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An experimental and numerical study of evaporation reduction in a salt-gradient solar pond using floating discs

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ABSTRACT

Salt-gradient solar ponds are water bodies that act as solar collectors with integrated storage that are a promising renewable energy source for low-temperature applications. Evaporation is an important challenge for efficient operation of solar ponds, especially in arid locations without water sources to replenish the evaporative losses. In this work, transparent partial covers were used to investigate how evaporation suppression affects both the water and energy balance of a laboratory-scale solar pond. In our experiments, the evaporation reduction efficiency was related to the cube root of the relative covered area. This evaporation reduction efficiency is smaller than that of natural water bodies because of the influence of the warm lower convective zone. Also, as the covered fraction of the surface area increased, the thickness of the non-convective zone decreased and the heat losses through this zone increased. As a result, the temperature in the lower convective zone did not increase as the covered fraction increased. Nonetheless, the heat content within the solar pond slightly increased, demonstrating that the reduction of evaporation improves the heat storage capacity of the pond. Moreover, an economic analysis showed that although the evaporation reduction efficiency in solar ponds is smaller than that of natural water bodies or reservoirs, the benefits related to the additional energy collected in the solar pond when reducing evaporation overcome the smaller water saving benefits. Therefore, suppressing evaporation in solar ponds not only is valuable in locations with no water to replenish the evaporative losses but also improves its economic benefits.

1. Introduction

A solar pond is a water body that is warmed by solar radiation and that can provide long-term heat storage (Rabl and Nielsen, 1975; Suárez et al., 2010a,b; Valderrama et al., 2011; Sayer et al., 2016). These ponds are artificially stratified so the heat is stored in its bottom (Suárez et al., 2010c; Alcaraz et al., 2016). A typical salt-gradient solar pond is comprised by three characteristic layers. The uppermost layer is called the upper convective zone (UCZ), which is a relatively thin layer of water with a small or negligible salt concentration. The middle layer is named non-convective zone (NCZ) and it has a strong salt (or density) gradient that stabilizes the fluid within the pond. When the pond is warmed, the NCZ exhibits a thermal gradient that increases with depth. The NCZ is probably the most important layer in a solar pond because it suppresses global convection within the pond. At the same time, the NCZ acts as a thermal insulator of the bottommost layer of the pond – the lower convective zone (LCZ). The LCZ is a layer of high-salinity brine that is warmed by solar radiation absorption. The LCZ reaches the highest temperature inside the pond and is where solar energy can be stored as heat. Temperatures higher than 80 °C have been achieved in many salt-gradient solar ponds around the world (Kumar and Kishore, 1999; Lu et al., 2004). Hence, the energy collected in these systems can be used for low-temperature thermal applications such as space or greenhouse heating, underfloor heating, thermal desalination, industrial water heating, among others (Rabl and Nielsen, 1975; Shah et al., 1981; Mohamud, 1995; Lu et al., 2001; Garrido and Vergara, 2013; Suárez et al., 2015).

Salt-gradient solar ponds differ with most natural water bodies in that the temperature of the bottom of the pond is warmer

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Nomenclature

c	parameter used to scale the evaporation reduction efficiency (ε) as a function of the covered fraction of the surface area (χ)
dz	thickness of a differential element used to derive the energy balance
i	node or index to reference the position inside the solar pond
k	thermal conductivity of the fluid
q_b	heat loss through the bottom of the pond
q_i	incident radiation
q_k	vertical conductive heat flux through the NCZ
q_{kL}	conductive heat flux transmitted from the LCZ to the NCZ
q_{kU}	conductive heat flux coming from the NCZ towards the UCZ
q_r	shortwave radiation that penetrates into the water column
q_{rL}	shortwave radiation that crosses the NCZ-LCZ interface ($z = z_L$)
q_{rU}	shortwave radiation that is stored in the UCZ
$q_r\,(z)$	shortwave radiation flux at a depth z
q_s	heat loss through the water surface
q_{use}	useful energy extracted from the LCZ
q_{wL}	heat loss through the sidewalls of the LCZ
q_{wN}	heat loss through the sidewalls of the NCZ
q_{wU}	heat loss through the sidewalls of the UCZ
z_U	depth of the UCZ-NCZ interface
z_L	depth of the NCZ-LCZ interface
B_i	constant that appears in the solution of the energy equation
C_1	integration constant that appears when solving the energy equation
C_2	integration constant that appears when solving the energy equation
EC	electrical conductivity
E	evaporation rate for an uncovered reservoir
E_C	evaporation rate for a partially covered reservoir
LCZ	lower convective zone
N	number of data points used to determine the $RMSE$
NCZ	non-convective zone
P	perimeter of the pond
$RMSE$	root mean square error
S_C	evaporating area of a partially covered reservoir
S	evaporating area of an uncovered reservoir
$T\,(z)$	thermal profile
T_g	temperature of the environment that surrounds the sidewalls of the pond
T_i^e	experimental temperature at position i
T_i^m	modeled temperature at position i
T_L	temperature of the LCZ
T_U	temperature of the UCZ
UCZ	upper convective zone
U_N	overall heat transfer coefficient of the NCZ sidewalls
α	fraction of radiation that penetrates the water surface
χ	covered fraction of the surface area ($\chi = 1 - S_C/S$)
ε	evaporation reduction efficiency ($\varepsilon = 1 - E_C/E$)
ξ	auxiliary variable used to solve the energy equation
λ	extinction coefficient of light in the fluid
$\theta\,(z)$	auxiliary variable used to solve the energy equation
Φ_h	shortwave radiation modeled as a volumetric heat source

than that of the surface. This warmer water also transports heat to the surface of the water body, warming the UCZ. Therefore, the temperature of the surface of a solar pond is typically larger than that of a natural lake. As a consequence, the evaporation rates in solar ponds are expected to be larger than those observed in natural water bodies. Moreover, one of the inefficiencies of solar ponds is the water loss due to evaporation (Ruskowitz et al., 2014; Suárez et al., 2014a, 2015), which is intrinsically linked to heat losses through the surface of the pond (Bozkurt et al., 2014). Therefore, evaporation suppression represents an important challenge in the operation of solar ponds, particularly in locations that do not have a sustainable water supply to replenish the water that evaporates from the UCZ. Recently, some efforts have been carried out to improve the performance of salt-gradient solar pond by studying different methods to reduce evaporation (Bozkurt et al., 2014; Ruskowitz et al., 2014), but the scientific literature lacks of studies about this subject.

This work combines experiments and numerical simulations with the aim of exploring how evaporation reduction – using transparent floating covers – influences both the water and energy balance inside the pond. It investigates how the internal configuration affects the performance of a solar pond, and provides economic considerations that must be taken into account when suppressing evaporation using floating covers. The structure of this paper is as follows: first, we present a literature review on evaporation suppression both in reservoirs and in solar ponds. Then, we describe the materials and methods used in this investigation. Next, we present the results and discussions. Finally, the most important conclusions are highlighted.

2. Literature review

2.1. Evaporation suppression in reservoirs

One of the main problems in reservoirs around the world is water loss through evaporation (van Dijk and van Vuuren, 2009; Al-Hassoun et al., 2009; Assouline et al., 2011). Reducing this water loss has become an important matter, especially in Countries with high availability of solar radiation (Assouline et al., 2010; Bozkurt et al., 2014). Many studies of evaporation suppression have been carried out in water reservoirs (Cooley and Myers, 1973; Burston and Akbarzadeh, 1999; Burston, 2002; Craig, 2005; Martínez-Álvarez et al., 2006; van Dijk and van Vuuren, 2009; Al-Hassoun et al., 2009; Gallego-Elvira et al., 2010). van Dijk and van Vuuren (2009) performed a study in South Africa to reduce surface evaporation by injecting air bubbles into the reservoir to de-stratify the water column. The idea behind this approach was to drive the cooler water particles that are in the bottom of the reservoir towards the water surface to reduce the vapor pressure deficit that drives evaporation. van Dijk and van Vuuren (2009) were not able to confirm their hypothesis because the reservoirs they used were too shallow. Additionally, note that this approach for evaporation reduction is not appropriate for salt-gradient solar ponds because it destructs the stability of the water body. Al-Hassoun et al. (2009) performed an evaporation suppression study by covering a reservoir with small palm leaves. They were able to reduce evaporation losses in 63% when the reservoir surface was fully covered with the leaves. In addition, the leaves did not have negative effects on the reservoir's water quality. Although this study demonstrated the effectiveness of covering a reservoir to