Solar Energy 157 (2017) 869–879

Contents lists available at ScienceDirect

Solar Energy

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

Numerical investigation of the nanofluid effects on the heat extraction process of solar ponds in the transient step

Mohamad Aramesh, Fathollah Pourfayaz*, Alibakhsh Kasaeian

Department of Renewable Energies and Environment, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran

ARTICLE INFO

Keywords:
Solar pond
Nanofluid
Thermal performance
Transient modeling
Numerical simulation

ABSTRACT

In this paper, a modification of previous thermal modeling methods of solar ponds has been employed to simulate the heat extraction process by nanofluids in the transient step. A hypothetical rectangular solar pond with a cross section of 10 × 10 m^2, and 2.7 m depth has been considered as the case study. The city of Tehran has been assumed to be the location of the pond. Using the synoptic data of the location, the heat storage process is modeled in August 2016. The model showed that after 24 days, the temperature of the lower convective zone (LCZ) reaches to 98.66 °C with 40.5093 GJ of stored thermal energy. At this point, the heat extraction process is modeled for a 48 h period after which this pond cannot provide enough thermal energy anymore. The thermal performance of heat removal for water and six different water-based nanofluids are investigated and compared theoretically. The nanofluids include Ag/water, Cu/water, CuO/water, Al_2O_3/water, SWCNT/water, and MWCNT/water. Also, different volume fractions between 0.1% and 5% are modeled. The amounts of the extracted heat for 15 different concentrations of the selected nanoparticle types are calculated. Using the results, the threshold concentration has been determined for each type. Moreover, the heat extraction rate, the percentage of the extracted heat, and the mean outlet temperature are investigated at the threshold concentrations. For all of these parameters, the SWCNT/water nanofluid has determined to have the best performance at its threshold concentration of 0.1%v/v. For the amount of the extracted heat, the model showed the minimum amount of 5.8141 GJ for water, and the maximum amount of 10.2892 GJ for the SWCNT/water nanofluid at its threshold concentrations.

1. Introduction

Nowadays, many countries in the world are looking for sustainable sources of energy (Kasaeian et al., 2017b; Maleki et al., 2016). Many of the developed and developing countries are using the renewable energies for this purpose (Yousefi et al., 2017). Salt gradient solar pond is counted as a reliable renewable energy source, especially for the low-grade thermal applications (Singh et al., 2011). Solar ponds can store the solar thermal energy, and this energy can be used to produce heat or electricity (Alcaraz et al., 2016). In the recent years, many scientists have studied the performance of the solar ponds (Abdullah et al., 2017; Assari et al., 2017; Bozkurt and Karakilcik, 2015b; Ganguly et al., 2017). One of the ways to improve the thermal performance of the solar energy technologies is employing nanofluids as the working fluid (Kasaeian et al., 2015, 2017a; Khanjari et al., 2016, 2017). However, there are few researches on the applications of the nanofluids in the solar ponds. In a review paper, Mahian et al. (2013) have investigated the different applications of nanofluids in the solar energy systems. For the solar ponds, they have proposed a setup to use a nanofluid for heat extraction from the pond. In the setup, nanofluid is stored in an external tank, and it flows through the bottom of the pond by a tube. However, no similar studies have been reported in their work.

Al-Nimr and Al-Dafaie (2014) have presented a novel design for solar ponds without the salt gradient inside. In this design, the pond is composed of two layers. The top and the bottom layers are composed of mineral oil and Ag/water nanofluid, respectively. They have reported 216% more heat storage in the designed pond in comparison with an identical salt gradient solar pond. In another study, Ding et al. (2016) have designed and constructed a solar pond combined with thermoelectric cells for electric power generation. In their work, they have proposed that the nanofluids can be employed to enhance the performance of the thermoelectric generator by improving the heat exchanger efficiency.

Also, in some other studies, utilizing nanofluids in the solar ponds has been only proposed and not investigated (Hemmat Esfe et al., 2015; Kashani et al., 2014; Srinivasacharya and Surender, 2014). To study the effects of employing the nanofluids, it is needed to simulate the heat extraction operation from the solar ponds. Most of the modeling

---

* Corresponding author.
E-mail address: pourfayaz@ut.ac.ir (F. Pourfayaz).

http://dx.doi.org/10.1016/j.solener.2017.09.011
Received 15 June 2017; Received in revised form 21 August 2017; Accepted 1 September 2017

methods presented for solar ponds does not include the heat extraction process. These methods are focused on predicting the energy storage performance of the pond. Karakilcik et al. (2013) have modeled the heat storage step of a solar pond in two different cases of neglecting the walls shading effect and considering it. In another study, Bozkurt and Karakilcik (2015a) have modeled the heat storage inside the solar pond and investigated the walls shading effect on the performance of the pond in four different sizes.

Boudhiaf and Baccar (2014) have modeled the heat storage process in a transient manner, from the beginning of the process to its final steady state. Sakhrieh and Al-Salaymeh (2013) have modeled the heat storage performance of a solar pond and compared it with the experimental data. They have reported a good agreement between the theoretical and experimental results. Moreover, Atiz et al. (2014) have included the water turbidity effects in their modeling method and have predicted the heat storage performance of a solar pond.

Recently, scientists have focused on modeling the heat extraction process of solar ponds. Aramesh et al. (2017a, 2017b) have presented two modeling methods to simulate the heat storage and heat extraction operation of solar ponds. In the study on the heat extraction operation, the heat is removed by a flow inside a tube passing through the LCZ layer. The changes in the depth and length directions are considered for the LCZ layer and the fluid inside the tube. However, it neglects the incoming solar thermal energy. Also, Abbassi Monjezi and Campbell (2017) has modeled the heat extraction process. The presented model includes the incoming solar thermal energy during the heat removal but it considers the LCZ layer as a bulk component, and it investigates the changes in the pond only in the depth direction. The heat extraction occurs by removing the hot brine from the LCZ layer.

In this paper, a combination of the methods presented in our previous works along with some modifications has been employed to theoretically model both the heat storage and heat extraction processes of solar ponds. Furthermore, the method has been utilized to predict the impacts of using nanofluids on the heat extraction operation of solar ponds. Six different common nanofluid types are studied including two metal, two metal oxide, and two CNT nanofluids. The modeling method presented in this paper, and also the effects of using nanofluids on the heat extraction operation have not been investigated in the literature.

2. The heat extraction process

In this section, firstly the principals of the modeling method are presented, and then the types of the nanofluids and their effects on the heat extraction process are described.

2.1. The modeling method

Two modeling methods presented in the previous works along with some modifications have been employed in this paper. Firstly, the heat storage step is modeled by modifying the method presented by Aramesh et al. (2017a). This method can predict the heat storage performance of a rectangular solar pond with a good accuracy, especially in the small-scales. By determining the pond temperature profile after storing the thermal energy of the sun, the heat extraction process is modeled in a transient manner. For this purpose, the method presented in another work by Aramesh et al. (2017b) has been employed with some modifications. Here, the heat extraction is considered to be done by a heat transfer fluid flowing inside a tube, and not by removing the brine from the pond. Also, the incoming solar energy and the changes in the depth and length directions are considered in the model.

According to the cylindrical shape of the tube, the cylindrical form of the differential heat equation is a suitable choice to model the flow inside the tube and the brine inside LCZ layer. The cylindrical form can easily model the tube and most parts of the LCZ layer. The remaining parts outside of the cylindrical domain can be modeled using the simplifying assumptions. This method has been thoroughly investigated in the literature (Aramesh et al., 2017b). Eq. (1) shows the governing equation for the flow inside the tube (Aramesh et al., 2017b):

$$\rho_t c_{p.t}\left(\frac{\partial T}{\partial t} + u_{z.t}\frac{\partial T}{\partial z}\right) - k_t\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) - \frac{32\mu_t u_{z.t}^2}{D^2} = 0 \tag{1}$$

where ρ_t is the density of the fluid inside the tube (kg/m^3); is its specific heat capacity (J/kg K); $u_{z.t}$ is its average velocity in the length direction (m/s); k_t is its thermal conductivity (W/m K); μ_t is its dynamic viscosity (kg/m s); T is the temperature (°C); t is the time (s); z is the length direction; r is the radius direction; and D is the inner radius of the tube (m).

In the same equation system, the governing equation on the LCZ layer will be as follows (Aramesh et al., 2017b):

$$\rho_{LCZ} c_{p.LCZ}\frac{\partial T}{\partial t} - k_{LCZ}\left(\frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) = 0 \tag{2}$$

where ρ_{LCZ}, $c_{p.LCZ}$, and k_{LCZ} are the density (kg/m^3), specific heat capacity (J/kg K), and the thermal conductivity (W/m K) of the LCZ fluid, respectively. In this equation, the incident solar thermal energy during the day is neglected. This assumption is acceptable for the small-scale ponds in which the heat extraction rate is much higher than the heat storage rate. Considering the incoming solar thermal energy will make the model more accurate and also makes it applicable for the large-scales. This energy can be assumed as an internal heat source while modeling the pond (Suárez et al., 2014). Therefore, Eq. (2) can be modified as belows:

$$\rho_{LCZ} c_{p.LCZ}\frac{\partial T}{\partial t} - k_{LCZ}\left(\frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) + \dot{q} = 0 \tag{3}$$

where $\dot{q}$ is the heat generation rate (W). The amount and the rate of the solar energy received by the pond differs with depth. Bansal and Kaushik (1981) have introduced a precise empirical relation for calculation of the solar insolation at every depths of a solar pond:

$$E(z) = \tau E_0 \sum_{j=1}^{5} \mu_j e^{-n_j z} \tag{4}$$

where $E(z)$ is the solar insolation at the depth of z (W/m^2), and τ is the water transmittance which can be assumed to be at the constant value of 0.94 (Bansal and Kaushik, 1981). Moreover, is the irradiance at the surface of the pond (W/m^2), and μ_j is the fraction of the solar radiation with the absorption coefficient of n_j. The values of μ_j and n_j are as listed in Table 1:

The heat generation rate can be calculated for each moment, using the amount of the energy reaching the pond:

$$\dot{q}(z,t) = \frac{E(z,t)}{\Delta t} \tag{5}$$

where (z,t) shows the dependency of the heat generation and solar heat flux on the depth and time, and Δt is the corresponding period during which the values of the heat generation and heat flux are considered.

To model the heat extraction process, Eqs. (1) and (3) must be solved simultaneously. The numerical method of Crank-Nicolson along with the Alternating Direction Implicit (ADI) technic have been utilized to solve the equations. This method has been explained in our previous work thoroughly (Aramesh et al., 2017b) and only the required initial and boundary conditions must be explained. These conditions are given

Table 1
The constants for calculating solar insolation in different depths (Bansal and Kaushik, 1981).

Index	1	2	3	4	5
μ_j	0.237	0.193	0.167	0.179	0.224
n_j (m^{-1})	0.032	0.45	3	35	225