

Thermal performance of shallow solar pond under open and closed cycle modes of heat extraction

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Received 26 November 2011; received in revised form 3 May 2012; accepted 30 May 2013

Available online 28 June 2013

Communicated by: Associate Editor Aliakbar Akbarzadeh

Abstract

In this paper, the thermal performance of a shallow solar pond (SSP) under the open and closed cycle continuous flow heating modes of heat extraction was investigated theoretically and experimentally. Computer programs were developed based on analytical solutions of the energy-balance equations for the various elements of the system. In order to improve the system performance, optimization of the different constructing elements of the system was carried out. Serpentine heat exchangers were inserted within the SSP's water and the storage tank for extracting the heat. Year-round performance of the system under the best configurational and operational conditions was investigated by computer simulation. It was indicated that the present SSP could be used as a heat source for most domestic and low temperature industrial applications all year-round. The daily efficiencies were obtained as 59% and 33% when the pond is operated under the closed and open cycle modes, respectively.

Comparisons between experimental and theoretical results showed that the proposed mathematical models could be used for investigating the thermal performance of the SSP with reasonable accuracy.

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Keywords: Shallow solar ponds; Heat extraction; Open and closed modes; Efficiency

1. Introduction

The shallow solar pond (SSP) is a solar collector that can be used for collecting and storing heat. The name implies that the depth of water in the SSP is relatively small, typically 4–15 cm, which is like a conventional solar still consisting of a blackened tray holding some water in it. In the SSP, the black bottom of the pond absorbs the sun's rays; as a result, the water gets heated. The solar energy collection efficiency of the SSP is directly proportional to water depth; whereas, the water temperature is inversely proportional to water depth. Solar energy is converted to

thermal energy by heating the water during the day (Garg et al., 1982). Sodha et al. (1985) fabricated a SSP system using PVC films in the form of a bag. The special feature of the system is the use of two transparent foils separated by a honeycomb structure. Using mini solar ponds for preheating saline water of solar stills had been studied (Velmurugan et al., 2007, 2009; Velmurugan et al., 2009). It was concluded that the optimum value of salinity in the mini solar pond is 80 g/kg of water. Effect of using the SSP for preheating of the basin water of a single basin solar still on the still performance was investigated in previous work (El-Sebaili et al., 2008, 2011). The annual average values of the daily productivity and efficiency of the still with the SSP were found to be higher than those obtained without the SSP by 52.36% and 43.80%, respectively. Ould Dah et al. (2010) studied the influence of heat extraction on the performance and stability of a mini solar

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Nomenclature

A	total surface area of the SSP (m^2)	P	perimeter of the pond HE's tube (m)
A_g	surface area of the glass cover (m^2)	Pr	Prandtl number (dimensionless)
A_{he}	surface area of the HE's tube (m^2), ($2\pi r L_{he}$)	P_t	perimeter of the storage tank HE's tube (m)
A_p	surface area of the absorber plate (m^2)	$\dot{Q}_{coll.}$	rate of energy collected by the pond (W)
A_s	surface area of the sides insulating material (m^2)	$\dot{Q}_{he}$	rate of thermal energy collected by the HE's fluid (W)
A_t	cross-sectional area of the HE's tube (m^2) (πr^2)	$\dot{Q}_{loss}$	total rate of energy losses from the storage tank (W)
A_{tank}	total area of the storage tank (m^2)	t	desired time period (s)
A_w	surface area of the pond water (m^2)	T_a	ambient air temperature ($^{\circ}\text{C}$)
C_w	specific heat of water (J/kg K)	T_f	temperature of the pond HE's fluid ($^{\circ}\text{C}$)
D_{he}	diameter of the pond heat exchanger tube (m)	T_{faw}	average temperature of the pond HE's fluid ($^{\circ}\text{C}$)
D_{het}	diameter of the storage tank heat exchanger tube (m)	T_{fi}	inlet temperature of the pond HE's fluid ($^{\circ}\text{C}$)
Gr	Grashof number (dimensionless)	T_{fo}	outlet temperature of the pond HE's fluid ($^{\circ}\text{C}$)
h_{clu}	convective heat transfer coefficient between the lower and upper glass covers ($\text{W/m}^2 \text{K}$)	T_{fot}	outlet temperature of the storage tank HE's fluid ($^{\circ}\text{C}$)
h_{cpf}	convective heat transfer coefficient between the absorber plate and the pond heat exchanger fluid ($\text{W/m}^2 \text{K}$)	T_{ft}	temperature of the storage tank HE's fluid ($^{\circ}\text{C}$)
h_{cpw}	convective heat transfer coefficient between the absorber plate and the pond water ($\text{W/m}^2 \text{K}$)	T_{gl}	lower glass cover temperature ($^{\circ}\text{C}$)
h_{cua}	convective heat transfer coefficient between the upper glass cover and ambient air ($\text{W/m}^2 \text{K}$)	T_{gu}	upper glass cover temperature ($^{\circ}\text{C}$)
h_{cwf}	convective heat transfer coefficient between the pond water and the pond heat exchanger fluid ($\text{W/m}^2 \text{K}$)	T_p	absorber plate temperature ($^{\circ}\text{C}$)
h_{cwft}	convective heat transfer coefficient between the water in the storage tank and the storage tank heat exchanger fluid ($\text{W/m}^2 \text{K}$)	T_s	sky temperature ($^{\circ}\text{C}$)
h_{cwl}	convective heat transfer coefficient from the pond water to the lower glass cover ($\text{W/m}^2 \text{K}$)	T_w	pond water temperature ($^{\circ}\text{C}$)
h_{rus}	radiative heat transfer coefficient from the upper glass cover to the sky ($\text{W/m}^2 \text{K}$)	T_{wf}	final temperature of the pond water ($^{\circ}\text{C}$)
h_{rlu}	radiative heat transfer coefficient between the lower and upper glass covers ($\text{W/m}^2 \text{K}$)	T_{wi}	initial temperature of the pond water ($^{\circ}\text{C}$)
HE	heat exchanger	T_{wt}	temperature of the water in the storage tank ($^{\circ}\text{C}$)
I	solar radiation on a horizontal surface (W/m^2)	U_b	bottom loss coefficient ($\text{W/m}^2 \text{K}$)
k_w	thermal conductivity of the pond water (W/m K)	U_l	overall loss coefficient ($\text{W/m}^2 \text{K}$)
L_{he}	length of the pond HE's tube (m)	U_{tank}	total loss coefficient of the storage tank ($\text{W/m}^2 \text{K}$)
L_{het}	length of the storage tank HE's tube (m)	V	wind speed (m/s)
$\dot{m}_f$	mass flow rate of the pond HE's fluid (kg/s)	Greek symbols	
$\dot{m}_{ft}$	mass flow rate of the storage tank HE's fluid (kg/s)	α_g	absorptivity of the glass cover
m_w	mass of the pond water (kg)	α_{he}	absorptivity of the HE's tube
m_{wt}	mass of water in the storage tank (kg)	α_p	absorptivity of the absorber plate
Nu	Nusselt number (dimensionless)	α_w	absorptivity of the pond water
		η_i	instantaneous collection efficiency of the SSP (%)
		η_d	daily collection efficiency of the SSP (%)
		μ_i	extinction coefficient (m^{-1})
		ψ_i	solar radiation fraction at the pond bottom
		τ_g	transmissivity of the glass cover
		τ'_w	transmissivity of the pond water in the presence of the pond HE's tube

pond. Heat extraction from the salinity gradient solar ponds using heat pipe heat exchangers had been investigated (Tundee et al., 2010). It was found that, there was a drop in the temperature of the lower convective zone from 40 to 39 $^{\circ}\text{C}$ in 3 h period of heat extraction. Spyridonos et al. (2003) investigated the thermal storage efficiency

of the solar fresh water ponds. They performed a comparative study between two types of solar ponds with surfaces covered by a thin layer of transparent paraffin oil or glass floating devices. They indicated that the first type could be used just after the sunset of the same day; while, the second to be used after one or more days of heat storage. The

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