Energy Conversion and Management 167 (2018) 45–62

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Transient theoretical model for the assessment of three heat exchanger designs in a large-scale salt gradient solar pond: Energy and exergy analysis

A. El Mansouri, M. Hasnaoui*, A. Amahmid, Y. Dahani

UCA, Faculty of Sciences Semlalia, Physics Department, LMFE, BP 2390 Marrakesh, Morocco

ARTICLE INFO

Keywords:
Salt gradient solar pond
Thermal storage
Heat extraction
Energy and exergy efficiencies
Heat exchangers

ABSTRACT

This paper deals with transient modelling of a large-scale salt gradient solar pond (SGSP – 50000 m^2) located in a semi-arid climate region. Precisely, the pond was exposed to meteorological data of the Agafay site (located 30 km south of Marrakesh-Morocco) covering the period from January 2015 to May 2017. We considered three different heat extraction technics (HET) including the reference one (R-HET) that limits the heat draw to the heat storage zone using horizontal tubes. The other two methods consider an additional heat draw from the intermediate non-convective zone using horizontal (HT-HET) and vertical (VT-HET) tubes. We elaborated a transient mathematical model based on energy balance equations for the pond (including the ground) and the extraction's tubes. This model was solved using a MATLAB code based on the fully implicit finite-difference scheme that has been developed for this purpose. The study focuses on the examination of the thermal performances of the considered SGSP for each of the three heat extraction methods based on energetic and exergetic analysis. The obtained results reveal that the third method of heat extraction (VT-HET) provides higher energy and exergy efficiencies by reducing the total heat losses towards the pond's surroundings and saving exergy from destruction. The amount of energy/exergy extraction improvement recorded is around 22.5%/30% compared to the reference heat extraction technic (R-HET) against an improvement of only 1.7%/0.6% for the HT-HET.

1. Introduction

Through the last decades, solar ponds have been introduced as a promising alternative to the conventional solar thermal collectors [1–3]. Like other types of solar ponds, the salt gradient solar ponds (SGSP) are characterized by a long-term integral thermal storage capacity suitable for seasonal storage of heat [4,5]. In practice, the SGSPs are always integrated with low-grade temperature applications [6–8] such as heat engines and generators (Rankine cycle) [3,9] for power generation or desalination systems for salt and fresh water production [3,10]. For instance, Saleh et al. [10] have demonstrated the feasibility of a SGSP of 3000 m^2 area coupled with a desalination facility near the Dead Sea in Jordan, able to produce 4 L per minute of hot water in annual average. Otherwise, the heat extracted from the storage zone of the pond (i.e. the heat storage zone: HSZ) is directly used for space heating [11] or provided to processes working with hot water [7]. The solar ponds are characterized by low thermodynamic efficiencies due to the important heat losses toward their environments. Previous attempts have been experimented to improve the thermal efficiency of the SGSP by increasing the amount of input energy and reducing the total heat losses. For example, the recourse to increase the solar radiation reaching the HSZ by using reflectors [12,13], solar collectors [14,15] or by maximizing the solar radiation transmitted toward the storage area (control of clarity) [16,17] are some technics that have been experimented in the past. Another technic that consists to reduce the distance between the free surface and the upper limit of the HSZ, allowing by this fact to shorten the solar radiation path between the free surface and the HSZ (reduction of the attenuation role) was also tested with the aim to improve the efficiency of the SGSP. However, the latter technic engenders an undesirable increase of the conductive heat losses from the HSZ towards the upper convective zone (UCZ). With the objective to reduce the total heat losses, many previous studies were dedicated to experience various heat extraction technics [9,18]. In fact, among other controlling factors (insulation, geometry of the pond, turbidity, etc.), the overall efficiency of the SGSP is highly dependent on the technic of heat extraction. The literature review shows that, in some studies [19,20], various ways of heat extraction were experimented to increase the thermal efficiency of the solar pond. Aboul-Enein et al. [19] have studied theoretically and experimentally the batch-mode of heat extraction. Abdullah et al. [20] have used horizontal polyethylene tubes fixed on the walls of the HSZ and NCZ for their experience of heat extraction from the pond. In previous solar pond's demonstrations

* Corresponding author.
E-mail address: hasnaoui@uca.ac.ma (M. Hasnaoui).

https://doi.org/10.1016/j.enconman.2018.04.087
Received 15 January 2018; Received in revised form 22 April 2018; Accepted 23 April 2018

Nomenclature

T	temperature, (°C)
C	salt concentration, (%)
t	time, (s)
C_p	heat capacity, ($JK^{-1}\,kg^{-1}$)
e	thickness, (m)
q	heat flux, (Wm^{-2})
Q	volumetric heat, (Wm^{-3})
z	height from pond bottom, (m)
U	heat transfer coefficient, ($Wm^{-2}\,K^{-1}$)
a	surface water Albedo
H	pond height, (m)
G_0	solar radiation, (Wm^{-2})
L	pipe length, (m)
i	solar incidence angle, (rad)
d	pipe diameter, (m)
S	pipe section, (m^2)
P	pipe perimeter, (m)
$\dot{m}$	mass flow rate, ($kg\,s^{-1}$)
En	energy surface density, ($MJ\,m^{-2}$)
Ex	exergy surface density, ($MJ\,m^{-2}$)
A	pond area, (m^2)
M	tubes total number
s	specific entropy, ($JK^{-1}\,kg^{-1}$)
h_c	convective heat transfer coefficient, ($Wm^{-2}\,K^{-1}$)
V_w	wind speed, (ms^{-1})

Greek symbols

ρ	fluid density, ($kg\,m^{-3}$)
κ	thermal conductivity, ($Wm^{-1}\,K^{-1}$)
λ	wavelength, (μm)
α	sunlight extinction coefficient in water, (m^{-1})
μ	solar radiation portion transported in a wavelength band
ε	turbidity parameter
τ	water transmissivity of solar radiation
θ	solar radiation refraction angle at the surface, (rad)
δ	declination angle, (rad)
ω	angular hour, (rad)
φ	latitude, (rad)
ϕ	relative humidity, (%)
ΔS	entropy generation, (JK^{-1})
Δt	time step, (s)
η	energy efficiency, (%)
ξ	exergy efficiency, (%)

Subscript & abbreviations

b	bottom
t	top
ab	absorbed
p	pipes
g	ground
c	convective
e	evaporative
r	radiative
a	atmospheric
h	horizontal
v	vertical
in	inlet flow
out	outlet flow
ds	dead state
SGSP	salt gradient solar pond
HTF	heat transfer fluid
R-HET	reference heat extraction technic
HT-HET	horizontal tubes heat extraction technic
VT-HET	vertical tubes heat extraction technic

[6,7], heat was drawn from the most heated zone (the HSZ) of the pond either by using in-pond heat exchangers or external compact heat exchangers. The former are generally shaped by a cluster of polyethylene tubes, placed on the walls and/or the ground of the pond. The hot brine pumped from the HSZ to the external heat exchanger releases its heat load to the heat transfer fluid (HTF) before returning to the pond. Such a technic is not adapted to the extraction from the NCZ. In fact, the extraction/reinjection of water from/to this zone may affect its stability by giving rise to unwanted fluid currents. However, previous studies [21,22] have shown that the extension of the in-pond heat exchanger (a network of tubes suitably arranged) to the NCZ is the most relevant technic proposed up to now for the enhancement of the SGSP global efficiency. For instance, the theoretical analysis conducted by Andrews and Akbarzadeh [21] has shown a considerable improvement (up to 50%) of the overall energy efficiency when extracting heat from both HSZ and NCZ. In fact, their steady state investigation has revealed that the overall efficiency of the studied SGSP has increased from 22% to reach 33%. This result was validated later by an experimental investigation [6] conducted on a small-scale solar pond of 53 m^2 constructed at the RMIT University of Melbourne. The overall efficiency enhancement recorded was about 55% (with respect to the reference case) by involving the NCZ in the heat removal. Furthermore, Date et al. [22] investigated the transient behavior of a SGSP focusing their study on the effect of the mass flow rate of the HTF circulating in the in-pond heat exchanger pipes. The importance of this parameter and the simultaneous heat extraction from the HSZ and NCZ in the enhancement of the SGSP thermal performance has been proved in this study. Regarding their results, the average annual efficiency could be increased from 17% (when they operate the extraction only from the HSZ with a mass flow rate of about 0.25 $g/m^2/s$) to 22% when the extraction is operated from both NCZ and HSZ with a mass flow rate of about 0.15 $g/m^2/s$. In addition, the authors argued that this efficiency could be increased up to 25% while maintaining a minimum temperature difference of about 20 °C between the UCZ and the HSZ. Similar conclusions have been formulated by Ould Dah et al. [23] in their experimental and numerical investigation. These authors have reported that the efficiency of a 0.64 m^2 SGSP could be increased to a value as high as 19.2% by an additional heat draw from the NCZ. However, the authors warned against an eventual reduction of the pond's stability, particularly at the interfaces limiting the NCZ.

Generally, the energetic analysis is commonly used to evaluate the efficiency of the thermal systems [3,24]. The total energy provided to the system is divided into useful and lost energy. For SGSPs, the useful energy is that stored in the pond and extracted from it. Even though the energetic analysis is very useful for the design improvement of the solar ponds, it remains however not enough when it comes to estimate the amount of useful energy. The irreversibility accompanying the thermodynamic processes (energy conversion and storage, heat transfer, etc.) leads inevitably to a reduction of the useful part of the available energy [24,25], named exergy. The unused part of the available energy undergoes a quality degradation termed exergy destruction that deviates the system from its expected ideal operating state. For instance, the energy available in a system that has reached an equilibrium with its surrounding is no longer suitable for use. Furthermore, the exergetic analysis preserves the energy conservation principle by introducing the quality degradation of energy caused by the entropy generation in real