using computer modeling. The shading of both direct (beam) radiation and diffuse radiation in a circular pond was theoretically considered. Hassab and El-Masry (1991) studied the pond edge effects on the collected solar energy in small solar ponds and found that shadowing effects for length and width aspect ratios of less than about 2 is significant. Jaefarzadeh (2004) studied the thermal behavior of a rectangular solar pond with wall shading effect with simple boundary conditions and the calculated results were compared with the data from an experimental study. It was concluded that the reduction of the sunny area due to the shading effect in small ponds would decrease the efficiency of the pond. Karakilcik et al. (2013) used a finite difference based mathematical model for determining the thermal performances of the rectangle solar pond with the shading

E-mail address: M.Khalilian@urmia.ac.ir.

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Nomenclature

A	total surface area of the layer (m^2)
A_e	sunny or effective radiation area (m^2)
A_{sh}	shaded area (m^2)
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_z	fraction of solar radiation that reaches a depth z (W/m^2)
R	reflection coefficient
U_g	over all heat transfer coefficient to the ground (W/m^2 K)
UCZ	upper convective zone
NCZ	non-convective zone
LCZ	lower convective zone
$S(z)$	shading factor
T_l	temperature of the LCZ (°C)
T_u	temperature of the UCZ (°C)
T_g	temperature of water table under the pond (°C)
T_{sky}	sky temperature (°C)
T_a	average of the ambient temperature (°C)
r	radius of the circular pond (m)
h	depth of the circular pond (m)
L	length of the pond (m)
W	width of the pond (m)
h_c	convective heat transfer coefficient to the air (W/m^2 K)
v	monthly average wind speed (m/s)
R_h	relative humidity (%)
P_a	the partial pressure of water vapor in the ambient temperature (mmHg)
P_{atm}	atmospheric pressure (mmHg)
P_u	vapour pressure of water at the surface (mmHg)
Q_{solar}	the radiation energy reaching and absorbing in each zone (W/m^2)
Q_{rad}	radiation heat loss from the surface (W/m^2)
Q_{conv}	convective heat loss from the surface (W/m^2)
Q_{evap}	evaporative heat loss from the surface (W/m^2)
Q_{wall}	heat loss through walls of the pond (W/m^2)
Q_{ground}	heat loss to the ground (W/m^2)
z	depth (m)
Z_g	distance of water table from pond's bottom (m)
t	time (s)
n	index of refraction

Greek

θ_i	angle of incidence
θ_r	angle of refraction
ρ	density (kg/m^3)
ε	emissivity of water
σ	Stefen-Boltzmann's constant (5.67×10^{-8} $W/m^2 K^4$)
λ	latent heat of vaporization (kJ/kg)
θ'	coefficient of the solar irradiation reduction
ξ	fraction of direct or beam radiation
α	profile angle

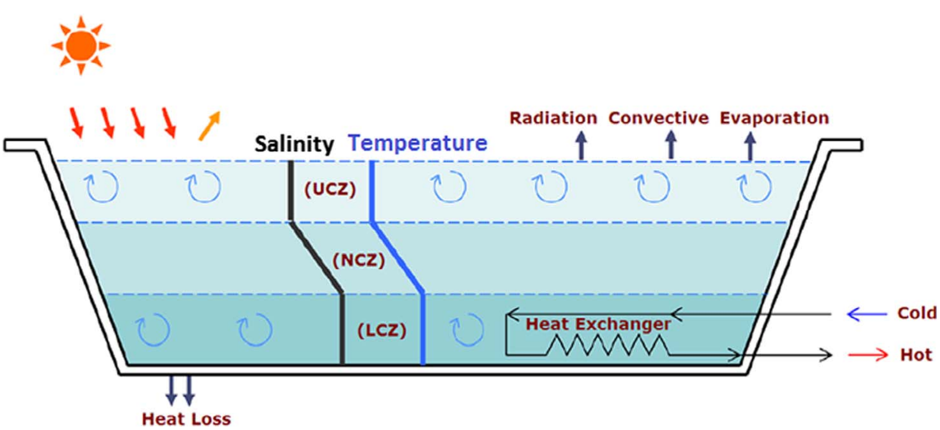

Fig. 1. Working principle of solar pond technology (modified from Garrido et al., 2012).

effect. However, the equations used by Karakilcik et al. for calculating the shading length of the layers, the net solar energy reached the surface of each layer (Q_{ns}), the transmission function (h_l) and transmission coefficient (β) were incorrect (Khalilian et al., 2015; Khalilian, 2016).

In addition, in previous studies on the rectangular ponds, only one of the pond's walls were considered to be effective on the shading (Karakilcik et al., 2006a, 2006b, 2013; Bozkurt and Karakilcik, 2015; Dincer and Rosen, 2012). This situation would occur only in a short periods because the direction of the solar incident to the pond will vary with the changes in the azimuth angle during the day and various shaded areas will be expected. Thus, to calculate the sunny areas, the effects of the both incident and azimuth refraction angles must be considered. These angles are dependent on time and location.

In the present study, a one-dimensional transient model was used for simulating the thermal behavior of the square and circular solar ponds with shading walls, and the numerical results are validated experimentally. The main objective of this paper is to represent pond performance by using correct format of governing equations in solar ponds, also the temperature variations of LCZ were given for different conditions.

2. Experimental apparatus and testing procedure

Two experimental, small scale solar ponds with square and circular cross-sections were built in Urmia University of Iran with a height of 1.1 m and area of 4 m^2. The circular pond diameter was 2.25 m and the side length of the square pond was 2.0 m. These ponds were constructed from 1.5 mm galvanized metal sheet. Fig. 2 shows schemes of the solar ponds used in the experiment. The inside of the ponds were painted black to ensure absorption of solar radiation, while the outside was insulated with 30 mm 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, with the concentration of 300 g/l and a