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Inverse prediction and optimization analysis of a solar pond powering a thermoelectric generator☆

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ABSTRACT

A given temperature difference across the upper and the lower convective zone of a solar pond is commonly sought in thermoelectric power generation. Based on this consideration, this work is aimed at predicting the lengths of various zones of a solar pond to ensure a minimum temperature potential throughout the year between its upper and lower convective zones. For predicting the critical lengths of various zones of the solar pond, at first, the heat energy conservation-based model available in the literature is modified by accounting the effect of salinity and temperature on various thermal parameters. The model is satisfactorily-validated with similar model and experimental data reported in the literature. Thereafter, considering the requirement of a thermoelectric power generator (*TEG*), an inverse problem is solved with the aid of a genetic algorithm-based optimization method to predict feasible lengths of various zones satisfying a minimum temperature potential across *TEG* considering suitable thermal resistances. The present results reveal improved pond dimensions achieving a better temperature profile at a lower total height than that available in the literature. Further, case studies of diverse meteorological conditions of India are carried out and it becomes apparent that, around the year, multiple combinations of convective and non-convective regions of the solar pond can ensure the required minimum (or more) temperature difference across relevant zones of the solar pond. Finally, the present study also reveals that the temperature of the upper convective zone is largely governed by the thickness of this zone, whereas, the thickness of the non-convective zone is largely responsible for the temperature within the storage zone. The present study provides a novel inverse methodology to predict and optimize the suitable dimensions of various regions of a salt-gradient solar pond to ensure a minimum temperature potential across the year for thermoelectric power generation.

1. Introduction

The necessity to use renewable energy resources is increasing due to adverse impacts on the planet, thanks to the use of fossil fuels and other non-renewable resources. Out of various renewable energy sources, solar energy possesses highest possible potential for future (Khalilian, 2017). Contrary to the commonly used solar collectors, solar ponds prove very promising to collect and store the solar energy economically (Velmurugan and Srithar, 2008). A solar pond is a radiation collecting device that traps the radiation either because of the halocline or any other method suppressing the natural convection to its upper layers (Sayer et al., 2018a; Velmurugan and Srithar, 2008). The concept of solar pond was discovered in Hungary where a temperature of 70 °C was observed in Medve Lake (El-Sebaii et al., 2011). Solar ponds are widely used in many applications such as organic Rankine cycle (Nguyen et al., 1995; Wright, 1982), solar desalination (Velmurugan and Srithar, 2007), thermoelectric power generation (Ding et al., 2018; Tundee et al., 2010) to name a few.

Considerable numerical and experimental work on salt-gradient solar ponds is reported in the literature. Initial efforts towards this direction were carried out by Weinberger (1964). In this study, a thermal energy balance model was proposed where the energy equation was solved by superimposing the effects of the radiation absorbed by the pond. This model was further modified by Rabl and Nielsen (1975) considering discrete zones within the pond. Kooi (1979) reported that if the thickness of the non-convective zone (*NCZ*) becomes too high, then it results in deterioration of the solar insolation reaching the storage zone. Furthermore, if the size of *NCZ* is too small, then it results in

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Nomenclature

A	surface area of the solar pond, m^2
A_e	evaporator's outer surface area, m^2
C_s	heat capacity of humid air, kJ/(kg·K)
$c_{p,LCZ}$	specific heat of water in *LCZ*, J/(kg·K)
$c_{p.UCZ}$	specific heat of water in *UCZ*, J/(kg·K)
c_{pl}	specific heat of thermosyphon fluid in liquid phase, J/(kg·K)
D_i,D_o	inner and outer diameters of the thermosyphon, m
F	objective function, °C^2
FR	filling ratio of thermosyphon fluid
f_1,f_2	functions defined for *LCZ* and *UCZ* in Eqs. (14) and (16) respectively
g	gravitational acceleration, m^2/s
h_c	convective heat transfer coefficient between *UCZ* and air, W/(m^2·K)
h_e	heat transfer coefficient outside evaporator, W/(m^2·K)
h_{vl}	latent heat of evaporation of thermosyphon fluid, W/(kg)
h_o	coefficient of heat transfer between atmosphere and outer wall, W/(m^2·K)
h_1	coefficient of heat transfer between *UCZ* and *NCZ*, W/(m^2·K)
h_2	coefficient of heat transfer between *NCZ* and *LCZ*, W/(m^2·K)
h_3	coefficient of heat transfer between *LCZ* with bottom of pond, W/(m^2·K)
h_4	heat transfer coefficient at the ground water level, W/(m^2·K)
I	intensity of solar radiation, W/m^2
I_{TEG}	current induced in *TEG*, A
k_T	thermal conductivity of thermosyphon material, W/(m·K)
k_g	thermal conductivity of soil below the solar pond, W/(m·K)
k_l	thermal conductivity of thermosyphon fluid in liquid phase, W/(m·K)
k_w	water thermal conductivity, W/(m·K)
k_1,k_2,k_3	thermal conductivities of various materials in Eq. (8), W/(m·K)
LB,UB	lower and upper bounds of unknown parameters
LCZ	lower convective zone
L_g	distance between pond's bottom and water table, m
L_{LCZ}	*LCZ* thickness, m
L_{NCZ}	*NCZ* thickness, m
L_{UCZ}	*UCZ* thickness, m
l_1,l_2,l_3	thicknesses of various materials in Eq. (8), m
N	number of discrete divisions of *NCZ*
NCZ	non convective zone
n	number of discrete divisions for time in months
P	power of *TEG*, W
p_a	partial pressure of water vapour at environment temperature, mm of Hg
p_{atm}	pressure due to atmosphere, mm of Hg
p_{UCZ}	partial pressure of water vapour at *UCZ* temperature, mm of Hg
Q	heat transfer rate in evaporator, W
Q_{base}	total heat transfer rate from *LCZ*, W
Q_{cond}	rate of conduction heat transfer between *LCZ* and *UCZ*, W
Q_{conv}	rate of convection heat transfer between *UCZ* and environment, W
Q_{evap}	rate of heat lost from *UCZ* by evaporative transfer, W
Q_{ground}	rate of heat lost to the ground, W
Q_{rad}	rate of heat lost from pond surface by radiative transfer, W
$Q_{s,UCZ}$	rate of heat stored in *UCZ* from the incident solar radiation, W
$Q_{s,LCZ}$	rate of heat stored from the incident solar radiation in *LCZ*, W
Q_{wall}	rate of heat lost from the side walls of the solar pond, W
R	internal electrical resistance of *TEG*, Ω
R_T	thermosyphon's total thermal resistance, K/W
R_1	convective resistance between thermosyphon's evaporator and *LCZ*, K/W
R_2	conduction resistance in thermosyphon wall at evaporator, K/W
$R_{3,p}$	resistance by pool boiling at evaporator, K/W
$R_{3,f}$	resistance due to film boiling at evaporator, K/W
R_4	thermal resistance due to vapour-liquid interface at evaporator, K/W
R_5	thermal resistance due to vapour flow in thermosyphon, K/W
R_6	thermal resistance due to vapour-liquid interface at evaporator, K/W
R_7	resistance due to film condensation at condenser, K/W
R_8	conduction resistance in thermosyphon wall at condenser, K/W
R_9	axial thermal conduction resistance, K/W
S	sensitivity coefficient, °C/m
s	salt concentration, kg/m^3
TEG	thermoelectric generator
T_a	mean environment temperature, °C
T_{HS}	temperature at hot side of *TEG*, °C
T_{sky}	temperature of sky, °C
t	time, s
T_{LCZ}	*LCZ* temperature, °C
T_{UCZ}	*UCZ* temperature, °C
UCZ	upper convective zone
v	mean wind velocity at a given geographical location, m/s
y	*FR* parameter denoting any unknown
y_1,y_2,y_3,y_4	slopes defined for updating T_{LCZ} in Eq. (14), °C/s
z_1,z_2,z_3,z_4	slopes defined for updating T_{UCZ} in Eq. (16), °C/s

Greek symbols

α	Seebeck coefficient, V/°C
χ_c	crossover probability in *FR*
χ_m	mutation probability in *FR*
ε	emissivity of water in the top layer of solar pond = 0.83
ϕ	relative humidity
φ_1,φ_2	figure of merit for pool and film boiling, respectively, K^{-1}
λ	latent heat of vaporization of water = 2250 kJ/kg
μ_l	viscosity of thermosyphon liquid, (N·s)/m^2
ρ_{LCZ},ρ_{UCZ}	water density in *LCZ* and *UCZ*, kg/m^3
ρ_l,ρ_v	working fluid density in liquid and vapour phases, respectively kg/m^3
σ	Stefan-Boltzmann's constant = 5.673 × 10^{-8} W/(m^2·K^4)

more heat losses from the lower-convective zone (*LCZ*) due to decreased insulation. Considering a lumped parameter model for *NCZ* and *LCZ*, Shah et al. (1981) proposed a model where the temperatures at the upper-convective zone (*UCZ*) and air dry bulb temperature were assumed equal. The limitation of their model was its inability to determine the temperature of *UCZ*. This limitation was addressed by Ali (1986), who modified the previous model to compute temperatures of both *UCZ* and *LCZ*. Results of this study were