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Research Paper

Experimental investigation and theoretical modelling of heat transfer in circular solar ponds by lumped capacitance model

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ABSTRACT

The present study develops a lumped capacitance model for modelling the heat transfer in a salinity gradient solar pond. This model is used to analyze the transient energy behaviour in each zone of the pond incorporating many processes that affect the performance of a solar pond. The effect of various parameters such as different solar attenuation models, thickness of each zone, heat loss from the pond's surface, and the wall-shading effect on the temperature of the storage zone would be investigated. The validity of the model is tested against experimental data for a small circular pond constructed in Urmia University, and a good agreement between theoretical and experimental data for the temperature in the storage zone has been obtained. The results indicated that the heat loss from the pond's surface occurs mostly by evaporation rather than radiation and convection. In addition, it is observed that the upper convective zone thickness should be as thin as possible and the lower convective zone thickness may be designed based on the application needs. It is concluded that wall-shading effect has a significant effect on the storage temperature of a small pond, however, the effect is found to be small in the large pond.

1. Introduction

Considering the shortage in fossil fuel resources and the increasing demand for power generation arising from increased population and economic developments across the majority of the world's countries, the use of renewable sources of energy seems to be the only solution in hand for power generation [1]. Solar energy can be harnessed to meet the need for energy, so as to have a sustainable future. Numerous technologies have been proposed for converting the thermal solar energy into a useful and efficient type of thermal energy. Anyway, it should be noted that solar energy is time-dependent and discontinuous source of renewable energy, therefore, the storage of the extracted energy to offset the increasing demand for energy is the major challenge in using this source of energy [2]. So it is required to develop and employ low-cost hybrid solar thermal collectors and storage systems. Solar pond represents a low-cost collector with long-term thermal energy storage capabilities [3].

A salinity-gradient solar pond (SGSP) is cost-effective and commonly used; it absorbs and stores solar radiation as thermal energy for a long period of time with an artificial stable salinity distribution [4]. It consists of three layers of saltwater with different depths named upper convective zone (UCZ), non-convective zone (NCZ) and lower convective (LCZ) zone. The surface layer, UCZ, is near ambient temperature has approximately the density of fresh water. In the middle layer, (NCZ), saline density increases in depth and hence natural convection is stopped and the heat transfer is occurred only through conduction, so this layer can be considered as a heat insulator. The bottom layer, (LCZ), is dense and convective; it has a relatively uniform density close to saline saturation. A part of solar irradiation is transmitted to this zone and increases it's temperature. The thermal energy collected in LCZ may be utilized later by a heat exchanger.

In recent decades, several studies have been conducted experimentally and numerically to analyze the performance of solar ponds and understand their functional mechanisms. The experimental studies have been mainly focused on constructing, utilizing and measuring the temperature and density of solar ponds [5–10], while the heat analyze of solar ponds subjected to different conditions using proper mathematical models is investigated in the numerical studies. So far, several models such as lumped capacitance model [11–15], transient heat transfer model [16–18] and transient heat and mass transfer model [19,20] have been introduced to investigation of the thermal performance of various types of solar ponds. The models and their governing equations are listed in Table 1.

There have been many studies used these mathematical models for thermal analysis of solar ponds such as the heat and mass

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Nomenclature

UCZ	upper convective zone
NCZ	non-convective zone
LCZ	lower convective zone
A_u	surface area of the UCZ (m^2)
A_l	surface area of the LCZ (m^2)
m	mass of the pond water (kg)
C_{p_u}	heat capacity of water in the UCZ (kJ/kg K)
C_{p_l}	heat capacity of water in the LCZ (kJ/kg K)
k_w	thermal conductivity of water (W/m K)
k_g	thermal conductivity of the soil under the pond (W/m K)
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
T_a	average of the ambient temperature (°C)
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
Z_u	thickness of the UCZ layer (m)
Z_l	distance of LCZ surface from pond surface (m)
U_g	over all heat transfer coefficient to the ground (W/m^2 K)
h_c	convective heat transfer coefficient to the air (W/m^2 K)
P_a	the partial pressure of water vapour in the ambient temperature (mm Hg)
S	salinity in the solar pond (%)
P_{atm}	atmospheric pressure (mm Hg)
P_u	vapour pressure of water at the surface (mm Hg)
v	monthly average wind speed
R_h	relative humidity
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_{NCZ}	thickness of the NCZ layer (m)
Z_g	distance of water table from pond's bottom (m)
t	time (s)
L	length of the pond (m)
W	width of the pond (m)
p	profile angle

Greek symbols

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
δ	uncertainty

transfer [16–20], the double diffusive convection [21,22], and the multi-reflection [23]. These studies are carried out to understand the characteristics of the heat-salt diffusion [24–26], stability [27,28], the turbidity [29,30], the heat extraction [31–34], etc.

The lumped capacitance model is one of the mathematical models for predicting the performance of the solar ponds [11]. To the best of the author's knowledge, so far, the model has been very limitedly used for modelling thermal behaviour of solar ponds. In 1980, Shah et al. used the model to analyze only the storage zone of a pond, where the UCZ layer was taken to be at the ambient temperature [12]. Their investigation on the total effective capacity enhancement within the storage zone of the pond, shows that a decrease in the gradient layer thickness and an increase in the storage zone size would have a positive effect on the pond performance.

Then in 1988, Ali used lumped capacitance model to analyze the heat transfer at all of the three zones within the pond, where the UCZ layer temperature was calculated by the energy balance equation at this layer [13]. The mathematical model was validated according to the experimental data obtained from a pond with a surface area of 8 m^2. It is worth noting that the effects of the wall-shading on the pond's thermal performance were further considered in the work by Ali.

More recently, in 2016, in a work presented by Sayer et al., the heat transfer in a solar pond was analyzed using the lumped capacitance model [14], and the validation was performed according to the small 8 m^2-pond presented by Ali [13], as well as a large rectangular 3000 m^2 pond presented by Huanmin et al. [35]. The effect of the wall-shading on the pond's thermal performance was ignored.

Table 1
Different types of model applying for solar pond modelling.

Model	Governing equations		Ref.
Lumped capacitance model	UCZ	$T_{UCZ} = T_{air}$ or $(\sum Q_{in} - \sum Q_{out})_{UCZ} = (mC_p \frac{dT}{dt})_{UCZ}$	[11–15]
	NCZ	$(Q_{in})_{NCZ} = (Q_{out})_{NCZ}$	
	LCZ	$(\sum Q_{in} - \sum Q_{out})_{LCZ} = (mC_p \frac{dT}{dt})_{LCZ}$	
Transient heat transfer model	UCZ	$T_{UCZ} = T_{air}$ or $(\sum Q_{in} - \sum Q_{out})_{UCZ} = (mC_p \frac{dT}{dt})_{UCZ}$	[16–18]
	NCZ	$\partial(\rho C_p T)/\partial t = \nabla \cdot (k \nabla T) + E$	
	LCZ	$(\sum Q_{in} - \sum Q_{out})_{LCZ} = (mC_p \frac{dT}{dt})_{LCZ}$	
Transient heat & mass transfer model (double- diffusive model)	UCZ	$T_{UCZ} = T_{air}$ or$(\sum Q_{in} - \sum Q_{out})_{UCZ} = (mC_p \frac{dT}{dt})_{UCZ}$	[19,20]
	NCZ	$\frac{\partial(\rho C_p T)}{\partial t} = \nabla \cdot (k \nabla T) + E$ $\partial(\rho S)/\partial t = \nabla \cdot (\rho D \nabla S)$	
	LCZ	$(\sum Q_{in} - \sum Q_{out})_{LCZ} = (mC_p \frac{dT}{dt})_{LCZ}$	