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An analytical estimation of salt concentration in the upper and lower convective zones of a salinity gradient solar pond with either a pond with vertical walls or trapezoidal cross section

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ABSTRACT

Renewables offer the best opportunity to reduce greenhouse gases and introduce sustainable and desirable solutions to the world's increasing demand for energy. Solar ponds are a simple, low-priced and efficient way to collect and store incident solar radiation; they have enormous capacity and huge unrealised potential. The most effective and widely-used type is the salinity gradient solar pond (SGSP), which can provide long-term storage, large capacity, and sufficient year-round power for a wide range of domestic, industrial and commercial purposes. It is essential to understand the best forms of construction and maintenance, including how to overcome the most significant challenge, that of establishing the different layers of water with their varying levels of saline concentration, as well as how to maintain these levels for optimal performance. This study investigates how to predict variations in salt concentrations over the pond's lifetime, in order to maintain maximum performance. The paper derives analytical formulae to calculate how concentrations in the upper and lower convective zones (UCZ and LCZ) change over time. It also explores the different responses of ponds with vertical walls and inclined walls. The computed concentrations were compared with actual measurements from a small experimental pond, which had a surface area of 1 m^2 and a total depth of 1 m, comprising UCZ, non-convective zone (NCZ) and LCZ with depths of 0.1, 0.5, and 0.4 m respectively. The results were also compared with the results of previous experiments from established ponds. An acceptable agreement was achieved. The results illustrated that the derived formulae can be used to estimate salt concentrations in the UCZ and LCZ. The outcomes also show that the inclination of the walls affects concentration levels in the UCZ, while its impact on the LCZ concentration is slight. The findings of this study could form the basis of future research, which could investigate other factors affecting salt concentration in the layers of a SGSP, such as wind speed, temperature and the timing of salt injections to the LCZ.

1. Introduction

The world is facing significant challenges in the field of energy, including tackling the high level of pollutants produced by the use of conventional fuels, and meeting increasing demand. This creates a need for clean energy sources, so greenhouse gas emissions can be eliminated or significantly reduced. Renewables are likely to be the best alternative to traditional fuels, because they are sustainable and clean, with zero or low emissions. Solar energy is appropriate for many developing and undeveloped countries, which have suitable weather for its exploitation. It is among the most significant categories of renewables and has seen a substantial increase in use in recent years (IPCC report, 2012; Napoleon and Akbarzadeh, 2013; Gude, 2015; Sayer et al., 2017).

A solar pond can be defined as a body of water which can collect and store solar energy. There are several types of solar pond, all of which can be classified as convective or non-convective (El-Sebaii et al., 2011; Ranjan and Kaushik, 2014). Sayer et al. (2016) demonstrated the types of solar pond with a diagram, shown in Fig. 1.

By definition, convection usually occurs in convective solar ponds. They are typically shallow, with a depth of 5–15 cm. Unlike in the non-convective solar ponds, there is no insulating layer or non-convective zone (NCZ) in the shallow ponds to suppress heat loss by convection (El-Sebaii, 2005). The limited heat capacity of the shallow pond confines its applications. The most significant type of non-convective ponds appearing in Fig. 1 is the salinity gradient solar pond (SGSP).

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Nomenclature

A_{cL}	the cross-sectional area of the LCZ (m^2) of a pond with a trapezoidal shape
A_{cu}	the cross-sectional area of the UCZ (m^2) of a pond with a trapezoidal shape
A_{LCZ}	the surface area of the LCZ (m^2) of a pond wit vertical walls
A_{sL}	the surface area of the LCZ (m^2) of a pond with a trapezoidal shape
A_{UCZ}	the surface area of the UCZ (m^2)
a	constant
C_{LCZ}	the concentrations of the LCZ (kg/m^3)
C_{UCZ}	the concentrations of the UCZ (kg/m^3)
c	constant
D	the salt diffusivity (m^2/s)
d	the pond's depth (m)
h	the chosen height along the depth of the pond (m)
h_{LCZ}	the depth of the LCZ (m)
h_{UCZ}	the depth of the UCZ (m)
K	an expression ($\frac{h_{LCZ} X_{NCZ}}{D}$)
K_1	an expression ($\left(\frac{W_{tL}+W_b}{2}\right) h_{LCZ} \frac{X_{NCZ}}{D W_{tL}}$)
L	laplace transform
L^{-1}	inverse Laplace transform
L_t	the length of the pond (m)
R	an expression ($\frac{h_{UCZ} X_{NCZ}}{D}$)
R_1	an expression ($\left(\frac{W_{bu}+W_t}{2}\right) h_{UCZ} \frac{X_{NCZ}}{D W_{bu}}$)
t	time (day)
V_{LCZ}	the volume of the LCZ (m^3)
V_{UCZ}	the volume of the UCZ (m^3)
W_b	the width at the bottom surface of the pond (m)
W_d	the width at a specific depth h (m)
W_t	the width at the top surface of the pond (m)
W_{tL}	the width of the pond at the top surface of the LCZ (m)
W_{bu}	the width of the pond at the bottom surface of the UCZ (m)
X_{NCZ}	the depth of the NCZ (m)
ΔC_{LCZ}	the change in the concentration of the LCZ at any time
ΔC_{UCZ}	the change in the concentration of the UCZ at any time

Abbreviation

LCZ	lower convective zone
NCZ	non-convective zone
UCZ	upper convective zone
SGSP	salinity gradient solar pond

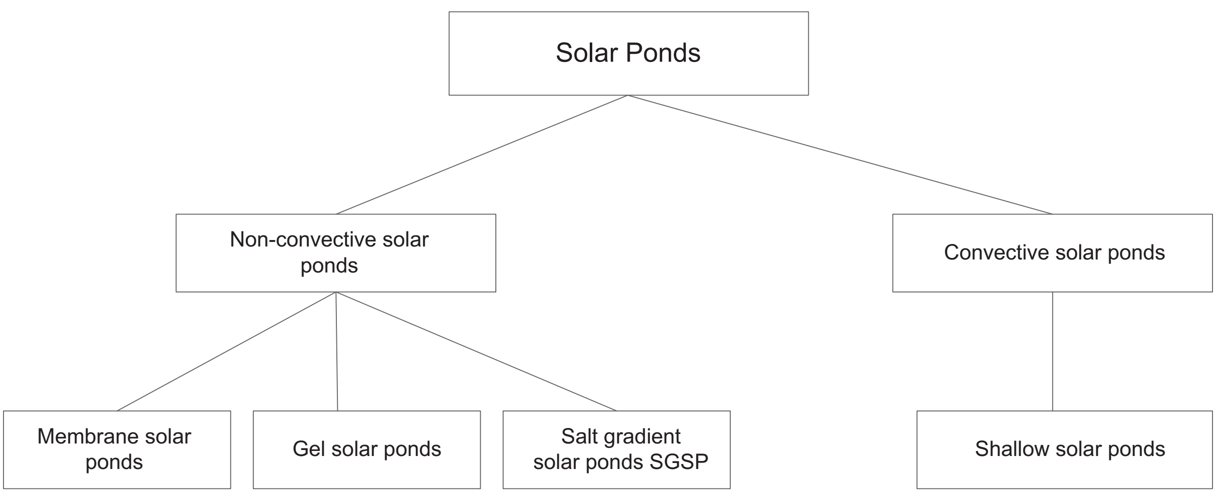

Fig. 1. Categories of solar ponds (Sayer et al., 2016).

1.1. Salinity gradient solar ponds

Salinity gradient solar ponds (SGSPs) are constructed in many parts of the world, and have many different purposes. Their most significant attractive characteristic is their ability to provide long-term storage and large thermal capacity. This storage enables the pond to supply heat throughout the entire year, regardless of the season. They can supply thermal energy to a wide range of applications that require low-grade heat to run, such as systems used for heating buildings, homes, greenhouses and swimming pools. They can also be exploited for power generation, through coupling to organic Rankine cycles, and water desalination; a range of industries such as dairy and food businesses have also been explored (Silva et al., 2017; Nakoa et al., 2016; Ruskowitz et al., 2014; Hull, 1980; Agha, 2009; Liu et al., 2013; Gude et al., 2012; Dehghan et al., 2013; Antipova et al., 2013; Ghaffour et al., 2014; Salata and Coppi, 2014; Abbassi Monjezi and Campbell, 2016). Ranjan and Kaushik (2014) pointed out that solar ponds with a surface area of 1000 m^2 or more are more cost effective than flat plate collectors. Abbassi Monjezi and Campbell, 2016's model showed that as the pond starts to get warmer; the hottest zone gradually moves from the NCZ towards the LCZ and settles there. They claimed that this phenomenon challenges the conventional model which assumes that the LCZ becomes the hottest zone in the SGSP directly after the beginning of the thermal heat collection operation.

A salinity gradient solar pond is comprised of three zones: the surface layer or upper convective zone (UCZ), the middle layer or non-convective zone (NCZ) and the lower convective zone (LCZ). The UCZ is approximately homogenous, and usually contains fresh water. The NCZ has a salinity gradient, with decreasing concentrations from the bottom to the top. The lower zone (LCZ) has the highest salinity, usually close to saturation, and is designed to store the incoming solar radiation (Date and Akbarzadeh, 2013; Jaefarzadeh, 2004; Alagao et al., 1994; Assari et al., 2015; Suarez et al., 2015; Ziapour et al., 2016). Because the NCZ has a downward positive salinity gradient, it suppresses the heat loss by natural convection which would be anticipated in fresh water. Scientists therefore named the pond the salt gradient solar pond or the salinity gradient solar pond (Velmurugan and Srithar, 2008; Sayer et al., 2016; Hull et al., 1984; Leblanc et al., 2011; Tundee et al., 2010).

A large number of studies have explored SGSPs, most of them