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Power generation enhancement in a salinity-gradient solar pond power plant using thermoelectric generator

Behrooz M. Ziapour *, Mohammad Saadat, Vahid Palideh, Sadegh Afzal

Department of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

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ABSTRACT

Salinity-gradient solar pond (SGSP) has been a reliable supply of heat source for power generation when it has been integrated with low temperature thermodynamics cycles like organic Rankine cycle (ORC). Also, thermoelectric generator (TEG) plays a critical role in the production of electricity from renewable energy sources. This paper investigates the potential of thermoelectric generator as a power generation system using heat from SGSP. In this work, thermoelectric generator was used instead of condenser of ORC with the purpose of improving the performance of system. Two new models of SGSP have been presented as: (1) SGSP using TEG in condenser of ORC without heat exchanger and (2) SGSP using TEG in condenser of ORC with heat exchanger. These proposed systems was evaluated through computer simulations. The ambient conditions were collected from beach of Urmia lake in IRAN. Simulation results indicated that, for identical conditions, the model 1 has higher performance than other model 2. For models 1 and 2 in T_{LCZ} = 90 °C, the overall thermal efficiency of the solar pond power plant, were obtained 0.21% and 0.2% more than ORC without TEG, respectively.

1. Introduction

The air pollution from production and utilization of fossil fuel are the primary causes of global warming [1]. Fossil fuel leads to long term environmental issues such as acid rain and greenhouse effect [2]. Under these conditions, the sustainable and environment-friendly energy resources such as solar energy has been identified as one of the promising sources of energy to replace the non-renewable energy resources. Solar energy, directly or indirectly is the major source of renewable energy available to humankind. In solar engineering of thermal processes, a set of enhancement techniques is widely used to improve the performance of heat exchangers. A salinity-gradient solar pond (SGSP) is a stratified body of water that collects and stores solar energy as thermal energy for long periods of time [3,4]. It normally consists of three layers: the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ). The upper convective zone is a layer of cooler, less salty water. The non-convective zone is a layer where salinity increases with increasing depth. This is the most important layer in a solar pond because the salt gradient suppresses global circulation within the pond. This layer acts as a transparent insulator that permits solar radiation to penetrate to the bottom of the pond. The lower convective zone is a layer of high-salinity brine, which even when heated, remains so dense that it cannot rise to the surface of the pond. This maintained stratification allows the radiation that reaches the bottom of the pond to be stored as heat in the lower convective zone. While is not as efficient as photovoltaic solar collectors, the costs of constructing and operating a solar pond are a fraction of the costs of photovoltaic cells [5]. Solar ponds can provide reliable heat at temperatures between 50 and 90 °C and have a low capital cost since they are based on locally available low- cost materials, and can be incorporated into salinity mitigation schemes [6]. One of the most important applications of solar ponds is to utilize thermal energy stored in LCZ to generate electrical power. For this purpose, solar pond is usually combined with an organic Rankine cycle (ORC) heat engine [7,8]. The ORC has been proven to be a suitable method of converting low-temperature energies into power because of its simplicity, high reliability and ease of maintenance. Due to the advantageous features of the organic fluids of ORC such as low boiling point and high evaporation pressure, the ORC is able to produce power using low-grade heat sources like solar thermal energy [9,10]. Suarez et al. [5] have investigated the main factors that result in differences between small- and large-scale solar pond performances by using a new approach that combines high-resolution DTS data with computational fluid dynamic simulations. Their investigation showed that experimental results

* Corresponding author.
E-mail address: behrooz_m_ziapour@yahoo.com (B.M. Ziapour).

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Nomenclature

A	pond outer surface area (solar pond size), m^2
A_{LCZ}	mean area of the LCZ surface, m^2
A_{NCZ}	mean area of the NCZ surface, m^2
A_{UCZ}	area of the UCZ top surface, m^2
I_r	radiation flux in water at the outer surface of pond, $W\,m^{-2}$
K_{b1}	conductivity of pond liquid relation with the brine LCZ, $W\,m^{-1}\,K^{-1}$
K_{b2}	conductivity of pond liquid relation with the brine UCZ, $W\,m^{-1}\,K^{-1}$
$\dot{Q}_{lb}$	heat loss rate from the pond bottom surface, W
$\dot{Q}_{lsr}$	absorbed heat rate by the LCZ due to solar radiation, W
$\dot{Q}_{lt}$	conduction heat loss through the LCZ top layers, W
$\dot{Q}_{lu}$	useful heat extraction rate from the LCZ, W
$\dot{Q}_{lw}$	heat loss rate from the pond wall surfaces, W
$\dot{Q}_e$	heat transfer rate to Rankine cycle, W
h_{LCZ}	convective heat transfer coefficient in LCZ, $W\,m^{-2}\,K^{-1}$
U_g	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
A_b	pond bottom surface area, m^2
I_{bl}	distance between aquifer and LCZ, m
U_{wl}	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
A_{wl}	area of pond in LCZ, m^2
$\dot{m}_b$	mass flow rate in in LCZ, kg/s
C_{pb}	specific heat of salty water, J/(kg K)
T_{bw}	temperature of outlet brine in LCZ, °C
T_{br}	temperature of inlet brine in LCZ, °C
T_{amb}	ambient temperature, K
T_c	condenser section working fluid temperature, K
T_{c1}	heat exchanger inlet cold side temperature, K
$\bar{T}_{eva}$	mean temperature of the evaporator section of the ORC cycle, K
T_{h1}	heat exchanger inlet hot side temperature, K
T_{h2}	heat exchanger outlet hot side temperature, K
T_{in}	inlet temperature of the evaporator section of the ORC cycle, K
T_{LCZ}	LCZ temperature, K
$TULZ$	ULZ temperature, K
$T_{NCZ,b}$	bottom surface of NCZ temperature, K
$T_{NCZ,t}$	top surface of NCZ temperature, K
T_{out}	outlet temperature of the evaporator section of the ORC cycle, K
$\dot{W}_{net}$	overall net work, W
$\dot{W}_{pump}$	ORC system pump work, W
$\dot{W}_{turbin}$	ORC system turbine work, W
CON	condenser
EVA	evaporator
G	generator
$H.E$	heat exchanger
TUR	turbine
$\dot{Q}_{uu}$	the useful heat transfer rate from the UCZ, W
$\dot{Q}_{usr}$	absorbed heat rate by UCZ due to solar radiation, W
$\dot{Q}_{ub}$	heat loss rate from bottom layer to UCZ, W
$\dot{Q}_{uw}$	heat loss rate from the pond wall surface, W
$\dot{Q}_{uc}$	convection heat loss through the UCZ to ambient, W
$\dot{Q}_{ur}$	radiation heat loss through the UCZ to ambient, W
$\dot{Q}_{ue}$	heat loss due to evaporation, W
h_{xu}	the value of solar radiation in UCZ, %
θ	radiation incident angle, deg
h_c	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
σ	constant of Stefan-Boltzman, $W/(m^2\,K^4)$
E_S	emissivity of the water surface
h_e	evaporation heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
γ	relative humidity, %
V	wind velocity, m/s
$\dot{Q}_{nu}$	the useful heat transfer rate from the NCZ, W
$\dot{Q}_{nsr}$	absorbed heat rate by NCZ due to solar radiation, W
$\dot{Q}_{nb}$	heat loss rate from bottom layer to NCZ, W
$\dot{Q}_{nt}$	conduction heat loss through the NCZ to UCZ, W
$\dot{Q}_{nw}$	heat loss rate from the pond wall surface, W
h_x	the value of solar radiation in NCZ, %
U_{wn}	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
$T_{aquifer}$	aquifer temperature near the NCZ, °C
t_i	insulation thickness, m
k_i	conductive heat transfer coefficient of insulation, $W\,m^{-1}\,K^{-1}$
l_{wn}	distance between aquifer and NCZ, m
K_g	conductive heat transfer coefficient of insulation of soil, $W\,m^{-1}\,K^{-1}$
Z	figure of merit, K^{-1}
T_H	the hot- side temperature of TEM, K
T_C	the cold-side temperature of TEM, K
K_{teg}	thermal conductivity of TEG, $W\,m^{-1}\,K^{-1}$

Greek letters

δ_{LCZ}	LCZ thickness, m
δ_{NCZ}	NCZ thickness, m
δ_{UCZ}	UCZ thickness, m
ε	effectiveness of the heat exchangers used in ORC systems
η_P	pond heat collection efficiency, %
η_0	overall thermal efficiency of the solar pond power plant, %
α	seebeck coefficient, $V\,K^{-1}$

from small- scale solar pond experiments can be used to investigate the expected performance of large-scale solar ponds, as well as the main issues that can decrease the thermal performance of solar ponds. Boudhiaf and Bacar [11] have numerically studied the problem of double-diffusive natural convection in a two dimensional salinity gradient solar pond to analyze the complex flow structure velocity, temperature and concentration distributions in transient regime. They have concluded that the internal Rayleigh number has a very important effect on the temperature of UCZ, NCZ and LCZ. Moreover, the solar heating effect has an important influence on the transient evolution of velocity, temperature and concentration fields.

Ziapour et al. [12] theoretically proposed and investigated an enhanced design of a large scale salinity-gradient solar pond power plant. In their proposed model, some ORC systems and two-phase closed thermosyphons are utilized to generate electricity. They have proved that the larger SGSP is more economically feasible. Their results shows that: (1) The size of the wickless heat pipe was decreased for water as a working fluid within it. (2) The selection of isobutane inside ORC system as a working fluid increases the solar pond power plant performance. (3) The change of pond size did not effect on the overall thermal efficiency of the solar pond power plant.

Agha [13] developed a simulation model describing the thermal behavior and economic feasibility of a solar pond coupled with multi-stage desalination (MSF) system under the conditions prevailing on Tripoli-Libya. Kumar and Kishore [14] reported the technical and economic viability of a 6000 (m^2) solar pond constructed at Bhuj in India. The pond attained a maximum temperature of 99.8 °C in May. The total cost of construction of the solar pond