MEMBRANE STRATIFIED SOLAR PONDS

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Membrane Stratified Solar Ponds

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Abstract

This project deals with the potential of membrane stratified solar ponds which consist of two water layers, where one is a salt solution here, and a separating translucent membrane. An experimental pond was set up to study the thermal behaviour of such collector systems. The input is mainly solar radiation, sometimes when the ambient temperatures are higher than the pond temperatures also heat from the environment is transferred into the pond.
The measured temperatures of the pond, the ambient temperature, the global radiation and wind speed were the basis data for thermal calculations which showed that the pond was working well as a solar collector and thermal storage system all in one. Heat was not extracted from the pond however, only the losses to the environment were studied.
It was found out that the pond temperatures were higher than the ambient temperature over the whole measurement period of 12 days, and insulation and pollution problems as well as future prospects and suggestions for further studies are discussed at the end of this paper.

Keywords

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1 Introduction

Solar ponds have been developed since the 1960s, especially in Israel and the USA. The concentration on sustainable and environmental friendly technologies to generate and to store energy in the last years made it possible to think about the idea of solar ponds again.

Most of the solar thermal energy systems today produce heat through raising the temperature of water in the collector by solar irradiation and pumping it then to an external storage tank.

A solar pond combines these two functions which makes the solar pond a cheap and simple system to produce and to store heat.

Recently there have been researches in India and Turkey where the solar irradiation is high enough to run solar ponds economically and relatively cheap land is available, which is needed to build efficient solar ponds.

![Figure 1: Simplified scheme of a salt-gradient Solar Pond.](image)

There are several types of solar ponds as it is pointed out later in this work but they all have in common the general function of capturing irradiation and storing the heat at the same place and time. In a solar pond, the irradiation coming from the sun or the environment is transmitted through the water and captured by the bottom of the pond. The key effect for this storage possibility is the wavelength-dependent absorption or emission coefficient of water. For low wavelengths, water behaves translucent and its absorption/emission coefficient is very low whereas its transmission coefficient is very high.

On the other hand, the absorption/emission coefficient of long wavelength radiation is very high and therefore its transmission coefficient is very low which describes the solar energy storage behaviour of water. These mechanisms will be discussed later in this work.

Usually, the water heated up through solar irradiation would rise to the surface of the pond due to its decrease in density and transfer its heat to the surrounding air.
through convection and evaporation, so the water in the pond would remain at a temperature close to the ambient temperature.

The idea behind solar ponds is to inhibit the water from losing its heat content through convection and evaporation to the environment. This can be accomplished either through physical covering or separation as it is done with shallow solar ponds or by adding salt or brine to the water but without mixing it like in salt-gradient solar ponds. This generates stable zones of several salt contents which increases the density of the heated water and hinders the water from rising to the surface, even if it is heated up to temperatures near the boiling point.

The heat from the bottom layer can be extracted now either by pumping out the salt water itself or by using a heat exchanger [1] [2], where liquid is evaporated or heated up through the hot salt water.

Another advantage of salt-gradient solar ponds is that they can produce fresh water too, which is a desire for dry and hot countries [3] [4].

All in all, salt-gradient solar ponds could be a low-tech solution for producing heat, electricity and maybe fresh water in developing countries or even for industrial countries because of the increasing importance of storing energy due to the low energy density and stable availability of renewable energy sources.

1.1 Existing systems

There are not many commercial solar ponds existing today that produce electricity and/or heat reliably but the following are three examples of real plants in the USA, in Israel and in India.

1.1.1 El Paso Solar Pond, Texas

The El Paso solar pond in Texas was a research project of the University of Texas and has been running since 1986. It produces up to 70kW electrical power which is fed to the grid through using an organic Rankine cycle. It also produces heat and fresh water. It has a surface of 3,000 m$^2$ and is 3.2 m deep [5].

1.1.2 Beith Ha’Avara Solar Pond, Israel [6]

This solar pond located in the West Bank in Israel was the largest solar pond ever built. It had an electrical output of 5 MW and had a surface area of 210,000 m$^2$. It operated until 1988 [7].

The design of the pond began with the electrical output of the Rankine cycle which is driven by the heat of the salt water layer. At that time, the condition for a connection to the local grid had a minimum electrical output of 5 MW. Based on this requirement, the size and performance of the pond was chosen.

The pond area was first estimated to have 1,000,000 m$^2$ where an electrical efficiency of 1.5 % and an irradiation of 1850 kWh/ m$^2$ per year was assumed but the engineers decided to be careful and to build only 250,000 m$^2$ in a first configuration level and to study the performance of this pond and to build the other 750,000 m$^2$ at a later time.
Solar Ponds

The power generation unit was kept however to generate 5 MW (e). The planned 250,000 m\(^2\) pond was then divided again in one 40,000 m\(^2\) pond to have the opportunity to learn about the construction and behaviour of such big solar ponds, and in one 210,000 m\(^2\) pond.

There are also some experimental ponds which allow it to conduct experiments without disturbing the power production and performance of the main pond and some 1,000 m\(^2\) cooling ponds, which were filled with the surface water from the main pond at night time and cooled the condensators when electricity was produced at peak demand.

![Figure 2: Beith Ha'Avara solar pond, Israel [6].](image)

1.1.3 Bhuj Solar Pond, India [8]

The solar pond in Bhuj has a surface of 6,000 m\(^2\) and heats up 80,000 l water daily up to about 70 °C [9].

It is 3 m deep and supplies the gained heat to a dairy.
2 Theory of Solar Ponds

There are two general types of solar ponds to be mentioned, convecting and non-convecting solar ponds. [10]
The non-convecting solar ponds are named like this because of their non-convecting zone (NCZ) which is formed between the upper convective zone (UCZ) and the heat storage zone (HSZ) [11]. Both types of solar ponds inhibit heat transfer by convection and evaporation from the system to the environment to limit heat losses. In most cases, this is carried out by covering the surface of the heat storing element or by encapsulating the heat storing element how it is implemented in shallow solar ponds. In this paper only non-convecting solar ponds are considered and only so called “salt-gradient” solar ponds and partitioned solar ponds are studied in detail. There have been several attempts to improve the basic salt-gradient pond which led to the diversification shown in figure 3.

![Classification of Solar Ponds](image)

Shallow Solar Ponds [4] use fresh water and do not require any addition of salt. They consist of a back insulation and usually a concrete-made frame in which a plastic tube is attached. This plastic tube is filled with fresh water and has a black bottom to absorb as much solar radiation as possible to heat up the water. In most cases, this plastic tube is covered by another glaze to reduce convection losses to the ambient air.

Saturated Solar Ponds [4] are saturated with salt at any depth of the pond. The amount of salt varies only because of the varying density and the resulting higher solubility due to the change in temperature. This means that by heating up the water in the bottom of the pond, its solubility increases and the water cannot rise to
the surface and lose its heat content. The choice of salt is of great importance here, since some kinds of salt make the solution decrease its density from a certain temperature on which would destroy the pond’s performance. Partitioned Solar Ponds [4] use a physical separation of at least the HSZ to increase the temperature in the HSZ and thus to increase the performance of the solar pond. This is usually achieved through the use of a membrane. It is important that such a separation has to be high-transmittant to solar radiation; otherwise the advantages from physically separating the HSZ could equal the losses through less irradiation into the HSZ. Another problem which can occur is the stress of the membrane due to thermal expansion of the HSZ or the gravitational pressure of the NCZ. If the HSZ cools down or if heat is taken out of the HSZ a negative thermal expansion will occur. A fracture in the membrane could affect the performance of the pond heavily and cause mixing of the layers. In Viscosity Stabilized Solar Ponds [4], a gel is used to make the water thicker which hinders convection losses. The requirements for such a gel are quite high as it should be thickening enough to avoid convection but also retain its temperature resistance and above all, still have a satisfying transmittance for solar radiation. Additionally, it should have a good physical resistance to withstand precipitation.

In this paper the focus lies on salt-gradient solar ponds and membrane stratified solar ponds, which belong to the group of partitioned solar ponds and their mechanisms. It is possible that later proposals and considerations overlap with the other types of salt-gradient solar ponds shown above.

2.1 Salt-gradient solar ponds

As described earlier, salt-gradient solar ponds use the addition of salt to the water to increase its density and therefore to avoid convection to the surface even if heated up. Besides problems and questions concerning this general function of a salt-gradient solar pond, there are a lot of other points to consider and of course a lot optimisation and improvement possibilities too. In this chapter is a description of the system solar pond’s several parts and their tasks as well as an explanation of their function and effects. To give a feeling of the potential of gaining or storing heat by the use of solar ponds, the possible heat content of 1 m³ of water when heated up from ambient temperature to almost boiling point can be calculated as follows:

Equation 1: heat content of 1 m³ water

\[
Q = \rho \cdot V \cdot c_p \cdot \Delta T = 1000 \frac{kg}{m^3} \cdot 1m^3 \cdot 4187 \frac{J}{kg \cdot K} \cdot \Delta (90 - 20) K = 293 MJ = 81 kWh
\]

That is the same amount of energy as driving for 1 hour on peak performance with an AUDI A4 1.9 TDI.
Notation: Because of the varying and by now unknown solubility of the added salt, the density of clear water is assumed here, but it has to be mentioned that the heat content of salt water will be higher due to the higher density which hinders it from rising to the surface.

2.1.1 Positioning and shape

Solar ponds are solar collectors and thus it is one of their tasks to collect as much solar radiation as possible. The earth rotates around its axis and it is moving around the sun, which creates a demand for a specific shape and position of a solar pond. First of all, it is necessary to know the angle of total reflection at the air-water surface because it will have influence on the shape of the wall or on a potential covering during the night.

Equation 2: Critical angle for total reflection air-water.

\[ \Theta_c = \arcsin \left( \frac{n_2}{n_1} \right) \]

The refractive indexes of air and water [12] are

\[ n_{2 \text{ (air)}} = 1.00 \text{ and } n_{1 \text{ (water)}} = 1.33. \]

This gives us the critical angle of total reflection for a water-air boundary layer of:

\[ \Theta_c = \arcsin \left( \frac{1.00}{1.33} \right) = 48.8^\circ \]

With equation 2 it is possible to calculate the critical angle for a water-air boundary layer. This angle is measured towards the vertical axis as shown in figure 4 and defines the angle form which on a light beam is totally reflected by the surface. This angle then also gives an idea of the angle of the side walls of a solar pond, since it is counter-intuitive to build a vertical sidewall because of shadowing effects.
Of course, this is only valid if the solar pond is orientated exactly towards the south. If another orientation is desired, the side walls could be varied in their angles.

Optimisation possibilities could also be found by considering the different zenith angles of the sun at different positions on the earth, but this should not have considerable effects on the performance.

However, J. Srinivasan showed in his study [13] that at least for a solar pond in the tropics, a side slope of 60° generates the highest temperatures in the HSZ whereas an angle of 0° towards the vertical axis yielded the lowest temperatures due to higher heat losses.

Other solar ponds which really have been built and studied showed an angle of approximately 30° [14] but it should be mentioned here that the angle has no serious effects on the performance of large solar ponds, it seems more to be a matter of the physical stability and construction problems of the side walls [6].

The depth of solar ponds is theoretically unlimited, but due to decreasing transmittance with increasing depth and stability problems of the salt gradient, the pond will not work effectively anymore which leads to an optimisation problem with an appropriate thickness of the HSZ, a transmittance as high as possible and a stable salt gradient which also affects the thickness of the several layers.

### 2.1.2 Size and depth

The size of a solar pond which is first determined by its surface is mainly an economical optimisation problem. Cheap land should be available to keep the investment costs low, but the pond should be as big as possible to increase the volume of the HSZ to be able to extract as much heat as possible to use it in a
Rankine Cycle for producing electricity or to use the heat itself as process heat or for room heating.

The depth of the pond should be big enough to guarantee the needed volume for the HSZ, but should be small enough to allow an adequate transmission of the sun light through the water to the bottom liner. The choice of the volume of the HSZ is the parameter which is chosen first when planning a new solar pond. Based on this energetic design, the whole depth of the pond is determined by its salt gradient, built by a filling technique developed by Zangrando [15].

If a certain height $H_s$ of the HSZ is desired, the pond should be filled with the brine or salt water of the required concentration $C_s$ for the HSZ up to $H_s$ and half of the wanted height for the NCZ.

For the next steps, the top side of the HSZ will be seen as the start point of a coordinate system with the vertical component $z$ with positive direction upwards. This is done for the following injection process of fresh water with a diffuser to create the salt gradient and the fresh water layer of the UCZ.

The injection process itself is now ruled by the speed of the diffuser moving upwards, the velocity of the fresh water flowing out of the diffuser and the discharge of the diffuser.

The speed of the ascending diffuser should be twice that of the rise of the surface according to Zangrando’s calculations to create a linear distribution of the salt concentration.

**Equation 3: Concentration gradient of NCZ [15].**

$$C(z) = C_s \left( \frac{H - z}{H} \right)$$

The last step of building the three layers is to add a fresh water layer on top of the NCZ, which will spread out over the salt-gradient zone due to its lower density and build the UCZ. This process should be done straight after the filling process, otherwise evaporation and convection effects can destroy the NCZ and the whole filling process has to be restarted.
2.2 Description of the mechanisms

2.2.1 Optical properties of water

The relation of absorption/emission coefficient, reflection coefficient and transmission coefficient is shown in equation 4 [16].

Equation 4: Relation between absorption, reflection and transmission.
\[ \rho + \alpha + \tau = 1 \]

One can see here that the sum of these optical parameters has to be 1 in all cases, which means if one addend changes considerably, the others have to change too. Furthermore it is to mention that \( \alpha = \varepsilon \) at the same wavelength.

The following chart [17] shows how the value of the absorption coefficient changes over the wavelength spectrum of light. The area of visible light is marked yellow and it is obvious here that the values of the absorption coefficient of high-frequent and low-wavelength radiation is very low compared to the absorption coefficient of low-frequent and long wavelength radiation.

Regarding the validity of equation 4 and assuming the same reflection coefficient, which is only a matter of angle and refraction index here, the transmission coefficient has to decrease with an increasing absorption coefficient which explains the characteristic of water to capture and store electromagnetic energy.
2.3 Membrane Stratified solar ponds

Membrane Stratified solar ponds belong to the group of partitioned solar ponds, where the HSZ is separated physically from the upper layer or layers. In previous works and descriptions of such ponds, the HSZ of a partitioned solar pond was covered by a transparent membrane, but a salt-gradient zone combined with a fresh water layer was installed on top of it too [4]. This system could be seen as a salt-gradient solar pond with an additional physical separation of the HSZ.

The big advantage of a physical separation of the HSZ from the rest of the system lies in the increased stability of the several layers when heat is extracted from the HSZ. A membrane does not allow any disruptions and interactions between the HSZ and the upper layer, no matter if it is a NCZ and a UCZ or only one fresh water layer.

Furthermore, the heat extraction in a salt-gradient solar pond is a complicated and technically difficult process, where diffusers with intelligent control have to be used for the inlet and outlet to guarantee a stable layer and to avoid eddies and interactions with the NCZ.

The disadvantage of adding a physical layer to a system where solar radiation is the only input is obviously the diminished total transmission of sunlight to the bottom of the pond. Since this is an optical boundary layer, there will be of course optical effects like reflection, transmission and absorption which counteract the performance of the pond.

There have been studies with even two membranes separating each of the three layers from each other [18]. There have been some interesting results showing that a single membrane salt-gradient pond has a higher efficiency than standard salt-gradient ponds.

2.4 Experimental study of a membrane-stratified solar pond

To understand the behaviour of membrane stratified solar ponds and to indentify the problems of these systems, it is essential to conduct a laboratory-scaled experiment to gain experience for further investigation and studies and to avoid mistakes and problems which could occur in real-size membrane stratified solar ponds, if built.

2.4.1 Idea of the pond structure, objective and limitations

The intention of the structure of the solar pond primarily lies in the applicability in sea water and an easy and not complicated construction. The main goal is a low-tech solution for hot water supply and maybe generation of electrical energy with an organic ranking cycle.

This led to the idea of using a 4% salt water solution to simulate the use of sea water in the HSZ and to study potential problems connected with or caused by the salt content.

As described later at the end of this study, the future prospect could be a self-maintaining system where a room beyond a membrane, which is fixed in separate housing, is filled by valves with sea water and the room above the membrane is filled with fresh water by precipitation.
Based on these considerations, the main structure of this experimental membrane stratified solar pond was set to a 4% salt-water layer as HSZ, a transparent membrane, a fresh water layer on top of it and insulation of the side walls. This experimental pond considered here, is of course not situated in sea water and not exposed to the movement of the surrounding water caused by wind and waves. However, to learn about the mechanisms and the performance of such ponds, it is not necessary to simulate the exact conditions, but to know the boundary conditions and limitations of the considered system. To do first approaches, the pond was not filled up close to the top of the rim as to generate a buffer layer which keeps the fresh water inside even if the pond is exposed to heavy movements and to have a certain wind shielding to reduce the losses to the environment and to reduce the movement of the water surface. Moreover, there is no heat technically extracted from this experimental pond. It is indeed not as problematic as in standard salt-gradient ponds, but extraction and injection of fluid or heat still creates a serious disturbance of the balance of the HSZ, which can cause convective currents and lead to high losses.

2.4.2 Location of the pond

The pond was placed on the roof of the laboratory facility of the University of Gävle in Brynäs. The University of Gävle has only been undertaking indoor climate research for approximately the last 10 years, but has completed outdoor measurements in the past. Most of the equipment had not been used since these times, but after a short inspection of the equipment it became clear that with a little effort the equipment could be used again for outdoor measurement. Gävle is a city in central Sweden, with the coordinates 60° 40’ 0” N, 17° 10’ 0” E, see Figure 7. Its climate is typical for central Sweden, with a considerable influence form the Baltic Sea with almost constant wind speed which can be seen later in the results chapter. The laboratory facility in Brynäs is proximal to the sea with almost no wind-shielding buildings or elements in the near surrounding, which will increase heat losses to the environment.
Figure 7: Location of Gävle (60° 40’ 0” N, 17° 10’ 0” E), Sweden (source: Wikipedia).
Due to the change of the solar altitude and the azimuth, and due to the shadowing effect of the side walls of the pond, the whole surface area of the HSZ, which is equivalent to the area of the membrane, will never be hit by the direct radiation from the sun. This will limit the performance of the pond of course, although it was attempted in this experimental study to orientate the pond in a way where it can work as effective as possible. I tried to do this by orientating the pond with one sidewall directly facing the south to always have a large area exposed to sunlight (Figure 9).

Figure 8: Roof place in Brynäs, Gävle (source: Google Earth).

Figure 9: Orientation of the pond model.
2.4.3 The experimental pond, construction and equipment

Experimental studies of membrane stratified solar ponds have been studied very little; it was mainly a matter of theoretical treatment.

The main idea behind separating a bottom layer from a top layer by a membrane is –like in salt-gradient solar ponds, too – to prevent the water from rising up due to its decrease of density when heated up.

That means that an intermediate salt-gradient layer, which is difficult to generate and to maintain, does not need to be installed here to segregate the UCZ and the HSZ. That allows more liberties for designing the pond since the energy producing and storing part is only the HSZ, the function of the UCZ and the NCZ is only to reduce heat losses, and especially the NCZ claims a lot of height due to a stable salt-gradient.

In this study an attempt was made to build and study the behaviour of a laboratory-scaled membrane stratified solar pond with a total water volume of 0,06 m$^3$ (UCZ: 0,01 m$^3$, HSZ: 0,05 m$^3$).

An acrylic glass container formed the housing which had been previously used for experiments concerning the mixture of salt and fresh water earlier. This pond had a removable intermediate acrylic glass layer with an opening in the middle to separate a salt water layer and a fresh water layer before allowing them to mix.

I decided to keep this intermediate layer in general but to replace the acrylic glass one by a wooden one because of the mechanical instability due to the opening in the middle.

The layer beyond this wooden layer with a height of 250 mm was left as it was, meaning there is a kind of air insulation between the wooden plate and the roof, which makes the calculation and interpretation of the losses much easier, since the composition of the roof and the temperatures underneath are unknown or at least difficult to determine.

This construction allows a good approach to calculate the losses and the thermal behaviour of the pond since all boundary conditions are determined and the needed parameters are known.

The next step of the setup of the pond was to add insulating panels (XPS – EN13164) of a thickness of 50 mm to the outside of the side walls. There is no need to insulate the bottom of the tank since there are no expected high temperatures and no heat storage. The insulation was fixed to the walls with double-sided adhesive tape.

Further, the bottom layer was installed. A thick sheet of black plastic which is normally used as a pond liner in garden ponds or other artificial bodies of water was used. It is important to have a colour as dark as possible to absorb as much radiation as possible. The plastic foil was matte too, which also reduces reflection losses and will therefore increase absorption because it is opaque to sunlight and transmission will be zero (see equation 4).

There should also be no problem with the salt content of the solution, and this was confirmed when I inspected the bottom layer when I dismantled the experimental pond after I finished my measurements.

For measuring the temperatures, the laboratory staff and I came to the conclusion that thermocouple thermometers should be the best solution since they have an acceptable accuracy and are uncomplicated to install and to operate. But there
remained an uncertainty about their stability in salt solution; corrosion could be a serious problem.

The three first thermocouples measuring the temperatures at several heights in the salt water layer were fixed to a wire construction running down the sidewall with three perpendicular wires reaching 250 mm to the middle of the pond.

The next step was to fill the pond with the salt water solution. I used exactly 50 litres of cold tap water and added 2 kg of 99,9% NaCl salt to it which gives the required salt concentration of 4%. It took about 1 hour to dissolve all the salt in the water due to the low temperature and coarseness of the salt, the particle size was between one and three millimetre. The process could be accelerated by stirring the solution.

The transparent membrane was laid down on the water surface of the salt water solution and filled with 10 litres of fresh tap water and put another perpendicular wire to the middle of the pond and fixed the thermocouple thermometer to it, which were bent upwards and downwards respectively to yield two measurement points in the fresh water layer. Finally, I mounted the last thermocouple temperature sensor to the rim of the pond to measure the exact ambient temperature at the pond and fixed the transparent plastic sheet to the outer side of the side walls. All the thermocouple thermometers were attached to the wires with shrinkdown plastic tubing.

Figure 10: Drawing of the pond model with temperature measurement points.
Table 1: Heights of temperature sensors from bottom level.

<table>
<thead>
<tr>
<th>Temperature sensor</th>
<th>Height from bottom level [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>35</td>
</tr>
<tr>
<td>T2</td>
<td>85</td>
</tr>
<tr>
<td>T3</td>
<td>135</td>
</tr>
<tr>
<td>T4</td>
<td>195</td>
</tr>
<tr>
<td>T5</td>
<td>225</td>
</tr>
</tbody>
</table>

In figure 11 the make up of the pond and the installation of the several temperature sensors can be seen very clearly. The recording of the temperatures began right after the salt was completely dissolved in the water, but the transparent membrane and the fresh water layer had not been added yet. At approximately 16:45 I put the other temperature sensors out of the shack on the roof so they registered a temperature drop from the indoor temperature there to ambient temperature. Almost one hour later, after finishing the construction of the pond, I placed the two fresh water temperature sensors in the UCZ where they recorded the higher temperature of the water. From that moment on the system was left on its own and it was decided that the beginning of the measurement taking would take place on the following day to eliminate any influence from the construction. This should also be a test phase to check if everything is working correctly and all temperatures were being measured and recorded. When I checked the experiment the next day, the pond itself and the data recording were working as I expected, so measurements could start on May 27th.
Figure 12 shows a photo of the pond model shortly after the pond was set up. One can see the pink insulation panels attached to the outside of the pond walls and top ends of the plastic sheets. To the right, the wires of the thermocouple thermometers (dark) and the end of the wire construction (bright) leave the pond.
3 Results

The data collected from May 27\textsuperscript{th} to June 7\textsuperscript{th} showed promising results. As I mentioned before, May 26\textsuperscript{th} was used as an initial phase and therefore gives no representative output (see figure 11).

In Figure 13 the distribution and correlation of ambient temperature, wind speed and global radiation over the whole 12 days is shown. On June 3\textsuperscript{rd} and June 4\textsuperscript{th} the daily temperatures were higher than the 12 day-average, which can be seen in the chart on the very top of figure 13. The ambient temperature - especially at night – dominates the thermal losses through evaporation and convection.

Furthermore, May 31\textsuperscript{st} until June 2\textsuperscript{nd} showed the best curves for the global radiation which is similar to the highest input and thus the highest temperatures were reached then.

The diagram at the very bottom shows the relation of wind speed and ambient air temperature. It is pointed out here how the wind speed by tendency decreases with decreasing temperatures at night time. This effect could be explained with the lacking sun radiation at night. During the day, some parts of the ground are heated up more than others or are shadowed by clouds. That leads to a temperature gap and causes movement of air masses which is expressed in wind.

At night time these temperature gaps are not as wide as during the day, so the displacement of air is not as noticeable.

This correlation affects the pond performance in a positive way since the losses due to convection decrease with decreasing wind speed and therefore limit the losses were they are at the highest level anyway, namely at night time where the temperature differences are biggest.

3.1 Measured results
Figure 13: Correlation of ambient temperature, global radiation and wind speed.
Because of the reasons mentioned above, the data of May 31\textsuperscript{st} until June 2\textsuperscript{nd} are the best to understand and study the behaviour of the pond system. In Figure 14 one can see that there have been almost no clouds on the entire day because the irradiation curve describes a bell shaped curve in the diagram. The global radiation did not reach its highest value though if the whole measurement period is considered, there must have been an evenly spread layer of particles or clouds, maybe in higher atmospheric altitudes.

It is interesting to see how delayed the pond temperatures react if the radiation curve and the pond temperature curves are considered, even after the radiation reached its maximum and decreased almost to its minimum on that day, the pond temperature is still slightly increasing and reaching the peak temperature of 24.68 °C on that day (see table 2).

This can be explained in the still quite high ambient temperature, which avoids higher losses to the environment. As soon as the ambient temperature decreases, the missing input through radiation and the increasing temperature gap to the environment causes high losses which decrease the pond temperature. As I mentioned before in this chapter, the wind speed and the temperature seem to be in close relation, not claiming which effect triggers the other. As the wind speed increases considerably at around 5:30 in the morning, the ambient temperature curve immediately deviates from its further slope but still rises until around 17:00.

This graph also describes a problem which occurred to the temperature sensors in the fresh water layer. The falling water level of this layer, due to evaporation and a damage of the attachment of the wire construction where the temperature sensors are fixed to, made these temperature sensors to become exposed to the air and measure the ambient temperature instead of the water temperature. Unfortunately, this problem started on May 29\textsuperscript{th} where I could not check the experiment for the next 3 days and occurred again on two days in June.

The wire construction was fixed on several points, but the most important point to avoid the construction to tilt and therefore to lift the upper two temperature sensors above the water level was fixing them to the side wall with adhesive tape right above the water level of the salt water solution. This tape was released by natural conditions which resulted in the wire construction being tilted, lifting the temperature sensors T4 and T5 out of the water.

However, this had no effects on the temperature sensors T1 – T3. They were only lifted by a few centimetres in the salt water layer, which should only have a small effect on the temperature measurement here. The temperature differences of the several heights in the salt water layer do not differ in a remarkable value anyway as it can be seen exemplarily in figure 15. I should be remembered that T1 is the lowest temperature measurement point, T5 is the highest temperature measurement point (see table 1).

The highest temperature sensor of the salt layer seems to be the most sensitive to temperature changes, both through losses and radiative heating. It records the lowest temperature at night time, but then increases the most but the highest temperature of all was still measured with T1 on May 31\textsuperscript{st}. 
The pond temperatures on June 1st were, for almost the entire day higher than the ambient temperature and were still higher than the average ambient temperature of that day. One can see here that the task of the membrane to avoid the salt water from rising up to the surface and losing its heat is fulfilled. The temperature of the salt water is always around one or two degrees higher than that of the fresh water layer on top of it, especially when the ambient temperature is decreasing. This effect shows the heat storage potential of solar ponds. Again, the relation between wind speed and the change in the slope of the ambient temperature distribution can be seen here.
Figure 16: Pond performance on June 1st.

Figure 17 represents how upcoming cloudiness affects the irradiation but keeps the ambient temperature at a rather high level compared to days with clear skies all day like June 1st. Furthermore, the high ambient temperature limits the losses to the environment and therefore allows the pond to reach very high temperatures again. Also, the slope of the decreasing pond temperatures is not as high as other times when the ambient temperature is at a lower level, which can be seen here from about 15:00 until the end of that day with a kink of the pond temperatures and a drastic fall of the ambient temperature at around 21:00. The drop of the wind speed to almost calm and the local peak of the ambient temperature at the same time shows again the close relation of these two parameters.

Figure 17: Pond performance on June 2nd.
A very interesting chart to study the behaviour of this experimental solar pond is shown in figure 18. On June 6th, the irradiation fell down to a minimum of around 100 W/m² which is a very low value for day time. The pond temperatures follow this trend with a delay of about one hour and decrease evenly until the end of that day. A short but very high peak of irradiation between 14:00 and 15:00 causes a slight reaction of the pond temperatures - also delayed by approximately one hour - but induces only a short stagnation of the salt water temperatures and a short rise of the fresh water temperatures, respectively. The water temperatures of both layers do not fall again below the mean air temperature of that day.

Figure 18: Pond performance on June 6th
Table 2: Maximum temperatures.

<table>
<thead>
<tr>
<th>Day</th>
<th>Mean air temperature $T_6$ [°C]</th>
<th>Max. daily temperature $T_6$ [°C]</th>
<th>Max. daily pond temperature $(T_1-T_3)$ [°C]</th>
<th>Max. daily pond temperature $(T_4-T_5)$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 27th</td>
<td>11,15</td>
<td>19,53</td>
<td>18,57</td>
<td>17,68</td>
</tr>
<tr>
<td>May 28th</td>
<td>13,55</td>
<td>26,62</td>
<td>18,63</td>
<td>20,01</td>
</tr>
<tr>
<td>May 29th</td>
<td>11,95</td>
<td>19,30</td>
<td>16,17</td>
<td>16,75</td>
</tr>
<tr>
<td>May 30th</td>
<td>15,67</td>
<td>27,32</td>
<td>22,27</td>
<td>(26,85)</td>
</tr>
<tr>
<td>May 31st</td>
<td>15,69</td>
<td>24,93</td>
<td>24,68</td>
<td>(24,23)</td>
</tr>
<tr>
<td>June 1st</td>
<td>13,82</td>
<td>22,51</td>
<td>23,46</td>
<td>21,74</td>
</tr>
<tr>
<td>June 2nd</td>
<td>16,56</td>
<td>25,06</td>
<td>24,58</td>
<td>23,18</td>
</tr>
<tr>
<td>June 3rd</td>
<td>19,47</td>
<td>28,20</td>
<td>24,30</td>
<td>22,79</td>
</tr>
<tr>
<td>June 4th</td>
<td>15,93</td>
<td>26,45</td>
<td>22,31</td>
<td>21,94</td>
</tr>
<tr>
<td>June 5th</td>
<td>16,29</td>
<td>26,91</td>
<td>22,78</td>
<td>21,46</td>
</tr>
<tr>
<td>June 6th</td>
<td>13,87</td>
<td>26,79</td>
<td>22,00</td>
<td>20,96</td>
</tr>
<tr>
<td>June 7th</td>
<td>12,27</td>
<td>24,50</td>
<td>22,00</td>
<td>20,96</td>
</tr>
</tbody>
</table>

Table 2 shows the maximum temperature distributions of the several measurement points over the whole period. As can be seen, the maximum pond temperatures are always explicitly higher than the mean air temperature of that day and sometimes even reach the maximum daily temperature, see June 1st.

One can also see that the maximum temperatures of the salt layer are higher than those of the fresh water layer.

It should be remembered here that the maximum temperatures of $T_4-T_5$ on May 30th and May 31st are not representative since the temperature sensors have been exposed to the ambient air.

Table 3: Maximum pond temperatures overall.

<table>
<thead>
<tr>
<th>$T_1$ [°C]</th>
<th>$T_2$ [°C]</th>
<th>$T_3$ [°C]</th>
<th>$T_4$ [°C]</th>
<th>$T_5$ [°C]</th>
<th>$T_6$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>24,68</td>
<td>24,65</td>
<td>24,65</td>
<td>-</td>
<td>-</td>
<td>28,20</td>
</tr>
</tbody>
</table>

Table 3 shows the recorded maximum temperatures for each temperature sensor. The highest temperature at all was reached in the very lowest measurement point in the pond, $T_1$. This seems to be logical since the dark bottom liner heats up the water directly on top first.

$T_4$ and $T_5$ give no reliable results here because of the reason mentioned above.

### 3.2 Calculated results based on collected data

Based on the five measured pond temperatures, I calculated an average pond temperature of every measurement point of the period to be able to calculate the heat flow from the several surfaces and mechanisms.

Here, I distinguish between the following heat flows:
- Heat flow through the ground construction
- Heat flow through the side wall construction
- Heat flow from the water surface to the environment

By adding these heat flows, I calculated the total heat flow. A positive heat flow means that the pond temperature is falling and heat is transferred from the pond to the environment, whereas a negative heat flow means a rising pond temperature and the heat flow direction is going from the environment to the pond. Together with the global radiation, this gives a good overview of the pond behaviour and illustrates the problems and potential of a solar pond (see figure 19).

![Figure 19: Heat flow balance of the pond.](image)

For a better understanding and referencing to the previous chapter where the measurements were presented, I show my calculations in the following charts for May 31st.

The heat flows were calculated as follows:

- Heat flow through the ground construction:

  Equation 5: Heat transfer.

  \[
  \dot{Q} = k A \Delta T
  \]

  with \( k \) calculated as:

  Equation 6: Total heat coefficient for ground construction.

  \[
  \frac{1}{k} = \frac{1}{\alpha_{\text{water}}} + \frac{d_{\text{foil}}}{\lambda_{\text{foil}}} + \frac{d_{\text{air.glass}}}{\lambda_{\text{air.glass}}} + \frac{d_{\text{wood}}}{\lambda_{\text{wood}}} + \frac{1}{\alpha_{\text{arr}}}
  \]
- Heat flow through the side wall construction:

\[ \dot{Q} = k \Delta T \]

with \( k \) calculated as:

**Equation 7: Total heat transfer coefficient for side wall construction.**

\[
\frac{1}{k} = \frac{1}{\alpha_{\text{water}}} + \frac{d_{\text{foil}}}{\lambda_{\text{foil}}} + \frac{d_{\text{air}}}{{\lambda_{\text{air}}} + \frac{d_{\text{insulation}}}{\lambda_{\text{insulation}}} + \frac{1}{\alpha_{\text{air}}(f(v_w))}}
\]

where \( \alpha_{\text{air}}(f(v_w)) \) is the heat transfer coefficient through convection, including wind effects and is calculated as:

**Equation 8: heat transfer coefficient through convection including wind effects.**

\[
\alpha = 2 + 12 \cdot \sqrt{v}
\]

Equation 8 is an empirical equation [19] and has the dimension \([\text{W/m}^2\text{K}]\).

- Heat flow from the water surface to the environment:

**Equation 9: Combined heat flow from the pond surface.**

\[
\dot{Q} = h(f(v_w)) A \Delta T + A \varepsilon \sigma (T_{\text{pond}}^4 - T_{\text{sky}}^4)
\]

with \( \sigma = 5.67 \times 10^{-8} \text{W/K}^4\text{m}^2 \) and \( \varepsilon = 0.67 \) [20] and \( \alpha_{\text{air}}(f(v_w)) \) is calculated as in equation 8.

The sky temperature was calculated as follows [21]:

**Equation 10: Calculation of sky temperature.**

\[
T_{\text{sky}} = 0.0552 \times [T_{\text{amb}}]^{1.5}
\]

This empirical equation is an acceptable assumption for clear skies condition which was true for almost the whole measurement period.
The data I used for these calculations are presented in table 4:

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$ [W/mK]</th>
<th>$\alpha$ [W/m²K]</th>
<th>$d$ [m]</th>
<th>$k$ [W/m²K]</th>
<th>$A$ [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom layer (PVC)</td>
<td>0,15</td>
<td>0,0057</td>
<td>0,0005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acrylic glass</td>
<td>0,184</td>
<td>0,01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>0,14</td>
<td>0,01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XPS-EN 13164 insulation</td>
<td>0,035</td>
<td>0,05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground construction</td>
<td></td>
<td></td>
<td>5,657327586</td>
<td>0,0625</td>
<td></td>
</tr>
<tr>
<td>Side wall construction</td>
<td></td>
<td>$f(v_{\text{wind}})$</td>
<td></td>
<td>0,235</td>
<td></td>
</tr>
<tr>
<td>Water surface area</td>
<td></td>
<td></td>
<td></td>
<td>0,0625</td>
<td></td>
</tr>
</tbody>
</table>

As mentioned before, a mean pond temperature was introduced to conduct these heat flow calculations. Since this model should show the relation between the several mechanisms, this simplification is acceptable here.

![Figure 20: Heat flows on May 31st.](image)

Figure 20 shows how the several heat flows affect each other and therefore influences the pond performance. The well insulated sidewalls and the ground allow the lowest heat flow, whereas the heat transfer from the surface to the environment seems to be dominating
especially the losses. The gains from the environment – the solar irradiation not considered – are very small compared to the heat going out from the system. If we compare the absolute values for the energy input through solar radiation on the one hand and thermal and radiative losses on the other hand, we can see in figure 21 why the pond temperatures are almost always higher than the ambient temperature, the input is higher than the losses. Total heat flow means here the thermal heat flow which was already shown in figure 20. This can also be explained by the second law of thermodynamics, which says – modified for the present model – that energy cannot be created or destroyed:

**Equation 11: First law of thermodynamics.**

\[ dU = \delta Q - \delta W \]

and because there is no mechanical work performed in this system, one can also write:

**Equation 12: First law of thermodynamics.**

\[ dU = \delta Q \]

Thus, the following equation has to be valid:

**Equation 13: Energy balance.**

\[ \dot{Q}_i = \dot{Q}_o + \frac{dE_{sys}}{dt} \]

So if the solar input exceeds the thermal losses by far, then the input is higher than the output which means that energy must remain in the system and is expressed here in increased pond temperatures compared to the environment.

![Pond performance; May 31st](image)

**Figure 21: Pond performance on May 31st.**
4 Discussion

The results of the experiment show the problems and the possibilities of a membrane stratified solar pond and solar ponds in general. The pond temperatures have been above the ambient temperature almost all the time but as soon as the irradiation decreases, the losses dominate the pond’s performance and therefore limit the reached temperatures at a level some degrees over ambient temperature.

In this experiment, the surface losses have the biggest share of the total losses of the pond and also show the most variation since it is coupled with the wind speed and also the radiative losses have to be assigned to the water surface. The side walls are coupled with wind effects too, but due to the good insulation this effect is less marked here. The ground has not been insulated in this experiment but there would be a big saving potential which would increase the achieved pond temperatures and would keep it longer when irradiation breaks away. Another step to increase the pond performance would be to add another transparent membrane on top of the fresh water layer, or to install a salt gradient on top of the first one to reduce the convectional losses in the upper layer. But as mentioned in the previous chapters, this is not easy to install and maintain and more salt would be needed, too which increases the costs of the pond.

Serious problems which occurred during the measurement period were contamination of the fresh water layer with insects, pollen and other organic material from the ambient flora. In salt-gradient ponds, these pollutants would sink to the black ground where they would not affect the pond’s performance in a considerable rate. But in membrane stratified solar ponds, these particles sink down on the membrane and decrease its transmittance. Even after only 12 days the membrane was considerably polluted and turbidity increased. For further studies there should be thinkings about how to clean the membrane, maybe even with an active system. One goal of this thesis was to study the effect of precipitation on the pond system. This could maybe have a cleaning effect too but unfortunately it has not been raining during the whole measurement period, which also led to another problem. It should be investigated if precipitation could equate the water mass losses of the fresh water layer and if this water would be clean enough to keep a high transmission of sun light. Furthermore, the physical stability of the membrane if rained on would have been of interest, but that will probably no problem. Due to the lack of fresh water after some warm days without any precipitation, I had to add another 10 l of water on June, 5th to keep an adequate fresh water level and to guarantee a good covering of the surface of the salt water layer. The less the amount of water got, the more of the left water gathered in the middle of the membrane and thus, the pressure on the side walls decreased which exposed more and more of the salt water surface to the air and therefore allowed more losses to the environment. Because I already had some days of data, I took the risk and added the water very fast and in one push. The membrane stayed stable and showed no damage, also not at the fixation on the outside of the pond.
5 Conclusion and future prospects

Solar ponds were shown to have good heat storage possibilities due to their big thermal inertia. Even drastic changes in irradiation or wind speed do hardly affect the pond’s thermal performance, their disadvantage is the low energy density and the low temperature level though, which makes them more interesting for thermal uses as for power generation.

Further work could be done in improving the insulation, especially at the ground and wind-shielding, also the shape could be a topic to think about in the future.

A very interesting application could be so called “sea cells” (named by the author of this paper). They are in general large swimming membrane stratified solar ponds with a bottom salt water layer which could be filled with sea water by valves, and a fresh water layer which could be filled by local precipitation. These two layers are separated by a translucent membrane or an acrylic glass construction.

Such sea cells could be used for generating hot water for room heating or heating of tap water for outlying settlements, research stations or even close to the coast. Their long term storage potential could help to supply hot water during winter months, maybe seasonal permanent covering would be necessary.

Figure 22: "Sea cell", a large membrane stratified solar pond.
Figure 23: Swimming "sea cells" in the ocean.
Acknowledgments

The author would like to thank the University of Gävle to have made it possible to conduct the experiment at their laboratory facility as well as the staff for helping me to build the pond. Thank is also given to Claes Blomqvist for the help with the measurement part and Hans Lundström for organizing and supervising this experiment. The author wishes to express his gratitude also to the programme coordinators Mathias Cehlin and Ulf Larsson, who made it even possible for me to write this thesis at the KTH Stockholm and for helping with the administrative problems. Special thanks to Peter Kjaerboe from the Department of Energy Technology of the Royal Institute of Technology in Stockholm for supervising this project and for the advice and ideas during the work progress.
References


[16] Dr. Ing. H. Drück, Prof. Dr. Dr. Ing. habil. H. Müller-Steinhagen, „Solartechnik 1“ (Lecture material), ITW Institut für Thermodynamik und Wärmetechnik Universität Stuttgart, 2010.


List of Symbols and Abbreviations

List of Abbreviations

UCZ    Upper Convective Zone
NCZ    Non-Convective Zone
HSZ    Heat Storage Zone

List of Symbols

\[\begin{array}{lll}
\rho & \text{Density} & [\text{kg/m}^3] \\
\rho' & \text{Reflection coefficient} & [-] \\
\varepsilon & \text{Emission coefficient} & [-] \\
\alpha & \text{Absorption coefficient} & [-] \\
\tau & \text{Transmission coefficient} & [-] \\
\Theta & \text{Critical angle of total reflection} & [^\circ] \\
\eta & \text{Refraction index} & [-] \\
Q & \text{Heat} & [\text{kWh}] \\
E & \text{Energy} & [\text{J}] \\
V & \text{Volume} & [\text{m}^3] \\
A & \text{Area} & [\text{m}^2] \\
H & \text{Heigth} & [\text{m}] \\
d & \text{thickness} & [\text{m}] \\
v & \text{velocity} & [\text{m/s}] \\
c_p & \text{Specific heat capacity} & [\text{J/kg K}] \\
m & \text{Mass} & [\text{kg}] \\
T & \text{Temperature} & [^\circ \text{C}] / [\text{K}] \\
\Delta T & \text{Temperature difference} & [^\circ \text{C}] / [\text{K}] \\
C_0 & \text{Salt concentration of UCZ} & [\text{kg}_{\text{Salt}}/ \text{m}^3_{\text{Water}}] \\
C_S & \text{Salt concentration of HSZ} & [\text{kg}_{\text{Salt}}/ \text{m}^3_{\text{Water}}] \\
z & \text{vertical coordinate} & [-] \\
\sigma & \text{Stefan-Boltzmann constant} & [\text{W/K}^4\text{m}^2] \\
k & \text{total heat transfer coefficient} & [\text{W/m}^2\text{K}] \\
\lambda & \text{heat conductivity coefficient} & [\text{W/mK}] \\
\alpha & \text{heat transfer coefficient, convection} & [\text{W/m}^2\text{K}] \\
\end{array}\]

Subscripts

\[\begin{array}{ll}
i & \text{in} \\
o & \text{out} \\
sys & \text{System} \\
w & \text{Wind} \\
\end{array}\]
Appendix

Appendix A – Tables

<table>
<thead>
<tr>
<th>Highest recorded radiation [W/m²]</th>
<th>Highest recorded wind speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1026,30</td>
<td>8,71</td>
</tr>
</tbody>
</table>

Table A 1: Highest values for radiation and wind speed.

<table>
<thead>
<tr>
<th>Highest energy input [kWh/m²] (5 min. value)</th>
<th>Total energy input [kWh/m²] (whole measurement period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,08553</td>
<td>74,79</td>
</tr>
</tbody>
</table>

Table A 2: Energy input, peak value and total value.

<table>
<thead>
<tr>
<th>Date</th>
<th>Highest daily radiation [W/m²]</th>
<th>Highest daily wind speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 27th</td>
<td>1003,80</td>
<td>8,09</td>
</tr>
<tr>
<td>May 28th</td>
<td>911,10</td>
<td>6,59</td>
</tr>
<tr>
<td>May 29th</td>
<td>786,00</td>
<td>5,94</td>
</tr>
<tr>
<td>May 30th</td>
<td>980,10</td>
<td>6,01</td>
</tr>
<tr>
<td>May 31st</td>
<td>788,50</td>
<td>7,45</td>
</tr>
<tr>
<td>June 1st</td>
<td>790,80</td>
<td>7,21</td>
</tr>
<tr>
<td>June 2nd</td>
<td>801,40</td>
<td>4,60</td>
</tr>
<tr>
<td>June 3rd</td>
<td>1026,30</td>
<td>6,64</td>
</tr>
<tr>
<td>June 4th</td>
<td>1004,00</td>
<td>8,71</td>
</tr>
<tr>
<td>June 5th</td>
<td>804,10</td>
<td>5,77</td>
</tr>
<tr>
<td>June 6th</td>
<td>927,60</td>
<td>7,69</td>
</tr>
<tr>
<td>June 7th</td>
<td>872,00</td>
<td>5,81</td>
</tr>
</tbody>
</table>

Table A 3: Peak radiation and peak wind speed over measurement period.

<table>
<thead>
<tr>
<th>Max. mean pond temperature [°C]</th>
<th>Max. temperature difference (mean-ambient) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>24,12</td>
<td>11,59</td>
</tr>
</tbody>
</table>

Table A 4: Maximum temperatures of the pond and maximum temperature difference.
Appendix B - Calculations

\[
\frac{1}{k_{\text{ground}}} = \frac{1}{10 \frac{W}{m^2K}} + 0.0005 \frac{m}{mK} + \frac{0.01 m}{mK} + \frac{0.01 m}{mK} + \frac{1}{10 \frac{W}{m^2K}} = 0.176 \frac{m^2K}{W}
\]

Calculation B 1: k-value of the ground construction.

\[
\frac{1}{k_{\text{wall}}} = \frac{1}{10 \frac{W}{m^2K}} + 0.0005 \frac{m}{mK} + \frac{0.01 m}{mK} + \frac{0.05 m}{mK} + \frac{1}{0.035 \frac{W}{mK}} \alpha_{\text{air}}(f(v_w))
\]

Calculation B 2: k-value of the wall construction.

Appendix C – Charts
Figure C 1: Heat flow, temperatures and radiation over whole measurement period.
Figure C 2: Maximum temperatures of every sensor.

Figure C 3: Wind speed variation over whole measurement period.
Figure C 4: Pond performance and influencing parameters on May 27th.

Figure C 5: Pond performance and influencing parameters on May 28th.
Figure C 6: Pond performance and influencing parameters on May 29th.

Figure C 7: Pond performance and influencing parameters on May 30th.
Figure C 8: Pond performance and influencing parameters on June 3rd.

Figure C 9: Pond performance and influencing parameters on June 4th.
Figure C 10: Pond performance and influencing parameters on June 5th.

Figure C 11: Pond performance and influencing parameters on June 7th.
Figure C 12: Recorded temperatures in salt layer on May 27th.

Figure C 13: Recorded temperatures in salt layer on May 28th.
Figure C 14: Recorded temperatures in salt layer on May 29th.

Figure C 15: Recorded temperatures in salt layer on May 30th.
Figure C 16: Recorded temperatures in salt layer on June 1st.

Figure C 17: Recorded temperatures in salt layer on June 2nd.
Figure C 18: Recorded temperatures in salt layer on June 3rd.

Figure C 19: Recorded temperatures in salt layer on June 4th.
Figure C 20: Recorded temperatures in salt layer on June 5th.

Figure C 21: Recorded temperatures in salt layer on June 6th.
Figure C 22: Recorded temperatures in salt layer on June 7th.

Figure C 23: Heat flow and irradiation on May 27th.
Figure C 24: Heat flow and irradiation on May 28th.

Figure C 25: Heat flow and irradiation on May 29th.
Figure C 26: Heat flow and irradiation on May 30th.

Figure C 27: Heat flow and irradiation on June 1st.
Figure C 28: Heat flow and irradiation on June 2nd.

Figure C 29: Heat flow and irradiation on June 3rd.
Figure C 30: Heat flow and irradiation on June 4th.

Figure C 31: Heat flow and irradiation on June 5th.
Figure C 32: Heat flow and irradiation on June 6th.

Figure C 33: Heat flow and irradiation on June 7th.
Figure C 34: Pond performance on June 1st.

Figure C 35: Pond performance on June 2nd.