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New theoretical modelling of heat transfer in solar ponds

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Abstract

Solar energy has a promising future as one of the most important types of renewable energy. Solar ponds can be an effective way of capturing and storing this energy. A new theoretical model for a heat transfer in a salinity gradient solar pond has been developed. The model is based on the energy balance for each zone of the pond; three separate zones have been considered, namely the upper convective zone, the lower convective zones, as well as the non-convective zone. The upper and lower zones are considered to be well mixed, which means the temperatures in these zones are uniform. The model shows that the temperature in the storage zone can reach more than 90 °C during the summer season whereas it can be more than 50 °C in winter if the pond is located in the Middle East. In addition, the time dependent temperature for the three layers has been found. Furthermore, it is concluded that heat loss from the pond's surface occurs mainly by evaporation, in comparison to convection and radiation. Heat loss to the ground has been calculated by using three different equations. It was found that the perimeter of the pond has a significant effect on heat loss to the ground from a small pond, while its effect is small in the case of large pond. The validity of the model is tested against experimental data for several established ponds; good agreement is observed.

Keywords: Solar pond; Solar energy; Solar storage

1. Introduction

Scientists are worried about the high levels of pollutants and they are seeking alternative sources of energy. The best alternatives to the traditional sources of energy are renewable energies; they are clean and have sustainable resources. Many different types of these energies have been used, such as wind energy, bio-energy and solar energy. Solar ponds were discovered as a natural phenomenon in Transylvania by Kalecsinsky when he presented measurements on Lake Medve. The temperature in summer was around 60 °C at a depth of 1.3 m; the sodium chloride concentration at the bottom was found to be near saturation. Interestingly, there was fresh water in the surface layer. Kalecsinsky concluded that artificial solar ponds might be useful for heat collection and storage. Significant research effort began in the 1960s, mostly concerned with generating electricity using the heat from the ponds (Nielsen, 1975). In 1977, a 1500 m^2 pond was constructed to generate 6 kW of electricity by a turbine operating a Rankine cycle. A pond of area 6250 m^2 in Ein Boqeq was built in the same year to generate 150 kW of electricity (Weinberg and Doron, 2010). In 1983, the El Paso solar pond was established and it has been in operation since

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Nomenclature

A_b area of the bottom surface of the pond (m^2)
A_l surface area of the LCZ (m^2)
A_u surface area of the UCZ (m^2)
a constant (0.36), Eq. (4)
b constant (0.08), Eq. (4)
CCSGSP closed cycle salt gradient solar pond
C_s humid heat capacity of (kJ/kg K)
c_{pl} heat capacity of water in the LCZ (J/kg K)
c_{pu} heat capacity of water in the UCZ (J/kg K)
D_g distance between the bottom insulation and the water table (m)
D_i thickness of the bottom insulation (m)
E pond's efficiency
EP evaporation pond
F_r refraction parameter
H solar radiation (W/m^2)
h_c convective heat transfer coefficient to the air (W/m^2 K)
h_x fraction of solar radiation that reaches a depth x (W/m^2)
h_o heat transfer coefficient from outside wall surface to the atmosphere (W/m^2 K)
h_1 heat transfer coefficient between the NCZ and the UCZ (W/m^2 K)
h_2 heat transfer coefficient between the LCZ and the NCZ (W/m^2 K)
h_3 heat transfer coefficient between the LCZ with surface at the bottom of the pond (W/m^2 K)
h_4 heat transfer coefficient at the surface of the ground water sink (W/m^2 K)
k_g thermal conductivity of the soil under the pond (W/m K)
k_w thermal conductivity of water (W/m K)
k_1 thermal conductivity of the first layer of insulation (W/m K)
k_2 thermal conductivity of polystyrene (W/m K)
k_3 thermal conductivity of wood (W/m K)
LCZ lower convective zone
l_1 thickness of the first layer of insulation (m)
l_2 thickness of polystyrene layer (m)
l_3 thickness of third layer of insulation (m)
m empirical parameter, Eq. (26)
NCZ non-convective zone
p pond perimeter (m)
p_a the partial pressure of water vapour in the ambient temperature (mmHg)
p_{atm} atmospheric pressure (mmHg)
p_u water vapour pressure at the upper layer temperature (mmHg)
Q_{ground} heat loss to the ground (W/m^2)
Q_{load} heat extracted from the LCZ (W/m^2)
Q_{loses} overall heat loss from the surface of the pond (W/m^2)
Q_R heat absorbed in any layer of the NCZ from solar radiation (W/m^2)
Q_{rin} solar radiation entering the UCZ (W/m^2)
Q_{rout} solar radiation exiting the UCZ (W/m^2)
Q_{rs} the solar radiation which enters and is stored in the LCZ (W/m^2)
Q_{ru} solar radiation that is absorbed in the NCZ (W/m^2)
Q_{ub} heat transfer by conduction to the UCZ (W/m^2)
Q_{uc} convective heat loss from the surface (W/m^2)
Q_{ue} evaporative heat loss from the surface (W/m^2)
Q_{ur} radiation heat loss from the surface (W/m^2)
Q_w heat loss through walls of the pond (W/m^2)
T_a average of the ambient temperature (°C)
T_g temperature of water table under the pond (°C)
T_k sky temperature
T_s temperature of the LCZ (°C)
T_u temperature of the UCZ (°C)
t time (s)
UCZ upper convective zone
U_{ground} over all heat transfer coefficient to the ground (W/m^2 K)
U_t overall heat transfer coefficient (W/m^2 K)
X_{NCZ} thickness of the NCZ (m)
X_l thickness of the LCZ (m)
X_u thickness of the UCZ (m)
x_g distance of water table from pond's bottom (m)
x thickness of water layer (m)

Greek letters
ϵ emissivity of water
ρ_l density of the LCZ
ρ_u density of the UCZ (kg/m^3)
v monthly average wind speed in the region of study (m/s)
λ latent heat of vaporisation (kJ/kg)
γ_h relative humidity
σ Stefen–Boltzmann's constant (5.673×10^{-8} W/m^2 K^4)

1985 (Alenezi, 2012). Currently, the research on the El Paso pond is focused on coupled desalination and brine management and enhancement of the techniques of solar pond operation and maintenance (Benjamin Schober, 2010; Huanmin et al., 2004). There are two types of solar ponds, (i) convective and (ii) non-convective ponds (Alrowaished et al., 2013). A simple diagram (Fig. 1) can be drawn to demonstrate the types of solar ponds.