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A numerical study to predict the energy and exergy performances of a salinity gradient solar pond with thermal extraction

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ABSTRACT

An investigation of the performance of a salinity gradient solar pond (SGSP) on the basis of energy and exergy considerations is presented. Unlike existing exergy studies, the transient 1-D numerical model developed in this study incorporates thermal extraction from the SGSP's lower convective zone (LCZ). Hence the efficiencies of the energy/exergy extractions were defined and determined in addition to the conventional efficiencies presented in existing studies. As is characteristic of solar thermal devices, irreversibilities were immense in all the zones, leading to the very low exergy efficiencies. The highest irreversibilities occurred in the upper convective zone, pointing to its need for prioritized attention in efforts aimed at improving pond performances. Most of the energy/exergy input to the solar pond is stored in the LCZ, though the exergy efficiencies of the non convective zone are comparable with those of the LCZ. A positive correlation was found to exist between the performance of solar ponds and prevailing heat extraction rates. Extraction energy and exergy efficiencies were obtained respectively as 63.0% and 3.2% for the LCZ, and as 19.4% and 1.0% for the entire pond, for a thermal extraction mass flux rate of 0.0003 $\mathrm{kg\,m^{-2}\,s^{-1}}$. At this thermal extraction mass flux rate, the exergy efficiencies were maximum in the pond considered, whereas no maxima in energy efficiencies were obtained. This shows that an exergy analysis is required for realistic appraisals of SGSP performance. Hence, it's use is recommended in such studies in future.

1. Introduction

Salinity gradient solar ponds (SGSP) simultaneously collect solar energy and store it as thermal energy, and involve a simple technology, with water and salt as the only working materials. With estimated costs as little as one tenth of the cost of equivalent flat plate collectors (Kaushika, 1984), they could easily find applications in low temperature industrial heating processes, including salt and mineral production (Ahmed et al., 2001; Yu et al., 2015), agriculture (Murthy and Pandey, 2002), desalination (Agha, 2009; Leblanc et al., 2010; Ziapour et al., 2016), etc. In addition, solar ponds may also be used for preheating in higher temperature industrial process applications, and power generation utilizing the Rankine cycle. They have also been proposed for thermoelectric power generation (Akbarzadeh et al., 2009; Singh et al., 2011; Ding et al., 2016).

In practice, any water pond with a black bottom is capable of collecting solar energy, as is the case in shallow solar ponds. However, the water heated at the bottom will rise by convection to the top and rapidly dissipate its heat to the environment, thus energy collection efficiencies are characteristically low (Njoku and Ekechukwu, 2011). In contrast, SGSP consist of three layers as shown in Fig. 1. There is an upper convective zone (UCZ) at the top, with a temperature close to ambient and having low salt concentration. There is also a lower convective zone (LCZ) at the bottom, which has a very high salt concentration (typically, close to saturation), and where the highest temperature in the pond is achieved. Temperatures and salt concentrations within these two layers are practically homogeneous due to convection effects. Separating the UCZ and LCZ is the non-convective gradient zone (NCZ), where salt concentration increases with depth. The water in the NCZ cannot rise into the UCZ which has a lower salt content and is therefore lighter. Neither can it fall into the LCZ which has a higher salt content and is thus heavier. Therefore, convective motions are hindered in the NCZ and heat transfer from the hot LCZ to the cold UCZ can only happen via conduction across the NCZ. But since water has a low thermal conductivity, the NCZ layer acts as a transparent insulator, permitting solar radiation to be absorbed and retained for long periods of time in the hot LCZ, from where useful heat may subsequently be withdrawn.

Initial investigations on solar ponds were experimental in nature, and focused on naturally occurring solar lakes (i.e., natural lakes which

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Nomenclature

A	pond cross-sectional area (m^2)
C	salt concentration ($kg\,m^{-3}$)
c_p	constant pressure specific heat ($J\,kg^{-1}\,K^{-1}$)
D	diffusion coefficient ($m^2\,s^{-1}$)
$\dot{E}$	energy flow rates (W)
h_c	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H	overall pond depth (m)
$\overline{H}$	monthly average solar irradiation ($kWh\,m^{-2}$)
L_v	latent heat of evaporation ($kJ\,kg^{-1}$)
m	mass (kg)
$\dot{m}_{ext}$	rate of extraction mass flux ($kg\,m^{-2}\,s^{-1}$)
m_w	extraction mass flow rate ($kg\,s^{-1}$)
P_a,P_{atm},P_v	air, atmospheric and vapor pressures (bars)
$\dot{q}_0$	solar radiation penetrating pond surface ($W\,m^{-2}$)
$\dot{q}_{solar}$	ambient solar radiation intensity ($W\,m^{-2}$)
$\dot{Q}$	thermal energy flow rates (W)
r	pond surface reflectance
R_{th}	thermal resistance (K/W)
RH	relative humidity (%)
$\dot{S}_R(x)$	solar radiation flux at pond depth x ($W\,m^{-2}$)
t	time (s)
T	temperature (K)
V	wind velocity ($m\,s^{-1}$)
x	distance from pond surface (m)

Abbreviations

LCZ	lower convective zone
NCZ	non convective zone
SGSP	salinity gradient solar pond
UCZ	upper convective zone

Greek symbols

δ	thickness (m)
Δ	pond layer thickness (m), change in given quantity
η	energy efficiency
η_x	exergy efficiency
ϵ	water surface emissivity
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan-Boltzamann constant ($W\,m^{-2}\,K^{-4}$)
$\dot{\Xi}$	exergy flow rates (W)

Subscripts and superscripts

0	reference state
amb	ambient
B	referring to bottom of the pond
conc	concrete
conv	convection
d	destruction
ext	extraction
evap	evaporation
g	ground
i	refers to the ith layer
in	input
l	losses
max	maximum
min	minimum
out	output
ov	overall
p	plastic lining
rad	radiation
s	source
st	storage
th	thermal

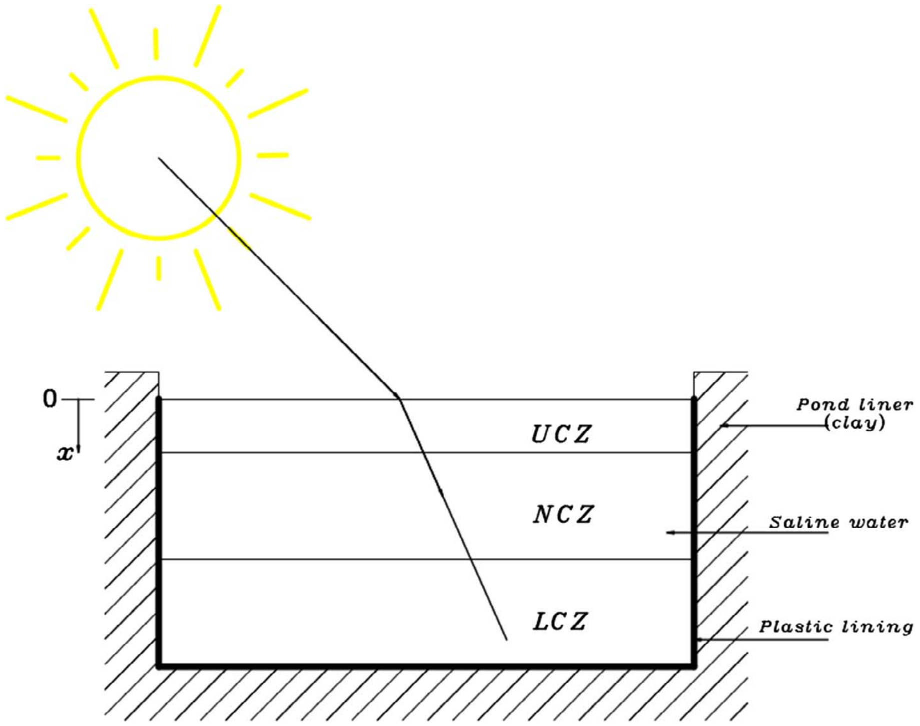

Fig. 1. A schematic representation of a salinity gradient solar pond.