

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

# CONSTRUCTAL DESIGN OF SALT-GRADIENT SOLAR POND FIELDS

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Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

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To my family and my girlfriend, for their constant support.

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#### RESUMEN

Las piscinas solares con gradiente salino (SGSPs) son cuerpos de agua que pueden capturar y acumular grandes cantidades de energía proveniente del sol. El diseño de un campo de SGSP nunca ha sido analizado en términos del estudio del número óptimo de piscinas que se deben construir para maximizar la energía útil generada por dicho campo, o la manera más conveniente de conectar las piscinas. En este estudio, se utiliza diseño constructal para encontrar la configuración óptima de un campo de SGSP. Se desarrolló un modelo térmico en estado estacionario para estimar la energía producida por cada SGSP, y luego se generó un modelo complementario para determinar la temperatura final de cierto flujo másico de un fluido que se calienta por intercambiadores de calor conectados a piscinas solares. Empleando diseño constructal, se evaluaron cuatro configuraciones para el campo de SGSP, con distinta distribución del área superficial: configuraciones serie, paralelo, mixta serie-paralelo y en forma de árbol. Para el sitio de estudio en esta investigación, se encontró que la configuración óptima de un campo de SGSP consiste en 30 piscinas solares con distribución creciente del área superficial conectadas en serie. Este campo de SGSP incrementa la temperatura final del fluido a calentar en un 22.9% en comparación a la obtenida para una única SGSP que cubra el mismo territorio. Los resultados de este estudio muestran que es posible utilizar la teoría constructal para optimizar aún más la transferencia de calor en un campo de SGSP. En el futuro serían útiles resultados experimentales de estas configuraciones para validar la metodología propuesta en este estudio.

Palabras Claves: Energía solar, piscinas solares con gradiente salino, diseño constructal.

#### ABSTRACT

Salt-gradient solar ponds (SGSPs) are water bodies that capture and accumulate large amounts of solar energy. The design of an SGSP field has never been analyzed in terms of studying the optimal number of solar ponds that must be built to maximize the useful energy that can be collected in the field, or the most convenient way to connect the ponds. In this study, constructal design is used to find the optimal configuration of an SGSP field. A steady-state thermal model was constructed to estimate the energy collected by each SGSP, and then a complementary model was developed to determine the final temperature of a defined mass flow rate of a fluid that will be heated by heat exchangers connected to the solar ponds. By applying constructal design, four configurations for the SGSP field, with different surface area distribution, were evaluated: series, parallel, mixed series-parallel and tree-shaped configurations. For the study site of this investigation, it was found that the optimal SGSP field consists of 30 solar ponds of increasing surface area connected in series. This SGSP field increases the final temperature of the fluid to be heated in 22.9%, compared to that obtained in a single SGSP. The results of this study show that is possible to use constructal theory to further optimize the heat transfer of an SGSP field. Experimental results of these configurations would be useful in future works to validate the methodology proposed in this study.

Keywords: Solar energy, salt-gradient solar pond, constructal design.

#### 1. INTRODUCTION

To achieve sustainable development, the current world approach to energy is toward finding more alternatives for renewable energy sources. In addition to the well-known methods to collect solar energy (e.g., photovoltaic cells, solar collectors and solar cells), salt-gradient solar ponds (SGSPs) appear as an alternative method for solar collection and storage of low-grade heat (Ranjan and Kaushik, 2014).

SGSPs are water bodies that capture and accumulate solar energy for long time periods (Ruskowitz et al., 2014; Suárez et al., 2014a). These are artificially stratified by dissolving salts with different concentrations to form three characteristic zones (Figure 1-1): the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ), which is also known as the storage zone. The UCZ is a thin layer of water with low salinity and temperature. The NCZ is a layer formed by a salinity gradient where temperature increases with depth. Because the effect that the salinity gradient has over the density of the fluid is larger than that of temperature, the NCZ acts as a static barrier of fluid that suppresses global convection within the solar pond. This density gradient allows the NCZ to insulate the LCZ. The LCZ is a layer of fluid with high levels of temperature and salinity. The solar radiation that reaches the LCZ warms the hot brine and allows storing significant amounts of energy (Ranjan and Kaushik, 2014), which can be used in low-temperature applications, such as building heating (Rabl and Nielsen, 1975; Styris et al., 1976), thermal desalination (Suárez et al., 2010a; Suárez et al., 2015), industrial heat process (Garrido et al., 2012; Garrido and Vergara, 2013), among other applications (Kumar and Kishore, 1999; Murthy and Pandey, 2002; Singh et al., 2014).

Solar ponds have been built in many locations around the world (Hull et al., 1989), ranging from small experimental solar ponds (~1 m<sup>2</sup> of surface area) to large solar ponds (~20 ha). For instance, the Beith Ha'Arava Solar Pond Power Plant had a surface area of 210,000 m<sup>2</sup> and sustained a 5 MW<sub>e</sub> power plant (Tabor and Doron, 1990). To store maximum energy, it is common to have a single SGSP with a surface area that covers most of the available land. Some works have proposed to build more than one SGSP to allow energy collection and storage in case one pond is not working properly (e.g., see Garrido and Vergara, 2013) or for another purposes (e.g. see Tabor and Doron, 1990). However, the design of a solar pond field has never been analyzed in terms of number of solar ponds that must be built to maximize the useful energy, or the most convenient way to connect the ponds.



Figure 1-1: Configuration of the SGSP and the heat fluxes used to develop the mathematical model.

A promising way to improve the architecture of a finite-size flow system is the use of constructal design (Bejan and Lorente, 2008). Constructal theory proclaims the existence of an equilibrium flow architecture; or nature flow architecture, where all the possibilities of incrementing the performance of the system have been exhausted. This theory indicates a pathway or a strategy to be followed that helps finding the best configuration of a system –in this case an SGSP field– to minimize the resistances of the system's flow currents. The flow currents could be fluid flow (Wechsatol et al., 2006), heat flow (Lorente et al., 2010a, 2015), strain (Lorente et al., 2010b), or the flow of any other substance that flows within the system (Kim et al., 2006; Lui et al., 2015).

Constructal theory has been utilized in many applications (Bejan and Lorente, 2008; Lorente et al., 2010; Feng et al., 2015). Wechsatol et al. (2001) developed an optimal design of a network of pipes to uniformly distribute hot water around an area. Kim et al. (2006) designed the optimal shape of the flow architecture in self-healing vascular materials. They systematically solved the best way to distribute the flows by reducing their global resistance, and then this finding was reinforced with an analytical optimization. Miguel (2008) investigated the generation of solar energy-based systems architecture using constructal theory. He studied a shading system to control the incoming solar radiation during summer and winter, a bundle of pipes to warm a room, and a distillation system integrated in the roof. Lorente et al. (2010a) showed how to use the constructal theory to design the most efficient geometry of a solar chimney power production plant on an available land area. First, they found the relationship between maximum power and geometry, and demonstrated that the maximum power increases monotonically with the length scale of the plant. They presented several arrangements for distributing the multi-scale plants on a square area: few large and many small in the right arrangement. The most important factor in their design is the land area allocated to the largest plant. They showed that the efficiency in power production also depends on the total land area that is being used. Lorente et al. (2012) presented the fundamental tradeoffs that underpin the design of a distributed energy system with two objectives: the production and distribution of electric power driven by solar heating, and desalinated water produced by consuming solar power.

This work evaluates the feasibility of designing an SGSP field using the principles of contructal law (Bejan and Lorente, 2008). The objective of this work is to find the best configuration of an SGSP field (shape and size of each solar pond, and distribution and number of ponds in the SGSP field) that can maximize the useful energy produced by the system. To achieve this objective, a one-dimensional steady-state thermal model was developed to estimate the energy collected by each SGSP; next, the final (outlet) temperature of a mass flow rate to be heated in an SGSP field of fixed land area was calculated for different architectures of the SGSP field. The application of the constructal theory not only allowed understanding of the processes that maximize the outlet temperature, but also why some configurations perform better than others. In this work, the methodology to design an SGSP field was applied in the province of Copiapó, Chile, to pursue sustainable urban development in the city. Nonetheless, the approach

#### 2. METHODS

First, a mathematical model was developed to estimate the thermal behavior of an SGSP. This model is used to determine the SGSP thermal profile, to optimize the size of the SGSP, and to estimate the temperatures of the heat exchanger used to extract the energy from the pond. Second, a complementary model was developed to determine the final temperature of a defined mass flow rate of a fluid (water) that will be heated through the heat exchangers connected to the SGSP field.

#### 2.1 Thermal behavior of a single SGSP

#### 2.1.1 SGSP model

Several computational models have been developed to optimize the performance of an SGSP. There are many one-dimensional studies in steady or transient conditions (Kurt et al., 2000; Dah et al., 2010; Suárez et al, 2010a), and more sophisticated two-dimensional models that analyze in detail the hydrodynamics inside the pond (Suárez et al., 2010b; Wang et al., 2011; Boudhiaf et al., 2012). In general, the one-dimensional steady models provide a good first approximation to determine the thermal performance of a solar pond, especially for analyzing changes in performance against parameter variations (Weinberger, 1964; Rabl y Nielsen, 1975; Kooi, 1979; Wang and Akbarzadeh, 1983; Ali, 1986).

In this study, a simplified one-dimensional thermal model has been developed for an SGSP under steady state conditions. The model estimates the thermal profile within the SGSP using the following assumptions: 1) the UCZ and LCZ are completely mixed, i.e., they have a uniform temperature; 2) the UCZ-NCZ and NCZ-LCZ interfaces are at a fixed depth  $z_U$  and  $z_L$ , respectively, as shown in Figure 1-1; 3) the SGSP has a stable configuration; 4) the thermal properties of the fluid are constant; 5) the temperature of the ground that surrounds the pond is constant and uniform; and 6) all the radiation that reaches the LCZ is absorbed by the fluid in this zone. Appendix A provides a detailed description of the mathematical model. Here we outline the principles used to develop the model.

The mathematical model is based on the energy conservation principle within the different zones of the SGSP. In the UCZ, the energy balance considers shortwave radiation, heat losses through the water surface, heat losses through the sidewalls, and conductive heat flux coming from the NCZ. In the LCZ, the energy balance takes into account shortwave radiation, heat losses through the bottom of the pond, heat losses through the sidewalls, useful energy, i.e., the energy extracted from the pond, and conductive heat flux transmitted to the NCZ. The energy balance in both the UCZ and LCZ considers that the temperatures of the UCZ  $(T_U)$  and the LCZ  $(T_L)$  are unknowns. These temperatures are related by the energy balance in the NCZ. Because the temperature in the NCZ is not uniform, the thermal analysis in this zone is slightly different than that performed in both the UCZ and the LCZ. Due to the density gradient, the fluid in the NCZ is static and thus the main heat transfer mechanisms in this zone are conduction and solar radiation absorption, besides heat losses to sidewalls. The equation that determines the temperature profile in the NCZ is (Appendix A):

$$\frac{\partial^2 T(z)}{\partial z^2} - \frac{T(z) - T_g}{\xi^2} = -\frac{\Phi_h(z)}{k}$$
(2.1)

where T(z) is the temperature at a depth z,  $T_g$  is the ground temperature,  $\xi$  is a characteristic length of the problem, k is the thermal conductivity of the fluid, and  $\Phi_h(z)$  is the shortwave radiation, which is modeled as a volumetric heat source. The shortwave radiation is considered to be distributed within the water column as this radiation flux penetrates the fluid surface and is attenuated through the water (Rabl and Nielsen, 1975; Kirk, 1983; Suárez et al., 2010b).

The solution of equation (2.1) is given by a linear combination between a homogeneous solution and a particular solution (Williamson, 1986), where the temperatures of the UCZ and LCZ are used as boundary conditions, i.e.,  $T(z_U) = T_U$  and  $T(z_L) = T_L$ . By coupling equation (2.1) with the energy balances in the UCZ and LCZ, the temperatures  $T_U$  and  $T_L$  are found, and then the solution of equation (2.1) provides the thermal distribution within the NCZ (all the details are presented in Appendix A). Therefore, for certain design parameters and meteorological conditions, the developed model informs the temperature profile and the useful energy of a solar pond under steady state conditions.

#### 2.1.2 Optimal shape and size of an SGSP

The shape of an SGSP has an impaction on the temperature that can be reached in the LCZ. Dehghan et al. (2013) demonstrated that, for the same surface area, circular solar ponds have superior thermal performance than square ones. This superior thermal performance is principally attributed to a reduction in the sidewalls heat losses due to a smaller perimeter per unit area of the circular pond (compared with a square solar pond). Typically, small ponds (<500 m<sup>2</sup>) tend to be

circular, while large ponds tend to be rectangular because the heat losses through their sidewalls are less important than those occurring in small ponds (Hull et al., 1989). However, in this investigation heat losses are an important factor since several solar ponds will be connected for the same fixed land area. Therefore, circular ponds will be used to optimize the SGSP field.

Another important aspect of the operation of an SGSP is to maximize the temperature in the LCZ, i.e., to optimize the thicknesses of each zone. In this work, the UCZ thickness is kept as small as possible to minimize heat losses to the environment (Suárez et al., 2010a). Here, we used an UCZ thickness of 0.3 m (Lu et al., 2004; Suárez et al., 2010a). On the other hand, in the LCZ the theoretical highest temperature is reached when the LCZ thickness approaches zero. However, this is not practical, since it must be designed to allow energy storage during operation. Also, a minimum depth of this zone is required to prevent erosion of the NCZ when withdrawing heat (Tabor and Doron, 1990). Hence, we used a fixed LCZ thickness of 1.1 m as suggested by Garrido and Vergara (2013). Note that the developed model assumes that all radiation that reaches NCZ-LCZ interface is absorbed in the LCZ fluid. Therefore, the thickness of this layer is only used for estimating the lateral heat losses to the ground.

As the thicknesses of the UCZ and the LCZ are fixed, the thickness of the NCZ (i.e., the depth of the interface NCZ-LCZ) is optimized for each pond to maximize the temperature in the LCZ. This can be achieved in two ways: 1) given a fixed volume of SGSP, an optimal surface area can be found; or 2) given a fixed surface area of the pond, an optimal depth can be found. Because in this study the

constrain for the SGSP field is a fixed land surface, the optimal depth of the pond will be found by fixing the SGSP surface area and maximizing the heat that can be extracted from the storage zone. This optimization is performed using the thermal model described in the previous section (also in Appendix A) by calculating the temperature of the LCZ for different depths of the pond.

#### 2.1.3 Heat extraction from the SGSP

For practical reasons, an external heat exchanger (Figure 2-1) will be used to extract the energy from the pond. This type of heat exchanger was selected because it has less maintenance costs than a heat exchanger installed in the highly corrosive environment of the LCZ (Leblanc et al., 2011). In this heat exchanger, the hot stream corresponds to the brine that is recirculated through the LCZ, and the cold stream is the fluid (water) to be heated. To analyze the temperatures in the heat exchanger, the concept of effectiveness,  $\mathcal{E}$ , is used. Hence, the outlet cold stream temperature of the heat exchanger,  $T_{Co}$ , is defined by (Mills, 1999):

$$T_{Co} = T_{Ci} + \mathcal{E}\frac{c_{min}}{c_C}(T_{Hi} - T_{Ci})$$
(2.2)

where  $C_{min}$  is the minimum between  $C_H$  and  $C_C$ , and these are the products between the mass flow rate and the specific heat of the hot and cold streams, respectively;  $T_{Hi}$  is the inlet temperature of hot stream (which is equal to the LCZ temperature of the SGSP); and  $T_{Ci}$  is the inlet temperature of the cold stream.



Figure 2-1: Schematic representation of the connection between the SGSP and the heat exchanger (HE).

The operation of the heat exchanger also is optimized to maximize the heat that can be transferred from the hot stream to the cold stream (see Appendix B for further details). Indeed, as the hot-side mass flow rate increases, the heat transferred towards the cold stream increases. However, there is an upper bound where an increase in the hot-side mass flow rate does not increase the outlet temperature of the cold stream. This upper bound is achieved when  $C_H = C_C$ (Mills, 1999). Therefore, the hot-stream mass flow rate is determined using this condition.

#### 2.2 Configurations of the SGSP field

As described before, a complementary mathematical model was developed to determine the final temperature of the mass flow rate to be heated by the heat exchangers connected to the solar ponds of the SGSP field. This section explains the different configurations that were used to connect the solar ponds, with the aim of finding the final temperature of the flow rate at the exit of the SGSP field.

There are two simple ways to connect the ponds when the total surface area is fixed: in series or in parallel. In addition to these configurations, the SGSP field can be formed by connecting ponds in more complex configurations: ponds combined in series and in parallel (termed "mixed series-parallel configuration"), and tree-shaped configurations. These configurations will be evaluated using the constructal theory, and adopting the following assumptions: 1) each SGSP has its own heat exchanger; 2) the pipes that connect the ponds are well insulated, thus, the heat losses in the pipes are negligible compared to the other heat fluxes; 3) there is excess of freshwater to replenish the evaporation losses on the SGSPs, and excess of salts to maintain the salinity gradient in each solar pond.

To find the cold stream outlet temperature in each heat exchanger connected to an SGSP, the temperature in the LCZ of the pond must be first determined. This estimation is carried out using the thermal model described above for a circular SGSP with an optimal depth. Then, each heat exchanger is analyzed to find the temperature  $T_{Co}$  that will be achieved by the mass flow rate of the cold side. The next subsections describe how the final temperature ( $T_F$ ) of the SGSP field is calculated for each one of the configurations described above. It is worth mentioning that the total land area ( $A_t$ ) is fixed and it is the same for all configurations, with no restriction on the shape of the land area.

#### 2.2.1 Configuration in series

In this configuration, the total area of the SGSP field  $(A_t)$  is distributed in ponds connected one after the other (Figure 2-2). Therefore, the cold stream outlet temperature of a certain heat exchanger is used as the cold stream inlet temperature of the next heat exchanger, and the final temperature of the water to be heated in the SGSP field will be equal to the outlet temperature of the last SGSP/heat exchanger system.



Figure 2-2: SGSP field comprised by *N* solar ponds/heat exchanger systems connected in series. Distribution of the SGSP field total area for: (a) ponds with uniform area; (b) ponds with increasing area; and (c) ponds with decreasing area.

Even when the total area of the SGSP field is fixed, the constant optimization that the constructal design teaches, induces to think that there are many ways to distribute this area among the ponds connected in series, where the different distributions can result in different final results. In this work, three combinations are evaluated: uniform, increasing and decreasing area distribution (Figure 2-2). The area of the  $i^{\text{th}}$  SGSP,  $A_i$ , is calculated as follows:

$$A_i^{uniform} = \frac{A_t}{N} \tag{2.3}$$

$$A_i^{increasing} = \frac{2i}{N(N+1)} A_t \tag{2.4}$$

$$A_i^{decreasing} = \frac{2(N+1-i)}{N(N+1)} A_t$$
(2.5)

where the superscripts *uniform*, *increasing* and *decreasing* refer to the way that the area of the ponds is distributed in the SGSP field, and N is the total number of ponds. In the configuration in series, the cold stream mass flow rate of all the heat exchangers will be the same.

#### 2.2.2 Configuration in parallel

In this configuration, the total area is distributed in ponds that are located side by side (Figure 2-3). Therefore, the cold stream inlet temperature of each heat exchanger ( $T_{ci}$ ) is the same as the temperature at the entrance of the SGSP field ( $T_o$ ). As configuration in series, following the constant optimization of the constructal design, there are different ways to distribute the total area among the ponds connected in parallel. In this case, the total area of the SGSP field can be distributed using solar ponds with uniform or variable areas (Figure 2-3). For the case of uniform area, the  $A_i^{uniform}$  is calculated using equation (2.3). For the case of variable area, the  $A_i^{variable}$  is estimated using equation (2.4).



Figure 2-3: SGSP field comprised by *N* solar ponds/heat exchanger systems connected in parallel. Distribution of the SGSP field total area for: (a) ponds with uniform area; (b) ponds with variable area and equal flow; and (c) ponds with variable area and proportional flow.

When the solar ponds are connected in parallel, the total mass flow rate entering the SGSP field  $(\dot{m}_t)$  can be equally distributed to the ponds (equal flow) or in proportion to the surface area of each pond (proportional flow). For both uniform or variable surface areas with equal distribution of the mass flow rate towards the ponds, the cold stream mass flow rate of each heat exchanger is:

$$\dot{m}_i = \frac{1}{N} \dot{m}_t \tag{2.6}$$

For variable surface areas with proportional distribution of the mass flow rate, the cold stream mass flow rate of each heat exchanger is:

$$\dot{m}_i = \frac{A_i}{A_t} \dot{m}_t \tag{2.7}$$

The final temperature of the water to be heated in the SGSP field,  $T_F$ , will be a weighted average of the temperature reached at each SGSP/heat exchanger system:

$$T_F = \frac{\sum_{i=1}^{N} (\dot{m}_i T_{Co_i})}{\dot{m}_t}$$
(2.8)

where  $T_{Co_i}$  is the cold stream outlet temperature of the *i*<sup>th</sup> heat exchanger.

#### 2.2.3 Mixed series-parallel

In this configuration the distribution of the total area is generated using a mixture between ponds connected in parallel and in series, as shown in Figure 2-4. First, the final temperature of the ponds connected in series is calculated. Then, this temperature is used to obtain the final temperature for the ponds connected in parallel. In this work, for simplicity, only mixed series-parallel configurations formed by the same number of ponds in series as in parallel are evaluated ("square" configuration). Therefore, in this configuration the number of ponds is:

$$N = N_s N_p \tag{2.9}$$

where  $N_s$  is the number of solar ponds connected in series and  $N_p$  is the number of solar ponds connected in parallel. The total area is distributed in a uniform way, as described in equation (2.3).



Figure 2-4: SGSP field comprised by *N* solar ponds/heat exchanger systems connected in a mixed series-parallel configuration.

#### 2.2.4 Tree-shaped configuration

A flow architecture derived from constructal law that is commonly used is the treeshaped (dendritic) design. This architecture has been used in various technological applications (e.g., Pramanick and Das, 2006; Daneshi et al., 2013; Feng et al., 2014). Because of their multiple scales and optimized complexity, tree flows offer greater densities of heat and mass transfer (Kim et al., 2006). Thus, it is propose to study tree-shaped configurations where the solar ponds have decreasing, increasing, or decreasing-increasing surface areas (Figure 2-5). As shown in Figure 2-5, the tree-shaped configurations are characterized by having *n* levels of solar ponds/heat exchanger systems. This type of configuration is a mixture between ponds connected in series and in parallel – the flow is bifurcated into two in each of the branches in the decreasing area configuration (Figure 2-5a), and the flow converges from two branches in the increasing area configuration (Figure 2-5b). The "mixed" decreasing-increasing area configuration (Figure 2-5c), which is similar than the trees matched canopy-to-canopy architecture (Kim et al., 2006), has solar ponds with variables areas, such that each surface area is proportional to the flow flowing in each heat exchanger of the corresponding SGSP.

To calculate the final temperature that is reached in such settings, only a single pond of each level (or branch) is modeled, because the other ponds of the level will be identical. Then, the total number of solar ponds for decreasing and increasing area configurations is calculated as:

$$N = \sum_{i=1}^{n} 2^{i-1} \tag{2.10}$$

where n is the number of levels of each configuration. For the "mixed" increasingdecreasing area configuration, the number of solar ponds is calculated as:

$$N = \begin{cases} \sum_{i=1}^{n/2} 2^{i} & \text{if } n \text{ is even} \\ 2^{(n-1)/2} + \sum_{i=1}^{(n-1)/2} 2^{i} & \text{if } n \text{ is odd} \end{cases}$$
(2.11)

Because the total area of the SGSP field remains constant, the distribution of surface area for a solar pond in the  $i^{th}$  level is as follows:



Figure 2-5: SGSP field comprised by *n* levels of solar ponds/heat exchanger systems connected in tree-shaped forms: (a) ponds with decreasing area; (b) ponds with increasing area; and (c) ponds with a mixed decreasing-increasing area.

$$A_i^{decreasing} = \frac{A_t}{n2^{i-1}} \tag{2.12}$$

$$A_i^{increasing} = \frac{A_t}{n2^{n-i}} \tag{2.13}$$

$$A_{i}^{mixed} = \begin{cases} \frac{A_{t}}{n2^{i-1}} & \text{if } i < \frac{n}{2} + 1\\ \frac{A_{t}}{n2^{n-i}} & \text{if } i > \frac{n}{2} + 1 \end{cases}$$
(2.14)

where the superscripts represent the type of configuration. The cold stream mass flow rate in each heat exchanger can be expressed as:

$$\dot{m}_i^{decreasing} = \frac{\dot{m}_t}{2^{i-1}} \tag{2.15}$$

$$\dot{m}_i^{increasing} = \frac{\dot{m}_t}{2^{n-i}} \tag{2.16}$$

$$\dot{m}_{i}^{mixed} = \begin{cases} \frac{\dot{m}_{t}}{2^{i-1}} & \text{if } i < \frac{n}{2} + 1\\ \frac{\dot{m}_{t}}{2^{n-i}} & \text{if } i > \frac{n}{2} + 1 \end{cases}$$
(2.17)

For clarity, a summary of all the SGSP field configurations that were evaluated is shown in Table 2-1.

#### Table 2-1: Summary of the SGSP field configurations that were

evaluated in the present study.

Configuration	Area Distribution	
	Uniform	
Series	Increasing	
	Decreasing	
	Uniform	
Parallel	Variable (with equal flow)	
	Variable (with proportional flow)	
Mixed series-parallel	Uniform	
	Decreasing	
Tree	Increasing	
	Mixed Decreasing-increasing	

#### 2.3 Parameters used to assess the performance of the SGSP field

It is evaluated the performance of the different configurations of an SGSP field placed near the city of Copiapó, Chile (27°30'S 70°30'W). This city is located in a

highly vulnerable basin that is currently in a state of acute water scarcity (Oyarzún and Oyarzún, 2011; Suárez et al., 2014b). Therefore, it is investigated the design of an SGSP field that could be used to provide energy for a thermal desalination system, such as that presented by Suárez et al. (2010a). Describing that water treatment technology is out of the scope of this work. What is relevant for the current analysis is that the performance of the desalination system increases with increased temperature of the feed water. Therefore, by maximizing the temperature of a fixed feed water flow rate, i.e., the mass flow rate to be heated in the SGSP field, the water treatment system will maximize its water production.

The operating parameters of the solar ponds used in this study were obtained from the performance optimization of each SGSP (as described above), and on the information available in the literature. It is used a total land area of 23,200 m<sup>2</sup> (2.3 ha) for the SGSP field and a total mass flow rate of 6 kg/s. These parameters are the same than those used by Garrido and Vergara (2013). In terms of water production, and based on the information provided by the SISS (2014), a mass flow rate of 6 kg/s represents the water consumption of ~3000 inhabitants in the city of Copiapó (~2% of the population of the city).

The meteorological parameters required to evaluate the performance of the SGSP field were obtained from Suárez et al. (2014b). It is used the mean annual values of the meteorological variables as the representative values for steady state conditions. The incident radiation was equal to 212.5 W/m<sup>2</sup>. The ambient temperature was 19.4°C, and it is assumed that in steady state conditions the ground temperature has a similar temperature than the air. The inlet temperature of

the SGSP field was set to 15.3°C (data obtained from the Hydrographic and Oceanic Service of the Chilean Navy, http://www.shoa.cl). This temperature corresponds to the annual average temperature of the ocean near the town of Caldera, which is where water is currently being withdrawn, desalinated, and then used in the mining industry of the region and for potable water use in the city of Copiapó (Suárez et al., 2014b).

For each pond, as described before, the thicknesses of the UCZ and LCZ were 0.3 and 1.1 m, respectively (Suárez et al., 2010a; Garrido and Vergara, 2013). The NCZ thickness was optimized as explained before, and a minimum thickness of 0.5 m is used to avoid problems of salt gradient stability (Hull et al. 1989). The thermal conductivity of the brine was 0.637 W/m-K (Hull et al., 1989). The heat transfer coefficient on the pond's surface ( $U_s$ ) was estimated in 92.24 W/m<sup>2</sup>-K. This value is based on the experimental data of Silva et al. (in preparation), and considers radiative, latent, and sensible heat fluxes. The heat transfer coefficients of the side walls  $(U_U, U_N, \text{ and } U_L \text{ for the UCZ, NCZ and LCZ, respectively})$ correspond to those obtained when it is assumed that conduction is the main heat transfer mechanism. Considering a ground thermal conductivity of 2.4 W/m-K, and a distance of 4 m from the pond wall to the point where  $T_g$  becomes constant (Beniwal et al., 1985), a value of 0.60  $W/m^2$ -K is obtained for all the heat transfer coefficients of the sidewalls. The heat transfer coefficient of the bottom  $(U_B)$  was set to 0.17  $W/m^2$ -K. This value was estimated assuming the same conditions than those used to estimate the sidewalls heat transfer coefficient, but considering a distance of 14 m from the pond's bottom to the point where  $T_g$  becomes constant (Beniwal et al., 1985).

The heat exchanger effectiveness depends on the type of heat exchanger (Mills, 1999) – the higher the effectiveness, the more energy that can be obtained from the ponds. For this study, the effectiveness was set to an arbitrary value of 70%. The specific heat of the hot stream (brine) of the heat exchanger was 3.570 kJ/kg-K (Hull et al., 1989), while the specific heat of the cold stream (water) was 4.181 kJ/kg-K (Mills, 1999).

#### 3. **RESULTS**

#### 3.1 Thermal behavior of a single SGSP

After defining the optimal shape of each solar pond (circular, as described above), it is necessary to determine the optimal thickness of the NCZ, i.e., the depth of the NCZ-LCZ interface,  $z_L$  (Figure 1-1). Figure 3-1a shows the temperatures of the heat exchanger streams as a function of  $z_L$ , for a single solar pond occupying all the available land area. Recall that the inlet temperature of the hot stream is equal to the temperature of the LCZ, i.e.,  $T_{Hi} = T_L$ . For each  $z_L$ , the outlet temperature of the heat exchanger cold stream ( $T_{Co}$ ) is smaller than the inlet temperature of the hot stream ( $T_{Hi}$ ) because the heat exchanger has a certain effectiveness. Even when the difference between  $T_{Hi}$  and  $T_{Co}$  depends on the value of the effectiveness, the highest  $T_L$  always agree with the highest  $T_{Co}$  and with the highest useful energy. The optimum  $z_L$  was found to be 2.57 m (a total depth of 3.67 m and a brine volume of 85,237 m<sup>3</sup>). This depth produces the highest temperature in the LCZ (68.5 °C, as shown in Figure 3-1b) and in the outlet of the heat exchanger cold stream (52.5 °C), delivering 933 kW of useful energy.



Figure 3-1: Optimization of the depth of the LCZ-NCZ interface for a single SGSP. (a) Temperatures of the heat exchanger streams as a function of  $z_L$ . (b)

Temperature profile within the SGSP for the optimal depth.

#### 3.2 Configurations of the SGSP field

The following results are expressed in dimensionless form, where the final temperature  $(T_F)$  and total brine volume (V) of a particular configuration are normalized using the results obtained in a single SGSP, i.e.,  $\overline{T} = T_F/T_{ref}$  and  $\overline{V} = V/V_{ref}$ , where  $T_{ref} = 52.5$  °C and  $V_{ref} = 85,237$  m<sup>3</sup> are the reference temperature and brine volume, respectively. Also, it is important to emphasize that the results of each of the following configurations use solar ponds operating under optimal conditions.

#### **3.2.1** Configuration in series

For all types of area distribution, it was found that solar ponds connected in series achieve higher temperatures than a single SGSP (Figure 3-2a). When the number of solar ponds increases, the final temperature increases. However, there is a threshold where an increase in the amount of solar ponds does not increase the final temperature. Consequently, there is an optimum number of solar ponds that maximizes the final temperature of the SGSP field. It is found that the optimum numbers of solar ponds are 23, 30 and 27, for ponds with uniform, increasing and decreasing area distribution, respectively. The corresponding final temperature increase of each area distribution are 22.1% (11.5 °C), 22.9% (11.8 °C) and 20.4% (10.8 °C), compared with the results of a single SGSP. Therefore, ponds connected in series with increasing area distribution result in more useful energy, i.e., a higher final temperature (for an optimal number of solar ponds).

When the number of solar ponds increases, the total brine volume required for the SGSP field decreases for any area distribution (Figure 3-2b). For optimal conditions (N = 30), the increasing area distribution uses 27.1% (23,106 m<sup>3</sup>) less brine than a single SGSP.



Figure 3-2: Performance of the configurations in series with different area distributions. (a) Dimensionless final temperature of the SGSP field. (b)

Dimensionless brine volume of the SGSP field.

#### **3.2.2** Configuration in parallel

For all the configurations in parallel, it was found that the final temperature of the SGSP field decreases compared to a single SGSP (Figure 3-3a). In addition, when the number of solar ponds increases, the final temperature decreases. Hence, the optimal number of solar ponds for any area distribution is two. In terms of the final temperature reached, the best configuration is the variable area distribution with the mass flow rate distributed in proportion to the surface area of each solar pond. Nevertheless, for a small number of solar ponds (N<5), the configuration with uniform area distribution is practically the same than the configuration with variable area distribution and proportional mass flow rate.

Moreover, the total brine volume of the SGSP field also decreases as the number of solar ponds increases (Figure 3-3b), except for the case N = 2 for variable area with equal flow. The uniform area distribution reaches the minimum total brine volume regardless the number of solar ponds.

![](_page_37_Figure_1.jpeg)

Figure 3-3: Performance of the configurations in parallel with different area distributions. (a) Dimensionless final temperature of the SGSP field. (b)

Dimensionless brine volume of the SGSP field.

#### 3.2.3 Mixed series-parallel configuration

In the mixed series-parallel configuration, intermediate final temperatures between the series and parallel configurations are achieved (Figure 3-4). This behavior is expected as this configuration is a mixture between the series and parallel configurations. These temperatures are always greater than a single pond. The optimal number of solar ponds (49) is greater than the optimal number for the configuration in series, since the mixed configuration has less solar ponds connected in series (7) than the configuration in series, which according to our results is more efficient than the parallel configuration (this is discussed in more details below). The mixed configuration reaches a final temperature that is 13.8% greater than that of a single SGSP. In terms of brine volume, intermediate final brine volumes between the series and parallel configurations are also achieved (data not shown).

![](_page_38_Figure_1.jpeg)

Figure 3-4: Dimensionless final temperature of the SGSP field for the configurations evaluated in this study. For the series configuration only the increasing area is shown, whereas for the parallel configuration only the variable area with proportional flow rate is shown.

#### **3.2.4 Tree-shaped configuration**

In the same way as in the mixed series-parallel configuration, all the tree-shaped configurations achieved intermediate final temperatures and brine volumes between the series and parallel configurations. Also, all the tree-shaped configurations reached higher final temperatures than a single pond (Figure 3-4). The tree-shaped configuration that achieves the highest final temperature is the mixed decreasing-increasing type, because the decreasing and the increasing configurations use more solar ponds connected in parallel for the same total amount of ponds, whereas the mixed decreasing-increasing configuration use more solar ponds for mixed decreasing-increasing configuration is 30 (8 levels), reaching a final temperature that is 17.0% greater than a single SGSP.

#### 4. **DISCUSSION**

First, there are two important factors that determine the optimal depth of each solar pond: the surface area and the cold stream inlet temperature. As these factors increase, the optimal depth increases. This behavior is also reported by Suárez et al. (2010a). The single solar pond has the largest surface area; consequently, it is the deepest pond of all the configurations. For the configurations that have ponds with smaller surface area and low cold stream inlet temperature, such as the ponds connected in parallel or the first ponds in the series connection, the solar ponds will be shallow and the total brine volume, required to operate under optimal conditions, will be less than a single SGSP.

Even though it has been reported that the performance of larger solar ponds is better than that of smaller ponds, as edge losses per unit area are smaller (Duffie and Beckman, 1980; Dehghan et al., 2013), it was found that the solar ponds that are connected in series behave differently. When the useful energy is extracted from the pond, the LCZ temperature also depends on the outlet temperature of the heat exchanger cold stream (or the mass flow rate of the fluid to be heated). Therefore, higher final temperatures in the SGSP field will be reached if the cold stream enters preheated into the heat exchanger. In other words, when the ponds are connected in series, the preceding solar ponds warm the cold stream of the following ponds. Thus, it is easier to obtain higher temperatures and a better performance (compared to a single pond). Nevertheless, there is a point where adding more solar ponds becomes inefficient because the total heat losses through the sidewalls significantly increases as the perimeter per unit area increases (Figure 4-1). Our results show that the benefit of preheating the cold stream is more important than the benefit of having larger ponds.

![](_page_41_Figure_1.jpeg)

Figure 4-1: Perimeter per unit area for an SGSP field with *N* solar ponds connected in series and for ponds with uniform and increasing area distribution.

These curves follows the relation  $\frac{P}{A_t} = \frac{2\sqrt{\pi}}{A_t} \sum_{i=1}^N \sqrt{A_i}$ , where *P* is the perimeter covered by all the SGSP field.

Although the uniform distribution area for the series configuration appears to be the best configuration for a reduced number of solar ponds (N<9), sidewall heat losses begin to be relevant when the number of solar pond increases, because the SGSP field with uniform area distribution has a greater total perimeter per unit area than the SGSP field with increasing area distribution (Figure 4-1). Therefore, when the number of solar pond increases, the SGSP field with increasing area distribution reaches larges temperatures than those obtained when all the ponds have the same area.

In parallel configurations, it is expected that by dividing the total stream in several currents, higher temperatures in each solar pond could have been reached because less energy is required to heat a smaller fluid volume. However, the sidewall heat losses become increasingly important as the number of solar ponds is increased, since the perimeter per unit area increases (in the same way than that shown in Figure 4-1 for the series configurations). If the sidewalls were completely insulated, the parallel configuration reaches a final temperature identical to that of a single SGSP. However, heat losses are inevitable and increase with the number of solar ponds.

In other constructal theory studies, the tree-shaped flow architecture appeared as the best flow architecture (Kim et al. 2006; Bejan and Lorente, 2008). However, in this study the tree-shaped configuration is not optimal because its design is the result of a combination between connections in series and in parallel, and it is showed that the parallel connection undermines the overall efficiency. Lorente et al. (2010a) highlights that the answer to the correct arrangement of solar chimney power plants ("few large and many *small*") is generally applicable to all types of power harvesting techniques from land areas that possess low-density resources. They concluded that the most important factor is the land area allocated to the largest plant. This conclusion can be extrapolated to the SGSP field with ponds connected in parallel, because when the ponds of this configuration have variable area distribution, the larger ponds will generate more energy per unit area than the smaller ponds (data now shown). However, the conclusion of Lorente et al. (2010a) cannot be extrapolated to the SGSP field with ponds connected in series, since in this configuration the solar ponds do not work independently, as they do when they are connected in parallel or in the case of the solar chimneys.

It is important to perform a sensitivity analysis to investigate the impact of the total area (in which the total flow is proportional to the total area) and of the climatic conditions on the SGSP field performance (Table 4-1). This sensitivity analysis can be used as a planning tool for solar pond construction to achieve the highest performance of an SGSP field in a determined geographical location. This analysis was performed for the configuration in series with increasing area distribution. On one hand, when the total surface area increases, the optimal number of solar ponds also increases. When the land area is smaller than 1,000  $\text{m}^2$  (0.1 ha), the optimal number of solar ponds is less than 12, regardless the geographical location. For land areas larger than 50,000  $\text{m}^2$  (5.0 ha), the optimal number of solar ponds is always greater than 19 (see Table 4-1 for intermediate values). As the total available land area increases, the percentage difference in final temperature (or useful energy) between the series configuration and the single solar pond also increases (at any geographical location). When the total land area increases the perimeter per unit area decreases (Figure 4-2). Therefore, more solar ponds connected in series are needed before heat losses begin to be relevant. On the other hand, the optimum number of solar ponds is proportional to the insolation of the place where the SGSP field will be built. An SGSP field constructed in a northern European climate (insolation of  $\sim 100 \text{ W/m}^2$ ) will require approximately half the number of ponds than those required for a tropical or subtropical climate ( $\sim 250 \text{ W/m}^2$ ). As solar radiation increases, the percentage difference in final temperature also increases. In tropical or subtropical climates, the final temperature increase is larger than 20%. Indeed, our results indicate that, in an SGSP field located in a tropical climate with a land area greater than 50,000  $\text{m}^2$ , the final temperature is 25% greater than that reached in a single SGSP (useful energy of 3.1 MW for the series configuration and 2.3 MW for the single pond). Therefore, replacing the single pond for several ponds in series is especially valuable for large land areas or high solar radiation.

Table 4-1: Sensitivity analysis for the configuration in series for circular

solar ponds with increasing area distribution and for different climates. The

insolation data were obtained from Hull et al. (1989) and the total flow was

calculated proportional to the total area. The dimensionless useful energy correspond

to  $\overline{E} = E/E_{ref}$ , where E is the total useful energy extracted of each configuration

and  $E_{ref}$  is the useful energy extracted of a single SGSP (that changes for each case).

Tropical and subtropical climate (Latitude 0-29°: Insolation 242 W/m <sup>2</sup> )						
Total Area, At [m <sup>2</sup> ]	Optimal number of solar ponds	Final temperature of a single SGSP, $T_{ref}$ [°C]	Dimensionless final temperature, $\overline{T}$	Useful energy of a single SGSP, <i>E<sub>ref</sub></i> [kW]	Dimensionless useful energy, $\overline{E}$	
1,000	12	55.0	1.20	43	1.27	
10,000	23	57.6	1.23	458	1.31	
50,000	37	58.5	1.25	2333	1.33	
Mediterranean to northern U.S. climate (Latitude 30-43°: Insolation 193 W/m <sup>2</sup> )						
Total Area, At [m <sup>2</sup> ]	Optimal number of solar ponds	Final temperature of a single SGSP, $T_{ref}$ [°C]	Dimensionless final temperature, $\overline{T}$	Useful energy of a single SGSP, <i>E<sub>ref</sub></i> [kW]	Dimensionless useful energy, $\overline{E}$	
1,000	10	46.0	1.17	33	1.25	
10,000	20	48.2	1.20	356	1.29	
50,000	33	48.9	1.22	1815	1.32	
Intermediateclimate (Latitude 44-49°: Insolation 145 W/m <sup>2</sup> )						

Total Area, At [m <sup>2</sup> ]	Optimal number of solar ponds	Final temperature of a single SGSP, $T_{ref}$ [°C]	Dimensionless final temperature, $\overline{T}$	Useful energy of a single SGSP, <i>E<sub>ref</sub></i> [kW]	Dimensionless useful energy, $\overline{E}$	
1,000	8	37.1	1.13	24	1.22	
10,000	16	39.0	1.16	256	1.26	
50,000	27	39.6	1.18	1310	1.29	
Northern European climate (Latitude 50-53°: Insolation 97 W/m <sup>2</sup> )						
Total Area, At [m <sup>2</sup> ]	Optimal number of solar ponds	Final temperature of a single SGSP, $T_{ref}$ [°C]	Dimensionless final temperature, $\overline{T}$	Useful energy of a single SGSP, E <sub>ref</sub> [kW]	Dimensionless useful energy, $\overline{E}$	
1,000	5	28.3	1.07	14	1.16	

29.8

10,000

11

![](_page_45_Figure_1.jpeg)

1.10

156

Figure 4-2: Perimeter per unit area as a function of the total land area  $A_t$  for an SGSP field (N = 1 to 5) with ponds connected in series and increasing area

distribution.

1.22

In this work, it was assumed that the heat losses in the piping system that connect the ponds are negligible. To understand the effect of assumption on the results, the energy losses in the piping system for the SGSP field with ponds connected in series were estimated. The heat losses through the pipes between each heat exchanger were determinate by (Bejan, 2013):

$$T_{out} = T_g - \frac{T_g - T_{in}}{\exp\left(\frac{h_p P_p L_p}{\rho A_p \nu C_p}\right)}$$
(4.1)

where  $T_{out}$  is the temperature of a fluid with density  $\rho$  and velocity v, at the end of a pipe of length  $L_p$ , cross sectional area  $A_p$ , perimeter P and heat transfer coefficient through the pipe wall  $h_p$ ;  $T_g$  is the ground temperature and  $T_{in}$  is the temperature that the fluid has at the inlet of the pipe. The length of each pipe was determined for each configuration assuming that the heat exchanger is located below and at the center of each SGSP. Assuming a heat transfer coefficient in the pipes of 13.1 W/m<sup>2</sup>-K (heat losses towards the ground), a friction factor of 0.015, and 0.10 m diameter pipe, a single SGSP with a piping system subject to heat losses has a final temperature that is 1.6 °C lower than that of the system without heat losses (for the meteorological conditions of the province of Copiapó). For the SGSP field with configuration in series, it was found that the optimum number of solar ponds decreases for each configuration, and that the final temperature of the SGSP field also decreases (Figure 4-3). Note, however, that when including heat losses in the piping system, the previous discussions and conclusions are still valid.

![](_page_47_Figure_0.jpeg)

Figure 4-3: Comparison of the SGSP field final temperatures with ponds connected in series with and without heat losses in the piping system. The results are shown for uniform, increasing and decreasing area distribution.

Finally, an advantage of having multiple SGSPs is that when a solar pond needs maintenance and must be stopped, the other ones can keep running and producing energy. In this situation, the pipe network needs to be designed in a way that allows the correct operation of the SGSP field even when one pond is not operating. For parallel connections this is not a problem, because the parallel connection itself creates many pathways for the circulation of the fluid to be heated. However, the series connection requires a bypass through each heat exchanger to allow the correct operation of the SGSP field.

#### 5. CONCLUSIONS

It is demonstrated that the contructal theory enables the design of SGSP fields. In this study, several configurations of an SGSP field were evaluated. The pond shape and depths of its internal layers were optimized to maximize the LCZ temperature. It was found that the shape of each of them must be circular since it minimizes the sidewalls heat losses.

The basic configurations evaluated in this study (in series and in parallel) delivered opposite results: the series configuration performs better than a single SGSP as the preceding solar ponds in series connection preheat the mass flow rate of the following ponds. Furthermore, there is a threshold where adding more solar ponds becomes inefficient because the total heat losses through the sidewalls significantly increases, resulting in an optimal number of solar ponds. In contrast, the parallel configuration fails to obtain higher temperatures than a single SGSP because of the increased sidewalls heat losses. Intermediate final temperatures between the series and the parallel configurations were obtained in the mixed series-parallel and in the tree-shaped configurations.

It was found that the best configuration is obtained when the ponds are connected in series with an increasing area distribution (Figure 2-2b). For the study site of this investigation, the optimum number of solar ponds is 30. This SGSP field reaches a final temperature that is 22.9% higher than that of a single SGSP, and uses 27.1% less brine than a single SGSP. These values vary depending on the land area and on the specific geographical location. Experimental results of these configurations would be useful in future works to corroborate the theoretical results obtained in this study.

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A P P E N D I X

#### **APPENDIX A : MATHEMATICAL MODEL**

The energy balance in the UCZ can be represented by (Figure A-1):

$$q_{rU} = q_s + q_{wU} + q_{kU} \tag{A.1}$$

where  $q_{rU}$  is the difference between the shortwave radiation that reaches the surface of the pond (z = 0) and the shortwave radiation that crosses the UCZ-NCZ interface ( $z = z_U$ ),  $q_s$  is the heat loss through the water surface,  $q_{wU}$  is the heat loss through the sidewalls of the UCZ and  $q_{kU}$  is the conductive heat flux coming from the NCZ, which is determined using Fourier's Law:

$$q_{kU} = -kA \frac{\partial T(z)}{\partial z}\Big|_{z_U} \tag{A.2}$$

where A is the surface area of the solar pond, k is the thermal conductivity of the fluid, and T(z) is the temperature at a depth z. A similar analysis for the LCZ yields (Figure A-1):

$$q_{rL} + q_{kL} = q_b + q_{wL} + q_{use}$$
(A.3)

where  $q_{rL}$  is the shortwave radiation that crosses the NCZ-LCZ interface  $(z = z_L)$ ,  $q_b$  is the heat loss through the bottom of the pond,  $q_{wL}$  is the heat loss through the sidewalls of the LCZ,  $q_{use}$  is the useful energy extracted from the LCZ, and  $q_{kL}$  is the conductive heat flux transmitted to the NCZ, given by:

$$q_{kL} = -kA \frac{\partial T(z)}{\partial z} \Big|_{z_L}$$
(A.4)

![](_page_55_Figure_0.jpeg)

Figure A-1: Energy balance in the different zones of an SGSP. The differential element of thickness dz is used to determine the thermal profile in the NCZ.

The other heat fluxes can be estimated using the following equations:

$$q_{rU} = A * \left( q_r''(0) - q_r''(z_U) \right)$$
(A.5)

$$q_s = U_s A (T_U - T_{air}) \tag{A.6}$$

$$q_{wU} = U_U A_U (T_U - T_g)$$
(A.7)

$$q_{rL} = Aq_r''(z_L) \tag{A.8}$$

$$q_b = U_b A \big( T_L - T_g \big) \tag{A.9}$$

$$q_{wL} = U_L A_L (T_L - T_g)$$
 (A.10)

$$q_{use} = C_H \left( T_L - T_{Ho} \right) \tag{A.11}$$

where  $q_r''(z)$  is the shortwave radiation flux at a depth z;  $U_s$ ,  $U_U$ ,  $U_L$ , and  $U_b$  are the overall heat transfer coefficient across the surface, the UCZ, the LCZ, and the bottom of the pond, respectively;  $A_U$  and  $A_L$  are the lateral areas of the UCZ and LCZ (i.e, wetted

perimeter times the thickness of each zone), respectively;  $T_U$  and  $T_L$  are the temperatures of the UCZ and LCZ, respectively;  $T_{air}$  is the air temperature,  $T_g$  is the ground temperature,  $T_{Ho}$  is the temperature of the brine that enters the LCZ after warmed in the hot side of the heat exchanger,  $C_H$  is the product of the specific heat of the brine and the brine mass flow rate that recirculates between the SGSP and the heat exchanger. The attenuation of the shortwave radiation is represented using the Rabl and Nielsen formula (1975):

$$q_r(z) = q_o \sum_{i=1}^4 S_i e^{\frac{-z}{\cos(\theta)\delta_i}}$$
(A.12)

where  $q_r''(z)$  is the shortwave radiation flux at a depth z;  $S_i$  and  $\delta_i$  are parameters to determine the attenuation of light within the water column;  $\theta$  is the refraction angle of the light; and  $q_o$  represents the solar radiation that penetrates the water surface, defined by:

$$q_o = (1 - r)q_i \tag{A.13}$$

where  $q_i$  is the incident radiation, and r is the reflectance of the solar radiation at the water surface.

Because the temperature in the NCZ is not uniform, the thermal analysis in this zone is slightly different than that of the UCZ and LCZ. Due to the density gradient, the fluid in the NCZ is static and thus the main heat transfer mechanisms in this zone are conduction and solar radiation absorption. To estimate the thermal profile within the NCZ, a differential analysis yields (Figure A-1):

$$\Phi_h A dz = dq_{wN} + dq_k \tag{A.14}$$

$$\Phi_h A dz = U_N P dz \left( T(z) - T_g \right) + d \left( -kA \frac{\partial T(z)}{\partial z} \right)$$
(A.15)

$$\Phi_h A = U_N P \left( T(z) - T_g \right) + \frac{d}{dz} \left( -kA \frac{\partial T(z)}{\partial z} \right)$$
(A.16)

where  $q_{wN}$  is the heat loss through the sidewalls of the NCZ,  $q_k$  is the conductive heat flux through the NCZ,  $U_N$  is the overall heat transfer coefficient of the NCZ sidewalls, P is the perimeter of the pond and  $\Phi_h$  is the shortwave radiation, modeled as a volumetric heat source (Rabl and Nielsen, 1975):

$$\Phi_h(z) = -\frac{\partial q_r''}{\partial z} = \frac{q_o}{\cos(\theta)} \sum_{i=1}^4 \frac{S_i}{\delta_i} e^{\frac{-z}{\cos(\theta)\delta_i}}$$
(A.17)

Defining the auxiliary variables  $\theta(z) = T(z) - T_g$ , and  $\xi = \sqrt{\frac{k*A}{U_n*P}}$ , equation (A.16) can be written as follows:

$$\frac{\partial^2 \theta(z)}{\partial z^2} - \frac{\theta(z)}{\xi^2} = -\frac{\Phi_h(z)}{k} \tag{A.18}$$

The solution of equation (A.18) is given by a linear combination between a homogeneous solution and a particular solution (Williamson, 1986):

$$\theta(z) = C_1 e^{-z/\xi} + C_2 e^{z/\xi} + \sum_{i=1}^4 \theta_{p_i}(z)$$
(A.19)

where each particular solution has the following mathematical form:

$$\theta_{p_i}(z) = B_i e^{\frac{-z}{\cos(\theta)\delta_i}} \tag{A.20}$$

In equation (A.20),  $B_i$  is a constant that can be found replacing each particular solution into equation (A.18):

$$B_i = \frac{Q_o S_i}{k \cos(\theta) \delta_i} \left( \frac{1}{\xi^2} - \frac{1}{\cos^2(\theta) \delta_i^2} \right)^{-1}$$
(A.21)

Thus, the thermal profile in the NCZ is given by:

$$T(z) = T_g + C_1 e^{-z/\xi} + C_2 e^{z/\xi} + \sum_{i=1}^4 B_i e^{\frac{-z}{\cos(\theta)\delta_i}}$$
(A.22)

The constants  $C_1$  and  $C_2$  can be obtained using the temperatures of the UCZ and LCZ as boundary conditions in equation (A.22), i.e.,  $T(z_U) = T_U$  and  $T(z_L) = T_L$ :

$$C_{1} = \frac{T_{L}e^{z_{U}/\xi} - T_{g}e^{z_{U}/\xi} - T_{U}e^{z_{L}/\xi} + T_{g}e^{z_{L}/\xi} + F_{z_{U}}e^{z_{L}/\xi} - F_{z_{L}}e^{z_{U}/\xi}}{e^{-z_{L}/\xi}e^{z_{U}/\xi} - e^{-z_{U}/\xi}e^{z_{L}/\xi}}$$
(A.23)

$$C_{2} = \frac{-T_{L}e^{-z_{U}/\xi} + T_{g}e^{-z_{U}/\xi} + T_{U}e^{-z_{L}/\xi} - T_{g}e^{-z_{L}/\xi} - F_{z_{U}}e^{-z_{L}/\xi} + F_{z_{L}}e^{-z_{U}/\xi}}{e^{-z_{L}/\xi}e^{z_{U}/\xi} - e^{-z_{U}/\xi}e^{z_{L}/\xi}}$$
(A.24)

where  $F_{z_U} = \sum_{i=1}^{4} B_i e^{\frac{-z_U}{\cos(\theta)\delta_i}}$  and  $F_{z_L} = \sum_{i=1}^{4} B_i e^{\frac{-z_L}{\cos(\theta)\delta_i}}$ . Replacing equation (A.22) into equations (A.2) and (A.4) yields:

$$q_{kU} = -kA\left(-\frac{C_1}{\xi}e^{-\frac{z_U}{\xi}} + \frac{C_2}{\xi}e^{\frac{z_U}{\xi}} - \frac{1}{\cos(\theta)}\sum_{i=1}^4 \frac{B_i}{\delta_i}e^{\frac{-z_U}{\cos(\theta)\delta_i}}\right)$$
(A.25)

$$q_{kL} = -kA\left(-\frac{C_1}{\xi}e^{-\frac{Z_L}{\xi}} + \frac{C_2}{\xi}e^{\frac{Z_L}{\xi}} - \frac{1}{\cos(\theta)}\sum_{i=1}^4 \frac{B_i}{\delta_i}e^{\frac{-Z_L}{\cos(\theta)\delta_i}}\right)$$
(A.26)

The previous equations can be then used to explicitly determine the temperatures in the UCZ and LCZ, and to find the thermal distribution within the NCZ through equation (A.22).

#### **APPENDIX B : TEMPERATURES IN THE HEAT EXCHANGER**

To analyze the temperatures in the heat exchanger, the concept of effectiveness,  $\mathcal{E}$ , was used (Mills, 1999):

$$\mathcal{E} = \frac{C_H(T_{Hi} - T_{Ho})}{C_{min}(T_{Hi} - T_{Ci})} = \frac{C_C(T_{Co} - T_{Ci})}{C_{min}(T_{Hi} - T_{Ci})}$$
(B.1)

where  $T_{Hi}$  and  $T_{Ho}$  are the inlet and outlet hot stream temperatures, respectively;  $T_{Ci}$  and  $T_{Co}$  are the inlet and outlet cold stream temperatures, respectively;  $C_H$  and  $C_C$  are the products between the mass flow rate and specific heat of the hot and cold streams, respectively; and  $C_{min}$  is the minimum between  $C_H$  and  $C_C$ . The outlet hot stream and cold stream temperatures can be found by rearranging equation (B.1), as the same as the outlet temperature of the cold side (equation (2.2)):

$$T_{Ho} = T_{Hi} - \varepsilon \frac{c_{min}}{c_H} (T_{Hi} - T_{Ci})$$
(B.2)

$$T_{Co} = T_{Ci} + \varepsilon \frac{c_{min}}{c_c} (T_{Hi} - T_{Ci})$$
(B.3)

Then, the useful heat can be expressed as:

$$q_{use} = \mathcal{E}C_{min}(T_{Hi} - T_{Ci}) \tag{B.4}$$