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A fully coupled, transient double-diffusive convective model for salt-gradient solar ponds

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ABSTRACT

A fully coupled two-dimensional, numerical model that evaluates, for the first time, the effects of double-diffusive convection in the thermal performance and stability of a salt-gradient solar pond is presented. The inclusion of circulation in the upper and lower convective zone clearly shows that erosion of the non-convective zone occurs. Model results show that in a two-week period, the temperature in the bottom of the solar pond increased from 20 °C to approximately 52 °C and, even though the insulating layer is being eroded by double-diffusive convection, the solar pond remained stable. Results from previous models that neglect the effect of double-diffusive convection are shown to over-estimate the temperatures in the bottom of the solar pond. Incorporation of convective mixing is shown to have profound impacts on the overall stability of a solar pond, and demonstrates the need to actively manage the mixing and heat transfer to maintain stability and an insulating non-convective zone.

1. Introduction

A salt-gradient solar pond (termed "solar pond" for this work) is a large-scale solar energy collection system which absorbs solar radiation and stores it as thermal energy for a long period of time [1]. A solar pond consists of three thermally distinct layers (Fig. 1): the upper convective zone, the non-convective zone, and the lower convective zone. The upper convective zone is a relatively thin layer of cooler, less salty water. The non-convective zone has gradients in temperature and salinity and acts as a critical insulator for the thermal storage zone, or lower convective zone. The lower convective zone is a layer of high salinity brine where temperatures are the highest. The solar radiation that penetrates the pond's upper layers and reaches the lower convective zone heats the highly concentrated brine. The heated brine will not rise beyond the lower convective zone because the effect of salinity on density is greater than the effect of temperature. The stored thermal energy can only escape back to the atmosphere from the lower convective zone by conduction, which makes the stability and thickness of the non-convective zone a critical operating parameter for efficient solar pond operation. Because the brine has a relatively low thermal conductivity, the heat losses by conduction are relatively small. The hot brine in the storage zone, which can reach temperatures greater than 90 °C, may then be used directly for heating, thermal desalination, or for other low-temperature thermal applications [2–5].

Previous studies on solar ponds include experimental, analytical, and numerical investigations carried out to understand the thermal behavior under different operating conditions [6–11]. However, almost all of the previous studies were performed using a one-dimensional thermal analysis without consideration of the dynamics of fluid layers. Kurt et al. [7] modeled the non-convective zone as a series of flat layers, including both heat and mass transfer between layers. The upper and lower convective zone were each modeled as a single, homogenous layer. The thicknesses of each zone were assumed fixed, implying that salt diffusion is negligible or controlled (this is reasonable only when freshwater is added to the upper convective zone and highly saline brine is added to the lower convective zone). This one-dimensional model was compared to experimental data from a prototype pond at Istanbul Technical University. The model predicted the shape of the temperature profile; however, the calculated temperature differed from the experimental data by as much as 8 °C. Atkinson and Harleman [8] developed a one-dimensional wind-mixed model for large-scale solar ponds. Using a turbulent entrainment model, they were able to predict the upper convective zone thickness. They showed that wind mixing is a major problem in large-scale solar ponds, and that management of wind effects via floating grids or

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Nomenclature

c_y	wind drag coefficient [–]
c_p	specific heat at constant pressure [J kg C^{-1}]
d	distance [m]
e_a	vapor pressure [N m^{-2}]
e_{sa}	saturation vapor pressure [N m^{-2}]
e_{sw}	saturated vapor pressure at the water surface [N m^{-2}]
f_i	fraction of energy in the ith bandwidth [–]
g	gravitational acceleration [m s^{-2}]
k	thermal conductivity [W m^{-1} C^{-1}]
t	time [s]
y	height [m]
z	depth [m]
A	empirical coefficient (Eq. (28)) [–]
A_s	surface albedo [–]
B	empirical coefficient (Eq. (28)) [–]
C	cloud fraction [–]
D/Dt	substantial (or material) time derivative
DDC	double-diffusive convection
F_{ep}	apparent salt flux [kg s^{-1}]
G_S	salt-gradient [kg m^{-4}]
G_T	temperature gradient [°C m^{-1}]
L	latent heat of vaporization [J kg^{-1}]
L_c	characteristic length [m]
LCZ	lower convective zone
NCZ	non-convective zone
P	pressure [N m^{-2}]
PP	precipitation [m s^{-1}]
P_{atm}	atmospheric pressure [N m^{-2}]
Pr	Prandtl number [–]
Q	heat flux [W m^{-2}]
Ra_S	solutal Rayleigh number [–]
Ra_T	thermal Rayleigh number [–]
RH	relative humidity [%]
S	salinity [%, w/w]
S_i	normalized spectral distribution [–]
Sc	Schmidt number [–]
T	temperature [°C or K]
T_{av}	virtual temperature of air [K]
T_{wv}	virtual temperature of water surface [K]
UCZ	upper convective zone
$\vec{U}$	wind velocity [m s^{-1}]
$\vec{V}$	velocity field [m s^{-1}]

Greek symbols

α_s	solar altitude angle [rad]
β_S	solutal expansion coefficient [%$^{-1}$]
β_T	thermal expansion coefficient [°C^{-1}]
δ_i	attenuation length [m]
ε_a	atmospheric emissivity [–]
η_i	composite attenuation coefficient [m^{-1}]
κ_S	solutal diffusivity [m^2 s^{-1}]
κ_T	thermal diffusivity [m^2 s^{-1}]
μ	dynamic viscosity [N s m^{-2}]
ν	kinematic viscosity [m^2 s^{-1}]
θ	refracted angle of the beam light [rad]
ρ	density [kg m^{-3}]
σ	Stefan-Boltzman constant [=5.67 × 10^{-8} W m^{-2} K^{-4}]
$\vec{\tau}$	wind shear stress [N m^{-2}]
Φ_h	rate of internal heat generation [W m^{-3}]
Δ	difference
∇	gradient
$\nabla\cdot$	divergence
∇^2	Laplace operator

Subscripts/superscripts

0	reference state
a	air
bottom	bottom of the pond
e	evaporative heat
forced	forced convection
free	free convection
i	incident
l	long-wave radiation
max	maximum
min	minimum
net	net heat flux
r	reflected
s	sensible heat
sed	sediment
swr	short-wave radiation
w	water
y	height
z	depth

other structures is important. This was the first work that allowed for a transient upper convective zone; however, the effect of solute (salt) transport on the entrainment process was neglected in their analysis.

Mansour et al. [12] studied the transient heat and mass transfer and stability within a solar pond using a two-dimensional model over a 46-week period. Using the density stability ratio, which is used for static stability, it was found that there are two critical zones: one immediately beneath the water surface, and the other near the bottom of the pond. However, the fluid motion caused by buoyancy within the solar pond was neglected. For this reason, the temperature profile did not show the existence of a well-mixed upper or lower convective zone (i.e., conduction was the dominant process in these zones). Thus, even though some of the instabilities were predicted, mixing in these zones and potential erosion of the non-convective zone were not.

While previous work on stability of solar ponds has been conducted, the coupling and potential mixing of both heat and salt transport has not been included, likely due to the complexity of coupling these transport phenomenons. Mixing, driven by coupled processes, is known as double-diffusive convection (DDC), in which convective motion is driven by buoyancy where two components with different diffusivities exist simultaneously and make opposing contributions to the vertical density gradient [13]. In solar ponds, as in the ocean, the components that are diffusing simultaneously are heat and salt. Several researchers have studied the stability of a thermohaline horizontal layer with linear gradients, such as in the non-convective zone, using linear perturbation theory [14–16]. Results obtained from these investigations have provided information concerning the onset of instabilities inside a solar pond as well as possible unstable or stable states. However, because of the assumption of infinitesimal perturbations or the boundary conditions used, these theoretical findings cannot be extrapolated to real situations where the solar pond is subject to large and drastic perturbations as a consequence of meteorological conditions. Only few researchers have taken into account the double-diffusive phenomena beyond the onset of convection within a solar pond in two dimensions [17,18]. Hammami et al. [17] studied the transient natural convection in an enclosure with a vertical solute gradient. This research used the Navier-Stokes, energy, and