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Thermal analysis and measurement of a solar pond prototype to study the non-convective zone salt gradient stability

Enrique Busquets, Vinod Kumar *, Javier Motta, Rene Chacon, Huanmin Lu

The University of Texas at El Paso, Department Mechanical Engineering, El Paso, TX 79968, USA

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Abstract

Solar ponds combine solar energy collection with long-term storage and can provide reliable thermal energy at temperature ranges from 50 to 90 °C. A solar pond consists of three distinct zones. The first zone, which is located at the top of the pond and contains the less dense saltwater mixture, is the absorption and transmission region, also known as the upper convective zone (UCZ). The second zone, which contains a variation of saltwater densities increasing with depth, is the gradient zone or non-convective zone (NCZ). The last zone is the storage zone or lower convective zone (LCZ). In this region, the density is uniform and near saturation. The stability of a solar pond prototype was experimentally performed. The setup is composed of an acrylic tube with a hot plate emulating the solar thermal energy input. A study of various salinity gradients was performed based on the Stability Margin Number (SMN) criterion, which is used to satisfy the dynamic stability criterion. It was observed that erosion of the NCZ was accelerated due to mass diffusion and convection in the LCZ. It can be determined that for this prototype the density of the NCZ is greatly affected as the SMN reaches 1.5.

Keywords: Salinity gradient solar pond; Stability Margin Number; SMN; UCZ; NCZ; LCZ

1. Introduction

A Solar Pond (SP) is a technology that provides the most convenient and least expensive option for heat storage for daily and seasonal cycles (Lu et al., 2002; Dickinson, 1976; Tabor, 1980). The solar pond consists of three distinct zones (Hassairi et al., 2001). The first zone, which is located at the top of the pond and contains the least dense saltwater mixture, is the absorption and transmission region, also known as the upper convective zone (UCZ). The second zone, which contains a variation of saltwater densities increasing with depth, is the gradient zone or non-convective zone (NCZ). The main purpose of this zone is to act as an insulator to prevent heat from escaping to the UCZ, maintaining higher temperatures at deeper zones.

The last zone is the storage zone or lower convective zone (LCZ). In this region, the density is uniform and near saturation. Fig. 1 shows the schematic of a closed cycle salt-gradient solar pond.

Solar pond operation depends on weather conditions and the physical and chemical characteristics of the brine. Evaporation and rainfall affect the salinity and depth of the SP and its thermal output relies on the available solar radiation (Alagao, 1996). Furthermore, the thermal performance of a solar pond is a function of solar irradiation, heat losses from the sides to the surroundings and from the LCZ towards the upper layers, and ultimate storage capacity (Jaefarzadeh, 2004; El-Sebaii et al., 2006). It is important therefore, to control external effects to its best. Physical conditions also have an impact on the efficiency, since the convection in the upper convective zone and lower convective zone lead to erosion at the boundaries

* Corresponding author.
E-mail address: vkumar@utep.edu (V. Kumar).

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Nomenclature

$\dot{Q}$	overall heat transfer rate (W)	*Greeks*	
T	temperature (T)	ρ_{sat}	density of the saturated brine (kg/m^3)
R	thermal resistance (W/m K)	ρ_z	average density of the nth step (kg/m^3)
A	area (m^2)		
k	thermal conductivity (W/m K)	*Subscripts*	
h	heat transfer coefficient (W/m^2 K)	∞	ambient
r	radius (m)	inj	injected
m	mass (kg)	sat	saturation
S	salinity (%/l)	surr	surroundings
V	volume (m^3)	total	equivalent
$\dot{V}$	volume flow rate (m^3/s)	z	height position
t	time (s)		

of the gradient zone. This shows the importance of the thickness and proper maintenance of the gradient layer, and the reason why researchers have spent so much time analyzing and studying the thickness and structure of the gradient zone to achieve maximum performance (Karakilcik, et al., 2008; Prasad and Rao, 1996; Simic, et al., 2009).

The purpose of the project is to predict the stability of the salt gradient in a laboratory-style solar pond prototype, with a heating element at the bottom of the pond providing the energy that the sun would otherwise provide. A computer algorithm is used to calculate a variety of pond parameters, which then are compared to experimental data. This data serves as validation for the solar pond prototype.

2. Technical background

During the past two decades, a substantial amount of research into solar energy desalination has been undertaken (Lu et al., 2002). A lot of theoretical studies have concentrated on modeling the heat and salt diffusion within the SP for predicting its stability and performance (Bezir et al., 2008; Dah et al., 2005; Karim et al., 2010; Liao, 1987; Suarez et al., 2010). Weinberger was the first to give a mathematical formulation of the behavior of a salinity-gradient SP. He identified and analyzed many important processes for the salinity gradient such as absorption of the solar radiation by the brine solution. He found that a difference of concentration of about 340 kg/m^3 is required to maintain the stability in a 1 m deep magnesium chloride pond having 0.2 m mixing layer at the bottom whereas a similar sodium chloride pond will go instable during periods of intense radiation (Weinberger, 1964). Nielsen showed that the boundary between surface and gradient zones moes down as a result of increasing salinity zone in the surface zone as a result. He showed that effect of daily ambient air temperature change on fluctuation of boundary level between surface and gradient zones can be negligible when the effect of the wind and evaporation is fairly small (Nielsen, 1978, 1980; Zhang and Nielsen, 1994). The internal stability of the gradient zone is defined by the Stability Margin Number (SMN), as introduced by Xu (1990). SMN is defined as the ratio of the measure stability coefficient to the calculated stability coefficient required to stability the dynamic stability criterion. Xu (1990) discussed thoroughly SP stability and other dynamical processes. Related works were reported by Witte and Newell (1985), Zangrando (1991), and Schladow (1985). Wang and Akbarzadeh (1982) modeled SP thermal behavior, and Subhakar and Murthy (1993) carried out parametric studies on saturated SP. Hull et al. (1989) discussed in detail SP thermal performance.

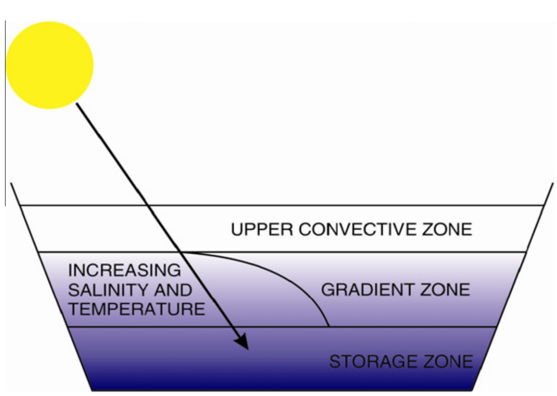

Fig. 1. Solar pond typical schematic (UTEP, 2011).

In 1996, Alagao stated that the upper convective zone salinity must be kept as low as practical, and the lower convective zone salinity as high enough to maintain high operating temperatures. He also studied one dimensional simulation model for a closed-cycle salt-gradient solar pond through three modes of salt recycling. These modes were the Rising Pond, with pure injection that dealt with injecting concentrated brine at the top of the lower convective zone, the Rising Pond, with simultaneous injection and withdrawal of brine, and finally the Seasonal Surface Flushing (Alagao, 1996). Here, he utilized Finite Difference equations to generate the one-dimensional salinity and temperature solutions.