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Enhancing the thermal efficiency of a salinity gradient solar pond: implementation of the study in the design, construction, salinity gradient establishment, operation and energy transfer at industrial scale

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Chemical engineering department
Ph. D. Program: Chemical processes engineering

Enhancing the thermal efficiency of a salinity gradient solar pond. Implementation of the study in the design, construction, salinity gradient establishment, operation and energy transfer at industrial scale

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“I am among those who think that science has great beauty.
A scientist in his laboratory is not only a technician, he is
also a child place before natural phenomenon, which
impress him like a fairy tale.”

Marie Curie

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This is the moment when you look back and images come to your mind, like flashlights turning on and off. Fast and apparently without any order. Then, you take a break, and make an effort to identify which is the first of all of them. For me, it is a conference poster hanged in the department's faculty office. That was the first time I saw a solar pond. Nobody could say that years later, I would be building one of those at industrial scale in Granada. This thesis has been a gift, and I have to thank with all my love to César Valderrama, Jose Luis Cortina and Adriana Farran, for all the support given during this time and for all I have learned by their side. Those years will always be in my memory. Thank you for being part of this chapter of my life.

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Abstract

The energy model in the last decades has been dominated by the consumption of fossil fuels assuming a high environmental cost. Global warming and the destruction of the ozone layer are two examples of the deterioration that is being suffered due to the use of these energy sources. Increasingly, the use of renewable energy one of the alternatives in building a sustainable economic model. Among renewables, solar energy is presented as an inexhaustible and accessible source of energy. The solar pond is a technology that meets all requirements to be considered an energy storage device. It can store solar energy, charging during the months of high solar incidence (Spring-Summer), storing the energy through the time and making possible its use when it is requested.

A salt gradient solar pond is a body of saline water with long term thermal storage capacity. The aim and scope of this PhD thesis is divided in two parts. First, the improvement of the efficiency of the solar pond technology through experimental evaluation the heat extraction and heat supply processes under different weather conditions. These experiments were carried out in a 50 m^2 solar pond pilot plant located in Martorell (Catalonia). Heat extraction experiments were performed using both heat exchangers installed (lateral and bottom) individually or both at the same time. The results demonstrated that the efficiency of the pond increases when the heat is removed from the lateral heat exchanger compared to either using the bottom heat exchanger or using both heat exchangers simultaneously. On the other hand, the use of solar collectors as an external source of heat were conducted together with heat extraction process under two different seasonal temperature conditions: winter and summer. The results indicated that the use of solar collectors allowed a 50% increase in daily efficiency during the cold season tests.

The second part was focused on the design, construction and operation of a 500 m^2 solar pond in Solvay Minerales facilities (Granada). The solar pond was designed to supply the heat required to preheat the water (> 60 °C) and the reagents in the mineral flotation unit at the mineral processing facility. The overall efficiencies obtained after the first and second operation periods are 9.7 and 12.3%, respectively, with maximum values of 28 and 24% obtained during the first months of operation. Regarding the economic savings, reductions of 52 and 68% were obtained in the first and second periods compared with the traditional system without solar pond. Also, the environmental impact is clearly reduced considering the reduction of CO_2 emissions. The experience of the Granada solar pond proves that the main advantage of a solar pond is the capacity to store energy in the months with the highest solar radiation to provide a flux of heat to an external system during the whole year even under strong weather conditions, as observed during the January 2015 snowfall.

Summary

1. INTRODUCTION

1. Introduction

1.1. Solar Energy Storage

In recent decades, a rapid worldwide population growth has led to a greater consumption of conventional energy resources, such as fuel, coal and oil. The consumption of these resources generates serious environmental problems such as climate change and other environmental impacts that represent the greatest challenge of today's society. Renewables are shown as one of the solutions to solve the challenges that arise to modify the current energy model. Thus, investment in these energies would decrease the reliance on traditional fossil fuels and consequently decrease the impact on the environment (Sayer et al., 2018).

Within the renewable energy, solar energy is one of the most important sources of energy and can be deployed to meet the energy needs of a low carbon economy. In recent years, different technologies have been proposed to use the solar thermal energy as a useful and efficient source (Khalilian, 2017).

Solar energy is abundance, free and clean as well as does not make any noise or generate pollution to the environment. Many industrial processes are involved in heat utilization with low (i.e. 20–200 ◦C), medium and medium-high (i.e.80–240 ◦C) temperature levels. However, solar energy is an intermittent and time-dependent source of energy; therefore, it is necessary systems to accumulate solar radiation, store and release it to an application (Mekhilef S. et al., 2011).

Energy storage is the ability to store some type of energy that can be used later for your any energy need. Normally, it is applied to balance the possible problem between energy supply and demand. These devices arise from the need of having the energy production dissociated from its supply and distribution. An energy storage process has three basic steps: Charging (loading), storing and discharging (releasing) (Gil et al., 2010).

The solar pond is a new technology that meets all requirements to be considered an energy storage device. It can store solar energy, charging during the months of high solar incidence (Spring-Summer), storing the energy through the time and making possible its use when it is needed.

1.2. Solar pond

In broad terms, a solar pond is a large body of water that collects and stores solar energy. The first investigation on the solar pond was conducted by Kalecsinsky (1902). This researcher studied the behaviour of the natural lake in Transylvania (Hungary) known as Lake Madoc. This lake showed temperatures as high as 70°C at a depth of 1.32 m in the summer season and salinity was about 26 % of NaCl at bottom. The minimal temperature was 26°C during early spring (Tundee et al., 2010). Similar observations were reported in other places of the world, such as the “Hot Lake” near Oroville in Washintong (Anderson 1958), Lake Vanda in the Antarctic (Wilson & Wellman 1962) a solar lake in the red sea between Africa and Asia (Por 1968), Uganda (Melack and Kilham, 1972), Los Roques in Venezuela (Hudec and Sonnenfeld, 1974) and Sinie in Africa (Cohen et al., 1977). These studies were used as a starting point for the study of artificial solar pond as a possible technology of solar energy storage.

The most commonly artificial solar pond used is salinity gradient solar pond (SGSP) followed by shallow solar pond (SSP). There are other types of artificial solar pond such as partitioned solar pond, saturated solar pond, membrane stratified solar pond and viscosity stabilized solar pond.

1.3. Salinity gradient solar pond

In practice, any water pond with a black bottom is capable of collecting solar energy, but the collection efficiency is poor, this is because the heated water at the bottom rises by convection to the top where the heat is rapidly dissipated to the environment.

The convections currents that normally develop due to the presence of hot water at the bottom and cold water at the top are minimized by presence of strong density gradient from bottom to top (Weinberger, 1964); (Bansal and Kaushik, 1981). This density gradient is obtained by using a high concentration of suitable salts such as NaCl at the bottom of the pond and low salinity water at the top. This density gradient acts as an insulating layer because the thermal conductivity of the salt solution decreases with increasing salinity (Garg, 1987).

A typical salinity gradient solar pond (SGSP) consists in three distinct zones (Zangrando 1980; Tabor & Weinberger 1981) as shown in Figure 1. The surface area formed by fresh water or low salinity water is called upper convective zone (UCZ) and it is a zone of constant temperature, close to the ambient temperature, and salinity, between 2-3%. The thickness of this area varies from 0.1 to 0.4 m. Below this UCZ, there is an intermediate zone consists on several layers with different density. The brine density gradually increases towards the bottom of the pond causing a concentration gradient. This gradient prevents the occurrence of convection currents and, as a result of solar energy absorption, a gradient of temperature is also established. The gradient zone is known as a non-convective zone (NCZ) and it is the key of this technology. The thickness of this intermediate area ranges from 1 to 1.5 m. The lower zone has the highest density (highest salinity concentration), near saturation, and it is known as low convective zone (LCZ). This zone acts as a thermal storage with temperature ranging between 50-90ºC depending on the size of the pond.

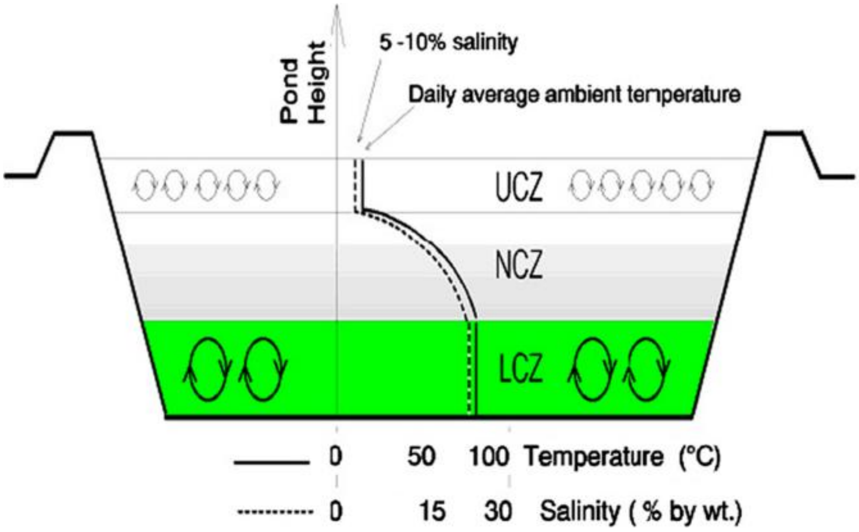

Figure 1. Scheme of salinity gradient solar pond with concentration and temperature profiles (Leblanc et al., 2011).

1.3.1 Pre-requisites to establishment a solar pond

The requirements to use this technology are:

- High solar radiation
- Availability of land surface
- Availability of salt at a relatively short distance
- Need for heat at low temperature

1.3.2 Establishment of salt gradient

The salt concentration gradient in the pond can be generated by several methods depending on local requirements (Kaushika, 1984). These methods include natural diffusion, stacking and redistribution.

- Natural diffusion

In this method, the lower half is filled with brine and the upper half is filled with tap water, top and bottom concentrations are maintained constant by regularly washing the surface and adding salt in the bottom. Due to the upward diffusion of salt, a salinity gradient will be established. This is a very slow method of establishing the salt gradient and should be considered if the pond is very large or if the starting time could be unlimited (Zangrando, 1980).

- Stacking

This method consists on fill the storage layer with high concentration solution and several other layers of salt solutions of differing concentration. The practical approach for stacking used is that the bottom layer is filled first and successively lighter layers are floated upon the lower denser layers. The concentration of salt in successive layers is changed in steps from near saturation at the bottom to fresh water at the top. For a typical pond of about 1 m depth, one might use about 10 layers. (Chepurniy & Savage 1975; Sayigh 1977).

- Redistribution

This method is considered to be the most convenient for larger ponds (Nielsen & Rabl 1976; Nielsen et al. 1977), the artificial pond is filled with high salinity brine to half of its gradient zone depth and then fresh water is added through a diffuser. Initially, a diffuser is placed at a level making the starting of the non- convective zone and fresh water is pumped through a diffuser for a pre-calculated time (flowrate). At the end of the first pumping period, the diffuser is raised to the next higher position and water is pumped again for a second period. The diffuser is thus moved upward continuously at a rate twice that of the increase in the pond water level. In parallel with this, solutions of appropriate density are injected for fine adjustment of the salinity gradient. Finally, a layer of fresh water is added to make the surface zone. At the completion of this process, a nearly uniform salt concentration gradient in the pond is obtained (Zangrando 1979).

1.4. Monitoring system

The measures of the temperature and density profiles are the most direct and simple way to define the different zones of the solar pond and to control its stability (Leblanc et al., 2011). A monitoring and sampling are needed to measure physical and chemical parameters such as temperature, density, pH and turbidity at different heights of the pond. The automatic monitoring system can include temperature sensors distributed at various heights inside the pond and connected to a data collection system for processing. Daily data collection provides a temperature profile as can be seen in Figure 2. Sampling is also required at different heights of the solar pond in order to measure the density, the pH and the turbidity at different pond depths. Once data is treated the concentration profile is obtained as is shown also in Figure 2. Furthermore, this information is essential to control and detect potentials instabilities that can occur into the system. The values of pH and turbidity are also critical since they are indicators of the level of clarity of the pond.

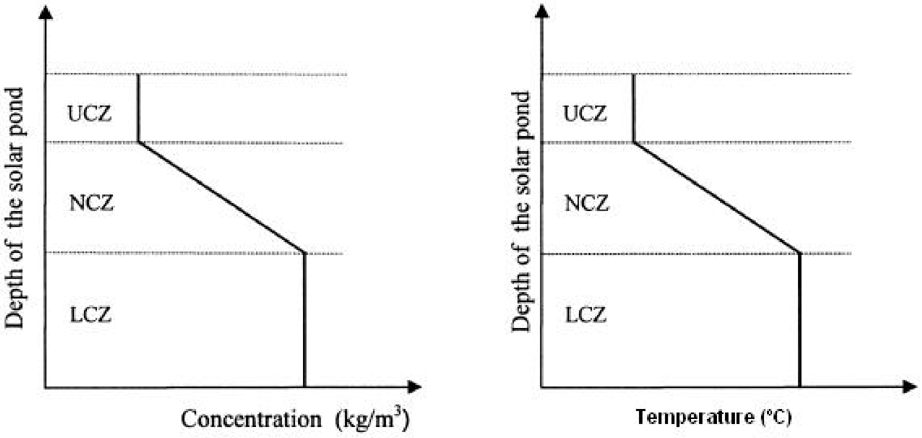

Figure 2. Schematic diagram of typical concentration and temperature profiles of the solar pond (Kurt et al., 2000).

1.5. Control variables

1.5.1 Maintenance of salt gradient

The stability of the gradient layers is necessary to achieve a successful operation of the solar pond. Both, the UCZ and LCZ zones cause erosion of the boundaries of the gradient zone. This erosion process causes the reduction of thickness of the NCZ (Karim et al., 2010). To maintain the stability of the gradient, it is necessary to control the salt concentrations (density) at the top and the bottom of the pond (Tabor, 1981). Therefore, two maintenance operations have to be carried out. Firstly, flush pond surface with fresh water is necessary to compensate evaporation losses and to remove the salt diffused from the bottom to the surface. If the surface is not flushed, the salinity of the UCZ would increase affecting the overall density gradient. The rate of flushing is approximately twice the average rate of water loss due to evaporation (Leblanc et al., 2011). The second maintenance operation is the addition of salt in the bottom. Two methods are used to perform this operation. On the one hand, injecting occasionally a concentrated salt solution in the bottom of the solar pond (Tabor 1981; Sherman & Mechanics 1992) and on the other hand, adding salt into a cylinder like a salt charger to replenish the salt at the bottom of the pond. The bottom of the cylinder is open and salt coming out confirming a salt pile in the shape of the semi cone around the charger (Jaefarzadeh and Akbarzadeh, 2003). Figure 3 shows a scheme of salt charger in the solar pond.

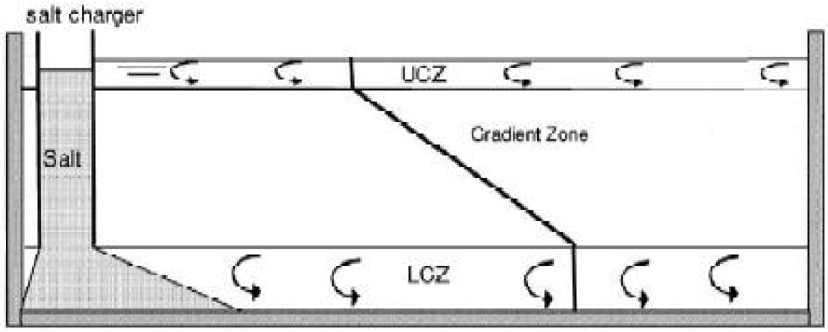

Figure 3. Schematic view of the pond with salt charger (Jaefarzadeh and Akbarzadeh, 2003)

1.5.2 Maintenance clarity of the system

A solar pond as a solar collector is depending on light transmission to the storage zone. The suspended particles and the growth of microbial and algae substances reduce the amount of solar energy reaching the LCZ (Wang & Seyed-Yagoobi 1995; Gasulla et al. 2011). Control of brine pH (< 4) is one of the most common strategies to maintaining the pond clarity by adding hydrochloric acid at different layers. Acidification of the pond provides a reliable and simple maintenance method for preventing algal blooms and maintaining high transparency. The acid should be added only in the UCZ and NCZ area. The addition of acid in the region near the interface LCZ-NCZ or storage area generates salt precipitation and causing instabilities in the salt gradient (Leblanc et al., 2011). Another disadvantage in the use of acid is the corrosion phenomena inside the pond.

Other method to keep the pond clarity is the use of brine shrimp to feed of and hence control the algal level (Wang & Seyed-Yagoobi 1995; Malik et al. 2011) or the use of copper sulphate to treat algae growths (Gasulla et al., 2011).

1.6. Applications of solar ponds

A solar pond can be an environmental and economical alternative in front of other large-scale solar thermal collectors. The main advantage of this technology is that it has an integrated thermal energy storage system, so it can supply thermal energy continuously regardless of the time day or the weather.

Solar ponds are particularly useful as an alternative to fossils fuels and it has a variety of applications like heat for industrial process, heating buildings, desalination, electrical power production, salinity mitigation and chemical production.

1.6.1.Heat for industrial process

Solar ponds can be economically viable for the supply of low temperature heat to an industrial process as an alternative to fossil fuels. El Paso solar pond became the first solar pond in the world to supply heat to an industry in 1985, where 350 x 10^6 kJ of thermal heat were delivered to a food canning plant (Reid et al. 1985; Swift et al. 1987). Other examples of this application can be the Bhuj solar pond, which provided 15000 m^3 of hot water to a dairy plant (Kumar and Kishore, 1999) or Pyramid Hill solar pond in Victoria (Leblanc et al., 2011).

1.6.2.Heating buildings

A solar pond has the capability of storing summer heat for winter applications, which is very suitable for heating buildings (Tabor, 1981). The use of the solar pond to heating buildings was studied by Rabl & Nielsen (1975). This study demonstrated that a solar pond can be used for a single house, where the pond surface area was approximately the same area as the floor area. Other research illustrates the use of solar pond even at high latitudes where the sunlight is lower as was studied in London by Bryant & Colbeck (1977).

1.6.3.Desalination

Thermal desalination by using a salinity gradient solar pond is a ground-breaking technology in a solar desalination (Lu et al., 2001). This application was studied in the El Paso solar pond since 1987 using a stage flash evaporation system. The study showed that this kind of technology can be an alternative with zero emissions and pollutions (Lu et al., 2004). Other authors have studied thermal desalination processes such as multiple effect evaporation or a multistage flash process by using heat from a salinity gradient solar pond to produce fresh water and salt, which can be recycled to the solar pond and hence reducing the cost of operation (Leblanc et al., 2010).

1.6.4.Electrical power production

A solar pond produces low temperature heat (70°C and 90°C) making it less attractive for electricity generation compared with conventional other renewable technologies. However, solar pond could be competitive as a power generator if compared with a diesel for producing electricity. The best practice is to couple the solar pond to an organic Rankine cycle to convert the low temperature heat supply to electricity using low boiling organic liquid as the working fluid. Figure 4 shows the diagram of this application.

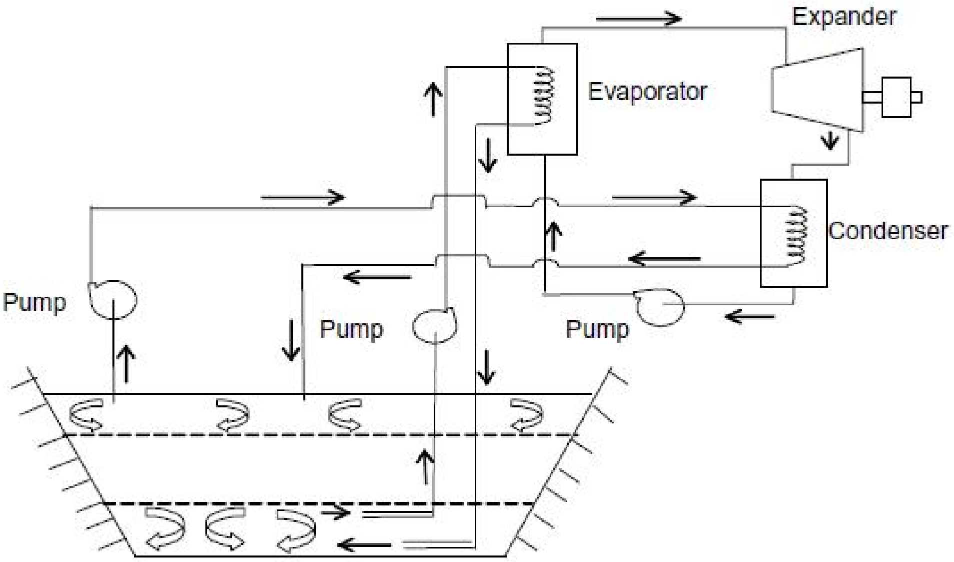

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Figure 4. Conventional method of extracting heat from solar pond for power generation using heat engine (Andrews and Akbarzadeh, 2005)

The first solar pond power station (SPPP) was constructed in Ein Boked in 1977 to produce power at approximately 20kW (Tabor, 1981). Other SPPP were constructed in Beith Ha’rava (Tabor and Doron, 1990), in Alice Spring (Collins, 1984) and in El Paso (J R Hull et al., 1989).

1.6.5.Salinity mitigation

Integration of solar ponds into salinity mitigation is an attractive application. Many areas of formerly productive land are suffering from rising salinity levels around the world as a result mainly of tree clearing and irrigation. Solar ponds provide simultaneous support for a potential application such as process heat. If evaporation ponds are established in a chain as a salt production line, the first few ponds in the chain provide ideal opportunities for creating solar ponds (Akbarzadeh et al., 2009).

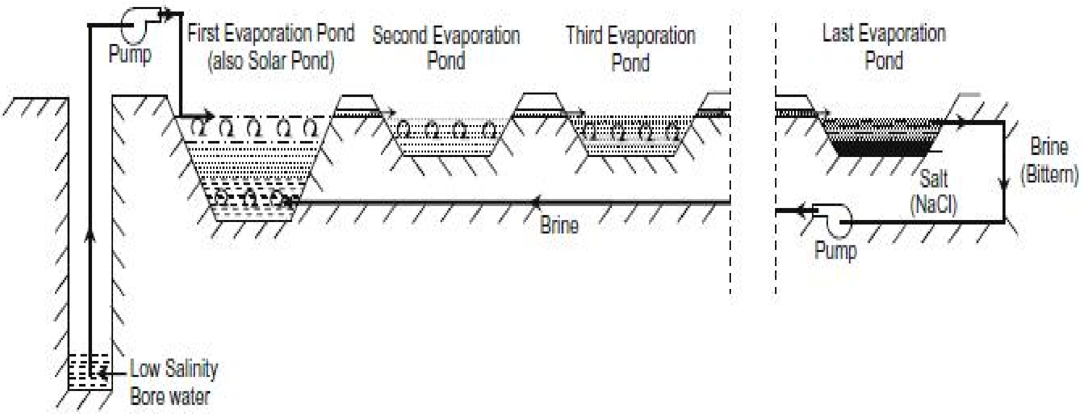

Figure 5. Integration of a solar pond into in a salinity control scheme (Akbarzadeh et al., 2009)

As can be seen in Figure 5 the solar pond is the first evaporation pond in the chain for salt production. Bore water is introduced to the surface of the pond for surface washing. The overflow from the first pond goes to the second pond and gravitates. The process continues in the others ponds in the chain. The evaporation causes the increases of the salinity in each pond. In the last pond, crystallisation of sodium chloride takes place. This material is usually disposed of as waste. A small amount of the bittern is pumped to the bottom of the solar pond to maintain the required salinity gradient in the pond (Akbarzadeh et al., 2009).

1.6.6. Chemical production

Other application of solar pond is its use in mines industries. Solar ponds can be used to produce chemicals using the heat provided by the pond. Lesino et al. (1990) reported the commercial use of 400 m^2 salinity gradient solar pond for sodium sulphate (Na_2SO_4) production. The sodium sulphate solution dissolves at 40°C, making the solar pond a useful component of the process. The use of this technology can provide substantial cost saving when it replaces the function of a conventional boiler.

1.7. Overview of solar ponds worldwide

In the last thirty years more than sixty solar ponds have been built around the world. Table 1 collects examples of different solar ponds built over time in different areas of the planet. It specifies the year of construction, the area, the maximum temperature reached in the LCZ and the applications of the heat delivered from the pond.

The construction of solar ponds had a great growth in the 70s and 80s being shown as a clean and economical technology. Due to be unable to compete with the low price of gas and other fossil fuels, many of these projects were abandoned during the 90s. In recent years, it has taken up the study of these devices appearing as an option to a sustainable energy model.

Figure 6 and 7 shows two photographs of the facilities of the El Paso Solar Pond and Pyramid Hill (Australia) as an example of the research carried out on this technology.

Figure 6. El Paso Solar Pond (Texas)

Figure 7.solar pond Pyramid Hill (Australia)

Table 1. Overview of solar pond around the world

		Name	Construction	Area (m^2)	Tmax (LCZ)	Applications	References
Israel	Eilat	Ein Boqek solar pond	1977	6250	85-90	Electrical production	(Tabor and Doron, 1986)
		Beith Ha’rava solar pond	1982	25000		Electrical production	(Tabor and Doron, 1990)
USA	Ohio	Ohio State University		200	62-69	Pilot Plant (research)	(Rabl and Nielsen, 1975)
		Ohio State University		400		Pilot Plant (research)	(Nielsen, 1980)
		Ohio Agriculture Research and Devel. Centre	1977	156	46	Heating building (Greenhouse)	(Fynn, 1981)
		Miamisburg	1978	2020	51.1	Heating building (Swimming pool and recreational building)	(Shah et al. 1981; Bryant et al. 1979)
	New Mexico	University of New Mexico (Albuquerque)	1975	175	93	Heating building (House)	(Wilkins et al. 1986; Zangrando 1991)
	Texas	University of Texas (El paso)	1983	3355	72	Industrial process heat (food canning factory); Desalination, electrical power production	(Reid et al. 1985; Swift et al. 1987; Liao et al. 1988; Hull & Nielsen 1988)
	Illinois	University of Illinois	1987	2000	70	Heating building (swine research facility)	(Newell et al., 1990)
India	Bhavnagar	Central Salt and Marine Chemicals Research Inst.	1970	1200		Pilot Plant (research)	(Srinivasan, 1993)
		Institute’s experimental salt farm	1980	1600	75	Pilot Plant (research)	(Mehta et al., 1988)
	Bangalore	Institute of science in Banglore (Pondicherry)		100	70	Pilot Plant (research)	(Patel and Gupta, 1981)
		Indian Institute of Science	1984	240	50-70	Pilot Plant (research)	(Srinivasan 1990; Akbarzadeh & Manins 1988)
	Karnataka	Masur		400		Heating building (Rural community)	(Srinivasan, 1993)
		Hubli		300		Heating building (To supply hot water for college)	
	Gujerat	Khuj Dairy (Bhuj)	1987-1991	6000	99.8	Industrial process heat (Milk processing dairy plant)	(Kumar and Kishore, 1999)

Australia	Aspendale (Victoria)	Commonwealth Scientific and Industrial Res. Org.	1964	44	63	Pilot Plant (research)	(Davey, 1968)
	Laverton (Victoria)	Cheetham Salt Works	1981	900		Pilot Plant (research)	(Golding et al., 1982)
	Alice Sprong	Northern Territory	1980	2000	80	Electrical power production	(Collins, 1984)
			1984	1600	80-85	Electrical power production	(Sherman and Imberger, 1991)
	Pyramid Hill (Victoria)	Pyramid Salt Ltd facility/ RMTI University	2000	3000	62	Industrial process heat	(Leblanc et al., 2011)
Other places	Argentina	Puna	1981	400		Chemical production	(Lesino et al. 1990; Lesino & Saravia 1991)
	Italy	Margherita Di Savoia		25000		Desalination	(Folchitto, 1997)
	China	Zabuya Lake (Qinghai Tibet Plateau)		2500	39	Chemical production	(Nie et al., 2011)
	Spain	Solvay Martorell (Catalonia)	2009	50	63	Pilot Plant (research)	(Valderrama et al. 2011; Bernad et al. 2013)

1.8. Methods of heat extraction

The extracting heat from a solar pond is performed by removing the heat from the LCZ by two common methods. The first method is pumping hot brine from the upper region of LCZ by means of a diffuser (extraction diffuser) through an external heat exchanger, where heat is transferred to a separate working fluid and hence delivered to the application, and then returning the brine at a lower temperature to the lower region of the LCZ through another diffuser (Return diffuser) as is depicted in Figure 8 (Andrews and Akbarzadeh, 2005).

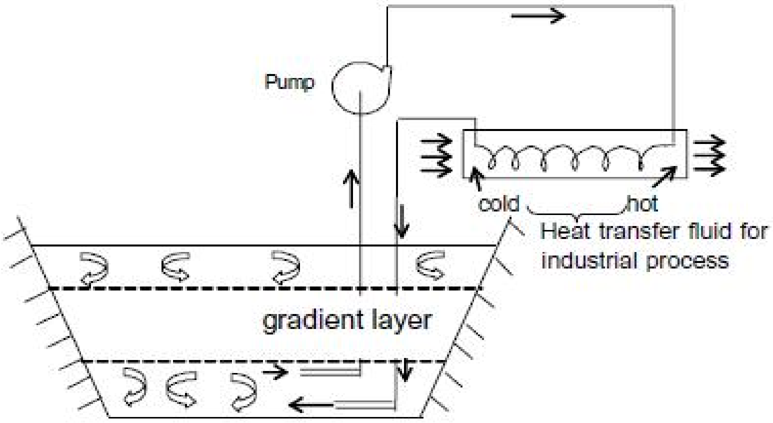

Figure 8. Conventional method of heat extraction from solar pond for industrial process heating using an external heat exchanger pumping the hot brine from LCZ. (Andrews and Akbarzadeh, 2005).

This method was used in several solar ponds worldwide as the El Paso, Texas (Xu et al., 1993), Kutch in India (Kumar and Kishore, 1999), Beith Ha’rava in Israel (Tabor and Doron, 1990) and Singapore (Kho et al., 1991).

These experiences indicate that the brine-withdrawal method is effective. The extraction diffuser can be moved to the height of maximum temperature in the storage zone and the return diffuser is placed below it. This method allows placement for both diffusers near the point of use. Also, this method ensures that the cooler brine is returned to the bottom, reducing ground losses (Leblanc et al., 2011). On the other hand, this method generates local temperatures differences, whose final effect is to destabilize the salinity gradient layer, because this brine extraction/injection process is performed at a specific point of solar pond (Angeli et al., 2006).

Another aspect to consider in this method of heat extraction is the material used in the design of diffusers and pipes because brine of LCZ is a corrosive medium. In the El Paso solar pond, the diffusers and pipes used in the heat extraction system were all made of steel. After several years of operation, they all indicated selective rusting. Besides the corrosion problem, the free ions of iron were suspected to contribute to clarity problems. A black layer appeared in the pond and the brine became very turbid (Abou-Chakra, 1992). Iron reduction bacteria were a possible cause. Based on this experience, the heat extraction system were redesigned and reconstructed and the steel diffusers were replaced with new ones made of polypropylene plate and connected by rubber hose to the external piping system (Leblanc et al., 2011).

In the second method fresh water circulates, in a closed cycle, through a series of pipes installed inside the pond as internal heat exchanger and transfers its thermal energy to an external heat exchanger. The common position for the internal heat exchanger is in the storage zone near to the gradient layer as can be seen in Figure 9. Thereby, this method stimulates the convection process in the thickness of the LCZ (Jaefarzadeh, 2006).

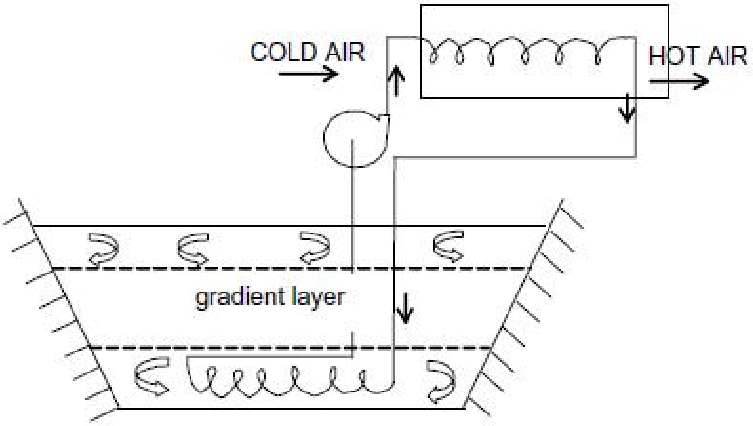

Figure 9. Conventional method of heat extraction using an internal heat exchanger (Leblanc et al., 2011).

This method has been proved by several studies as Pyramid Hill, Victoria (Leblanc et al., 2010), Marshad in Iran (Jaefarzadeh, 2006) and Ohio State University (Nielsen, 1980).

The internal heat exchanger may be made from metallic or plastic pipes. In the metallic pipe system, the maximum rate of heat extraction is controlled by the natural convection intensity. On the other hand, the corrosion process may occur and contribute in a decreased clarity. Whereas with plastic pipe system, the thermal conductivity of the plastic will restrain the heat removal. Therefore, a larger pipe area is needed for this case (J R Hull et al., 1989).

1.9. Methods to improve the thermal performance

The main problem to the scale application of solar ponds in industry has been the low solar thermal efficiency and in many cases low temperature heat available (below 60 °C) as discussed by Andrews & Akbarzadeh (2005) and Leblanc et al. (2011). Researchers have proposed many different ways of improving the thermal performance of solar ponds: i) improving the water clarity (Gasulla et al. 2011; Wang & Seyed-Yagoobi 1995; Malik et al. 2011; Jaefarzadeh & Akbarzadeh 2002), ii) increasing the thickness of LCZ and reducing the thickness of UCZ (Wang and Akbarzadeh, 1982), iii) introducing an additional upper NCZ (Husain et al., 2012), iv) putting an external reflector to reflect additional solar radiation into shallow solar pond (Aboul-Enein et al., 2004), v) placing a honeycomb surface insulation system to minimize the losses (Arulanantham et al., 1997), vi) using floating rings to reducing and maintaining the thickness of the UCZ (Akbarzadeh et al., 1983) or vii) integrating a solar pond with flat plate solar collectors (Bozkurt and Karakilcik, 2012).

Recent studies are focused on the removal of heat from salinity gradient zone to improve the overall thermal performance. An alternative method of extracting heat from NCZ using a lateral in-pond heat exchanger was performed theoretically (Andrews and Akbarzadeh, 2005). Later, an experimental research to confirm the theoretical result was carried out in 53 m^2 experimental solar pond (Leblanc et al., 2011). The results obtained shown that the heat extraction from NCZ has increased the overall thermal efficiency of SGSP by up to 50% compared to traditional methods of heat extraction and reducing the upward heat lost. However, the installation of lateral heat exchanger for larger scale solar pond is impractical and costly. Similar study has been conducted both numerically and experimentally for the 0.64 m^2 mini solar pond (Ould Dah et al., 2010). The result showed the improvement of the solar pond performance. A recent investigation has proposed a multi-layer heat extraction system remove heat at different level in NCZ by withdraw the hot brine and re-injecting it back at the same level (Yaakob et al. 2011).

1.10. Solar pond efficiency

Solar radiation goes through the different zones of the solar pond increasing the temperature and stored energy in each point of the system. Initially, solar radiation reaches the surface region. Part of this energy is lost as radiation reflected into the atmosphere. Another part is stored in this area increasing the temperature of the entire zone and the rest is transmitted towards to the gradient area. In the NCZ, part of the solar radiation is absorbed and stored in this zone. So, the NCZ temperature increases in each layer of the salinity gradient leading to the establishment of a thermal gradient. The rest of the solar radiation is transmitted to the LCZ where the majority of this energy is absorbed as a thermal energy. For this reason, the T_{LCZ} is increased getting the highest value of the system. In the present Ph.D. thesis, the efficiency of solar ponds is studied in order to increase its performance. Many authors have defined the efficiency of the solar pond from the point of view of thermal energy stored in the system relative to the incident radiation up on the pond (Bozkurt and Karakilcik, 2015; Karakilcik et al., 2006; Dehghan et al., 2013). Other studies have focused on defining solar pond efficiency as the extracted energy to the incident radiation (Andrews and Akbarzadeh, 2005; Leblanc et al., 2011).

The use of solar collectors as an additional source of heat have studied and the effect of the use of these devices on the efficiency of the solar pond (Bozkurt and Karakilcik, 2015b; Bozkurt and Karakilcik, 2012; Bozkurt et al., 2014). The heat stored in LCZ is defined as the heat gain by the solar collectors and the heat entering in the LCZ.

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2. THESIS OVERVIEW

2. Thesis overview

The dissertation is focuses on the technology of salinity gradient solar ponds and it is divided in two parts (Figure 10). The first part of the study is dedicated to improving the efficiency of the solar pond through the processes of heat extraction and heat supply (from an external source) to the system. In this section, a novel heat extraction method is used in which the heat is extracted from the gradient zone (NCZ) and also from the storage area (LCZ) (Publication 1). Afterwards, the use of solar collectors as an external heat source is evaluated using both in-pond heat exchangers at the storage area (LCZ) and in the saline gradient zone (NCZ) (Publication 2).

The second part contains the design, the construction, the establishment of the salinity gradient and the start-up of the first industrial solar pond in Europe (Granada, Spain). Likewise, the evolution of the system during the first two years of operation was studied by assessing the stability of the saline and thermal gradient. The efficiency of the pond as well as the economic and environmental saving during the first two years of operation was also evaluated within this section (Publication 3). The stability of the system as well as the influence on the solar pond efficiency operating in extreme temperature conditions was studied (Publication 4).

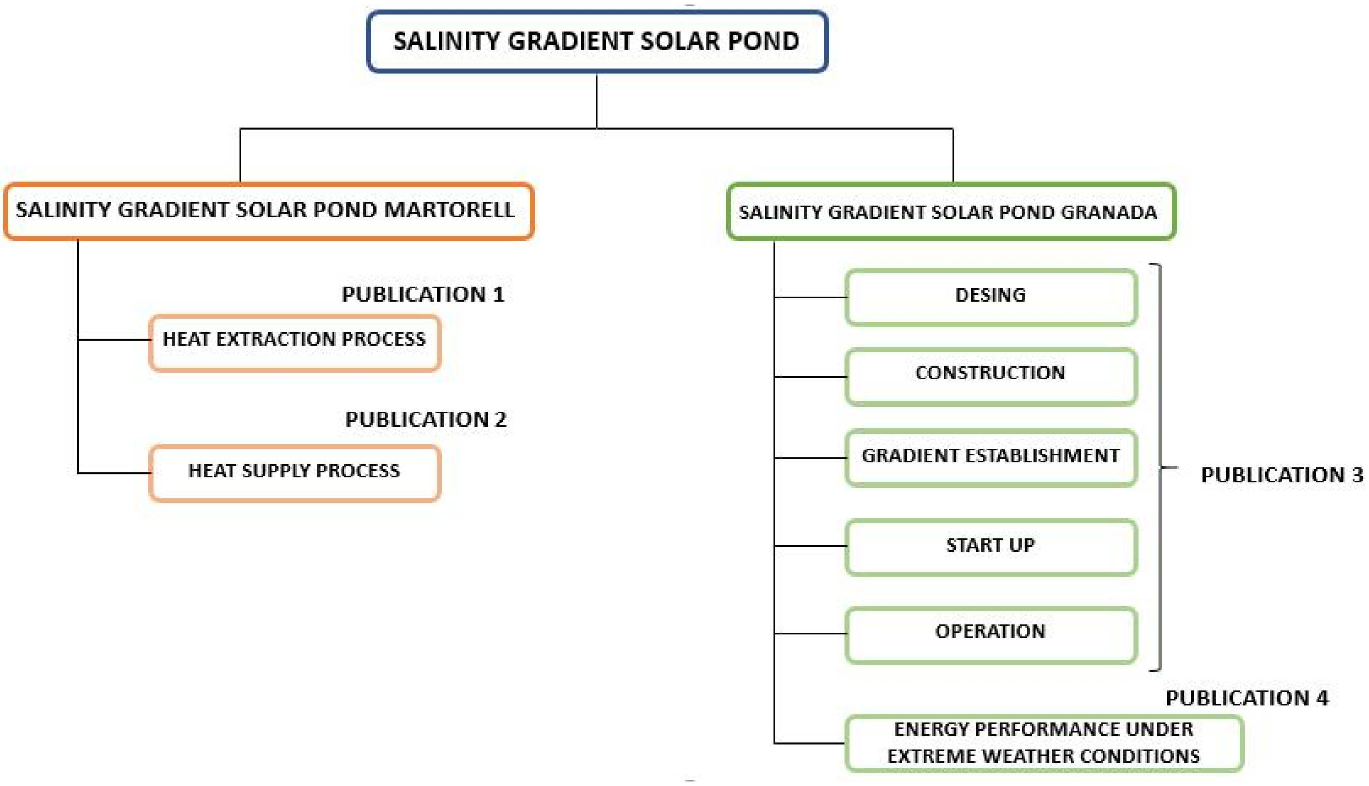

Figure 10. Thesis overview

Publication 1. A. Alcaraz, C. Valderrama, J.L. Cortina, A. Akbarzadeh, A. Farran. Enhancing the efficiency of solar pond heat extraction by using both lateral and bottom heat exchangers. Solar Energy 134 (2016), pp. 82–94

Publication 2. A. Alcaraz, M. Montalà, J.L. Cortina, A. Akbarzadeh, A. Farran, C. Valderrama. Increasing the storage capacity of a solar pond by using solar thermal collectors: Heat extraction and heat supply processes using in-pond heat exchangers. Solar Energy 171 (2018), pp. 112-121

Publication 3. A. Alcaraz, M. Montalà, J.L. Cortina, A. Akbarzadeh, C. Aladjem, A. Farran, C. Valderrama. Design, construction, and operation of the first industrial salinity-gradient solar pond in Europe: an efficiency analysis perspective. Solar Energy 164 (2018), pp. 316–326

Publication 4. A. Alcaraz, M. Montalà, J.L. Cortina, A. Akbarzadeh, A. Farran, C. Valderrama. Thermal performance of a 500m2 salinity gradient solar pond under strong weather conditions. Solar Energy 171 (2018), pp 223–228

3. OBJECTIVES

3. Objectives

The main objective of this Ph.D. thesis is the study of the technology of solar ponds as a source of renewable energy on a pilot scale to subsequently scale, build, operate on an industrial scale a solar pond of 500 m^2 that partially meets the energy needs of the flotation unit of a mining industry (Solvay Minerals) located in Granada (Spain). The use of solar energy instead of fossil fuels means both energy and environmental savings, which represents the main advantages of this technology.

As it is shown in Figure 11, all the knowledge acquired in the Martorell pilot-scale solar pond served as a starting point for scaling this technology on an industrial scale in the Granada solar pond.

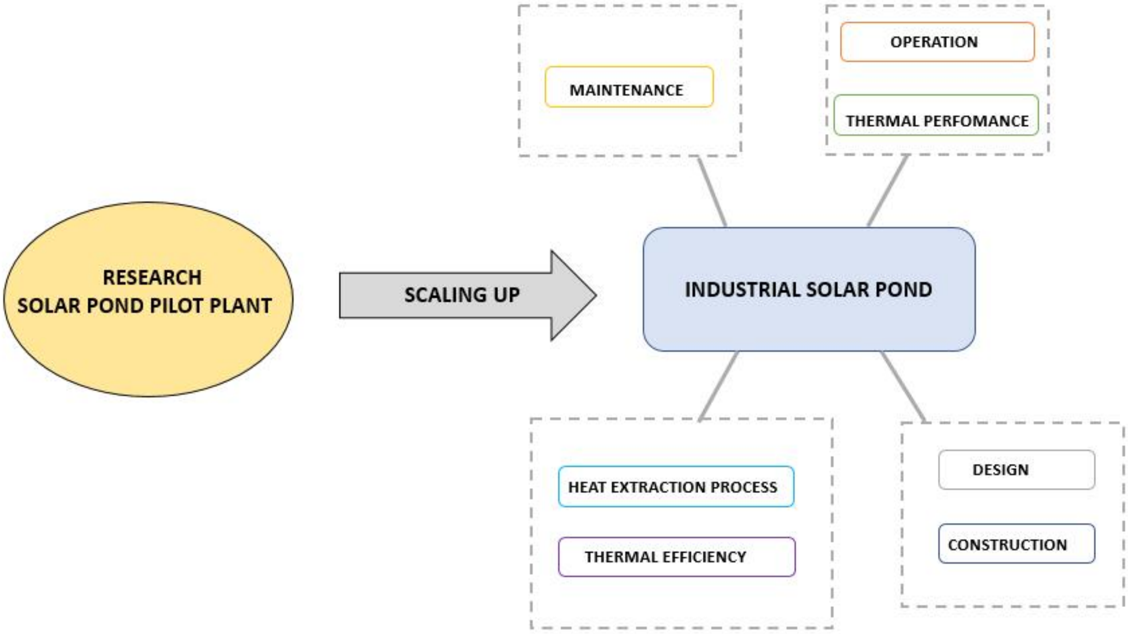

Figure 11. Thesis diagram scheme

For this purpose, specific objectives are proposed:

- To study the thermal performance of the solar pond under different operation conditions in a pilot scale.
- To evaluate the heat extraction from lateral in-pond heat exchanger to compare with the traditional method of heat extraction under different weather conditions in a pilot scale.
- To examine the possibility of the use of solar collectors to increases the energy efficiency of the solar pond under different weather conditions.
- To design the first industrial solar pond in Europe according with the energy needs of the flotation unit in Solvay Minerales.
- To construct and start-up of the 500m^2 industrial solar pond in Solvay Minerals.
- To operate the solar pond in order to minimize the consumption of fuel oil in Solvay Minerales.

4. METHODOLOGY

4. Methodology

4.1 Solar pond description

In the present Ph.D. thesis, the solar pond technology was studied and evaluated in two different scales. On one hand, the solar pond pilot plant (50 m^2) located in Martorell and, on the other hand, the industrial solar pond in Granada (500 m^2). The solar pond located in the facilities of Solvay in Martorell, was designed to carry out an experimental investigation of the operation of this technology, the control and maintenance systems were tested, as well as the heat extraction and the analysis of the efficiency of the system. With all this knowledge acquired, the design, construction and operation of the first industrial solar pond in Europe located in the facilities of the Solvay Minerals mining company in Granada was carried out.

4.2 Salinity gradient solar pond Martorell

4.2.1 Construction

In 2009 an experimental solar pond pilot plant was constructed in Solvay-Martorell facilities (Catalonia) to capture and store solar energy. The body of the pond was a cylindrical reinforced concrete tank, with 3 m height, 8 m diameter and total area of 50 m^2 (Bernard F. et al., 2013). A picture of the solar pond in Martorell is shown in Figure 12.

Figure 12. Solar pond Martorell

The lateral tank wall was insulated with 60 cm of rock wall, a layer of insulated material and a metallic external shell. Figure 13 shows the different thermal insulation layers.

Figure 13. Insulation of lateral wall

In 2012 in order to avoid heat losses and to improve the efficiency of the system, an insulation material was added at the bottom of the pond. This insulation layer consisted on 40mm of Polystyrene C3 TG CANTO with a thermal conductivity of 0.0395 W/mK and a thermal resistance of 1.012K/W. In addition; a concrete slab of 150mm was added on the top of the insulation layer. This concrete had a thermal conductivity of 0.47 W/mK and a thermal resistance of 0.32 K/W. Figure 14 shows the insulation and concrete process installation.

Figure 14. Insulation and concrete process installation in solar pond Martorell

4.2.2 Control of salinity gradient

A mobile PVC pipe (6mm of diameter and 3 m height) supported in a fixed tub and a peristaltic pump (3 L/h) was used as sampler mechanism to measure its density, pH and turbidity inside the pond at different heights. A portable density meter DMA 35 (Anton Par) was used for measurement of density. Further, pH and turbidity were measured by portable pH meter (Crison pH25), and portable turbidity meter (Hanna HI93703), respectively.

4.2.3 Maintenance of salinity gradient

To keep the salinity gradient and ensure its correct operation the addition of fresh water on the surface of the pond was required. For this purpose, a device shown in Figure 15b was used. The flushing system had a board on the surface that avoids to disturb the UCZ during the flushing procedure.
Furthermore, a salt charger was used to replace the salt in LCZ. It was made from a cylinder of polyvinyl chloride (PVC) with a diameter of 0.8 m installed on the wall of the pond as it is shown in Figure 15a. The bottom of the cylinder was designed to release salt by means of windows located at 0.6 m above the bottom, thus the border between the LCZ and NCZ was determined by the salt charger design.
The pH and the turbidity parameters were measured in order to control the clarity maintenance of the system. To control the growth of algae an acidification system was used. This system was composed of five tubs installed on the pond to delivered acid (9% v/v.) from the surface to different heights (0.2, 0.6, 0.95, 1.5 and 2.1 m) as can be seen in Figure 15c.

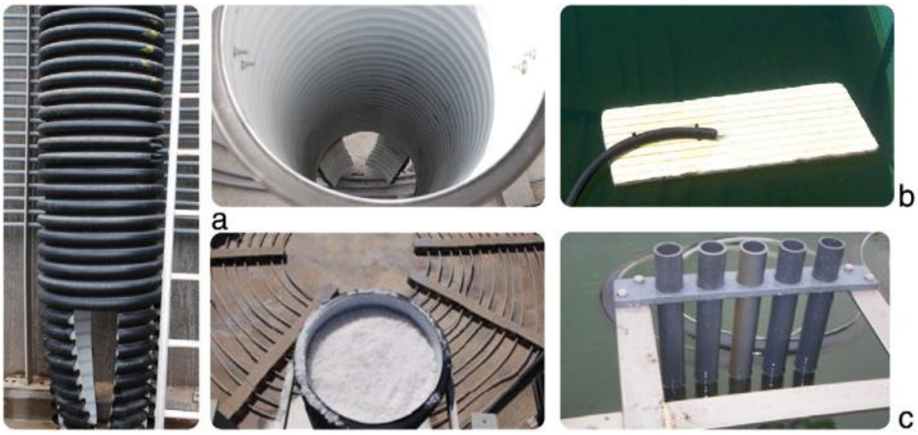

Figure 15. Maintenance equipment of salinity gradient: a) salt charger; b) fresh water supply system; c) control pH system

4.2.4 Thermal gradient control and weather conditions equipment

The temperature measurement at different heights was performed by means of 21 sensors (thermo-resistances Pt-100-K type, Abco, Spain) uniformly distributed each 14 cm (starting at 0.2 cm from the bottom) installed in a plastic support fixed to the pond wall. Heat losses by the wall and the bottom were also considered, thus, other 6 sensors were inside and outside of the wall concrete, and inside of the slab of the pond. The temperatures measured every 2 s and the averages after 10 min as well as the hourly and daily average were recorded.

The weather parameters were measured by means of an automatic weather station CR1000 Measurement and Control System (Campbell Scientific, Barcelona, Spain), which was programmed to measure and store data (Data logger CR1000) of different meteorological sensors with high accuracy as follows: rain gages, solar radiation, wind speed, relative humidity, barometric pressure and air temperature. The sensors took measures every 10 s, the hourly average was recorded as well as the daily average (24 h).

4.2.5 Heat extraction and external solar collectors

4.2.5.1 Lateral and Bottom Heat Exchanger

Two heat exchangers were installed in the solar pond. The bottom heat exchanger (250 m) located in the storage zone and the lateral heat exchanger that covers all lateral area (730m). Both coils were made of polybutylene and have 28 mm of diameter. Figure 16 shows both heat exchangers.

Figure 16. Lateral and bottom heat exchangers installed in solar pond Martorell

4.2.5.2 External solar collectors

The heat supply system is composed of the same circuit of both heat exchangers located at the bottom and in the lateral area of the solar pond. In this case, solar collectors are installed in order to study the performance of the integrated system. This system consists of four solar thermal collectors of 2.4 m^2 each. The solar collectors have been oriented directly toward the equator, facing south, while the tilt angle of the collector has been adjusted to the latitude of the Solvay facilities (41°S). The solar collectors have been connected to the heat exchangers by using PVC pipes, and all external pipes have been thermally insulated with neoprene. A scheme of the heat supply system is shown in Figure 17. For the operation of the heat supply system two temperature sensors (PT1000) were installed. One of them is located at the top of the LCZ (0.5 m from the bottom of the pond approximately), where the maximum temperature of the system is reached. A second sensor is installed at the exit of the solar collectors' pipe. When the system supplies heat to the LCZ, the hot water is pumped from the solar collectors to the heat exchanger located in the bottom area of the pond. The working fluid transfers the energy to the storage zone and then returns at a temperature near to the temperature of LCZ, to be heated by the solar thermal collectors. When the heat is supplied to the lateral area, the hot water is pumped from the solar collectors to the lateral heat exchanger. The hot water flows through the pipe from the top to the bottom of the pond along the lateral heat exchanger, transferring the heat through the NCZ and the LCZ and then exiting the pond to the solar collectors at a temperature approaching the temperature of the storage zone (Fig. 17). The water, after being heated, is then pumped back to the pond to start a new cycle. The cycle continues as long as the temperature difference between the two sensors remains above 15 °C.

The temperature and the flow rate of the working fluid are controlled by temperature sensors located in the inlet and the output circuit (PT100) and a flow meter situated in the input of the circuit (Flow meter SMC, Range: 0.5 - 4L/min) in both cases.

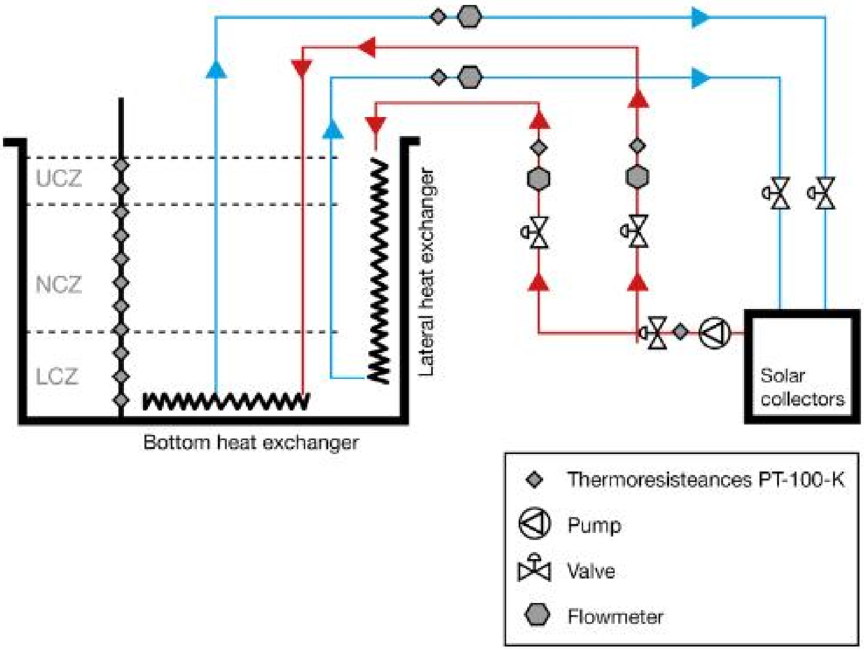

Figure 17. Scheme of heat supply system

4.2.5.3 *Heat extraction system equipment*

The heat extraction system was composed by a cooler (HRS024-AF-20 2.1kW SMC) and two heat exchangers. These devices were connected by a set of pipes made of PVC. Depending on the heat extraction circuit used the heat will be removed in a specific zone of the solar pond, bottom or lateral area. A scheme of the heat supply system is shown in Figure 18. The cooler is an air-cooled system formed by two circuits, the working fluid circuit and the refrigerant circuit. The working fluid, water in this case, runs through the circuit removing the heat from the solar pond. The refrigerant is a high-temperature and high-pressure gas that flows through the closed refrigerant circuit and cools the working fluid.

When the heat is extracted by the heat exchanger in the LCZ, the water flows through the pipe at the bottom of the pond removing heat from the LCZ. The fluid then exits the pond at a temperature near the temperature of the storage zone of the pond, to be cooled by the cooler system. The water, after being cooled, is then pumped back to the pond to start a new cycle. In the case of the lateral heat exchanger, the fluid flows through the pipe from the top (at the boundary between the UCZ and the NCZ) to the bottom of the pond along the lateral heat exchanger, extracting heat through the NCZ and the LCZ, then exiting the pond at a temperature near the temperature of the storage zone, then to be cooled by the cooler system. In both heat extraction methods, the working fluid passes slowly through the cooler layers of the NCZ and the UCZ causing a decrease of the temperature due to the temperature difference between the LCZ and the upper regions of the NCZ and the UCZ.

A temperature sensor (PT100) and a flow meter (SMC) located in the inlet and outlet pipes have been employed to measure the flow rate and the temperature of the working fluid for each heat exchanger.

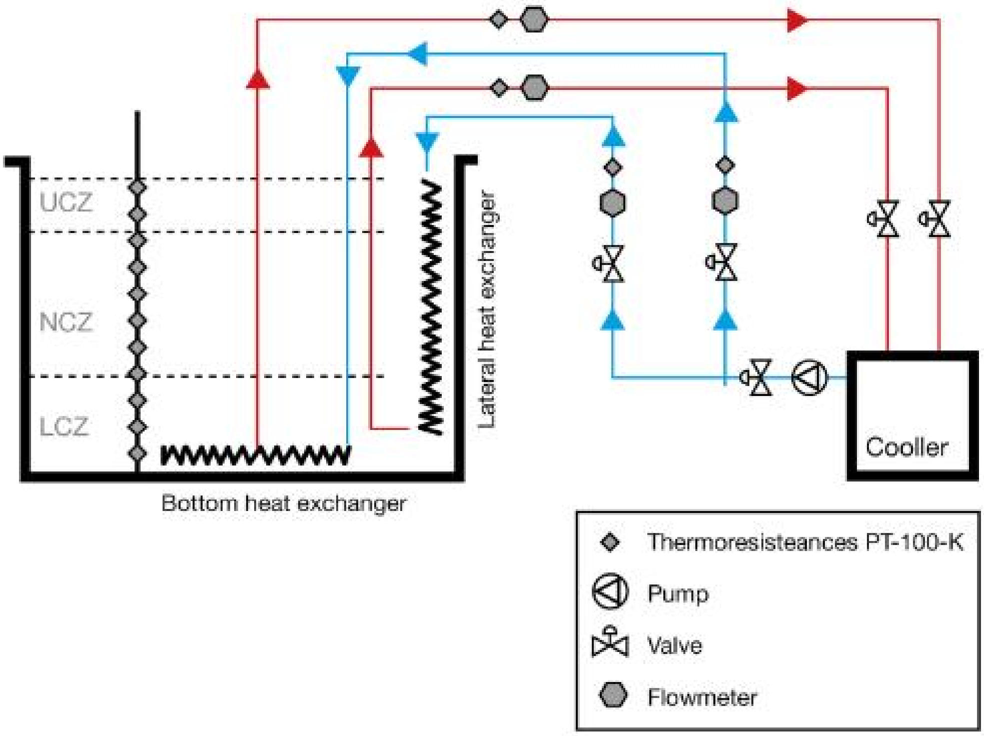

Figure 18. Scheme of heat extraction system

4.3 Salinity gradient solar pond Granada

4.3.1 Solvay Minerales description and energy needs

Solvay minerals is a mining company located in Granada (Spain). It is an open mine that extracts celestite in order to produce strontium sulphate. Strontium sulphate is the raw material in the production of strontium carbonate used in different sectors as automotive, electronics, conservation and storage energy. The mining operation consists of a crushing plant, pre-concentration by dense media, milling and flotation process that occupies an area of more than 70 hectares. In the flotation process water is used at a temperature of 60 °C to dissolve the reagents used in the process. Fuel oil was used for this purpose, and thus the installation of the SGSP offers significant benefits by reducing fuel oil consumption and minimizing its environmental impact, which is mainly associated with the greenhouse gas emissions.

4.3.2 Pond specifications and site arrangement

The Granada Solar Pond is a collaborative project between Universitat Politècnica de Catalunya (UPC), RMIT University and Solvay Iberica to study solar pond technology in order to capture and store solar energy and to use this energy as a low thermal application in a mining facility located at south of Spain. The purpose of this solar pond was to deliver the heat required to preheat the water (>60°C) and the reagents in the flotation unit. Fuel oil was used for this purpose, thus, the installation of the solar pond represented a benefit by reducing fuel oil consumption and minimizing its environmental impact mainly associated to the greenhouse gas emissions. In 2014, an industrial salinity gradient solar pond was constructed in Solvay Minerales in Granada, (south Spain). This solar pond was the first industrial solar pond in Europe. The total area of the pond is 500 m2 (20 x 25m) with a depth of 2.2 m. Table 2 shows the weather parameters of the solar pond location (Bernad et al., 2013). The low convective zone (LCZ) was designed to be 0.65 m thick, the non-convective zone (NCZ) 1.35 m and the upper convective zone (UCZ) 0.2 m.

Table 2. Location and weather parameters at Solvay Minerales mining facilities in Granada (Spain).

Coordinates	37° 3’ 0’’ N, 3° 45’ 0’’ W
Altitude (m)	929
Wind average speed (m/s)	2.3
Summer maxim temperature (°C)	33.0
Winter minimal temperature (°C)	-7.0

	January	February	March	April	May	June	July	August	Septembe	October	November	December
Temperature Average	3.1	4.2	7.3	10.0	13.3	18.1	21.9	21.4	18.1	12.0	7.2	4.1
Solar radiation (MJ/m^2 month)	283	346	496	618	734	813	838	748	565	400	275	227

4.3.3 Construction and establishment of the salinity gradient

The construction of the salinity gradient solar pond in Granada took place in 2014. From May to June of that year the earthworks, the thermal insulation of the system, the installation of the heat exchanger as well as the installation of all the devices to control the extraction process were carried out (Annex V). The salt gradient was established in July 2014 using the redistribution method. The establishment of the salinity gradient was carried out over 5 days (Annex IV). Once the gradient was formed, system operation and heat extraction process began. In the first month of operation, temperatures reached temperatures up to 90ºC. All the details of the design of the system can be found in Annex I, II and III.

4.3.4 Control of salinity gradient

To carry out the maintenance and control of the salinity gradient, the following parameters were measured: pH, turbidity and density at different height of the pond. The devices used were the same as in the solar pond of Martorell (a mobile PVC pipe as a sampler mechanism, density meter, pH meter and turbidity meter). All the details about this topic can be found in Annex V.

4.3.5 Maintenance of salinity gradient

The maintenance of the salinity gradient was carried out by adding fresh water by a flushing system as well as salt using two salt chargers to replace the salt in the storage area. The fresh water supply with a low salt concentration leaves the system and was stored in an auxiliary pond. The estimation of water supply, salt consumption and the volume of the auxiliary pond can be seen in Annex III.

To control the clarity of the system an acidification system was used. This system was composed by ten tubs to add acid at different heights. All the details of the devices used in the maintenance of salinity gradient can be seen in Annex V.

4.3.6 Thermal gradient control and weather conditions equipment

The thermal gradient of the solar pond was controlled and measured by 42 thermal sensors (thermo-resistances Pt-100-K type, Abco, Spain). The sensors were distributed every 0.5 cm from the bottom and connected to a data logger where the information was recorded (Annex V).

The weather parameters were measured by a meteorological station (CR1000 Measurement and Control System. Campbell Scientific, Barcelona, Spain), which was programmed to measure and store data (Data logger CR1000). The weather parameters measured were rain gages, solar radiation, wind speed, relative humidity, barometric pressure and air temperature (Annex V).

4.3.7 Heat extraction system

The heat extraction system installed in the Granada solar pool was composed of six independent concentric spirals of polyethylene pipes. The total length was 1200 m distributed in six individual spirals of 200m each one in all bottom area of the pond. The design and the installation of the heat exchanger can be seen in Annex II and Annex V, respectively.

4.4 Economic and thermal efficiency calculations

In the present PhD thesis, the efficiency of solar ponds in different systems has been calculated, both pilot plant and industrial scale. The more common definition of the solar pond is a system, which is capable of collecting solar radiation and storing this energy in the form of heat (Tabor and Weinberger, 1981; Hull et al., 1989) to supply this heat at a low temperature to a particular application. Accordingly, the instantaneous efficiency concept introduced by Date et al., 2013 was used in this work.

$$\eta = \frac{\sum_i Q_{available_i} + \sum_i Q_{extracted_i}}{\sum_i Q_{incident_i}} \tag{1}$$

where $Q_{incident_i}$ is the total incident radiation measured throughout day i $Q_{extracted_i}$ is the amount of heat extracted from the system during day i and is estimated according to method proposed by Leblanc et al. (Leblanc et al., 2011), and $Q_{available_i}$ represents the part of the solar radiation that the system is capable of storing in the LCZ during day i. In the research carried out in Granada solar pond some days, the energy stored in the LCZ may decrease; that is, the system loses its capability to store energy due to unfavourable solar radiation conditions; consequently, $Q_{available_i}$ is assumed to be 0. Thus, $Q_{extracted_i}$ and $Q_{available_i}$ are calculated by Eqs. 2 and 3 as shown below:

$$Q_{extracted_i} = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \tag{2}$$

$$Q_{available_i} = \begin{matrix} V_{LCZ} \cdot C_p \cdot \rho \cdot (T_{LCZ_i} - T_{LCZ_{i-1}}) & (T_{LCZ_i} - T_{LCZ_{i-1}}) > 0 \\ 0 & (T_{LCZ_i} - T_{LCZ_{i-1}}) < 0 \end{matrix} \tag{3}$$

In the research carried out with solar collectors (Publication 2) the energy supplied to the system is considered and equation 1 takes the following form (equation 4) where Q_{supply} is the total incident radiation in the solar collectors during the test.

$$\eta = \frac{\sum_i Q_{available_i} + \sum_i Q_{extracted_i}}{\sum_i Q_{incident_i} + \sum_i Q_{supply_i}} \tag{4}$$

The specific heat capacity of the salt solution (kJ/kg· K) is given by Eq. 5 (Wang and Akbarzadeh, 1982) where S is the salt concentration (kg/m3).

$$C_{p\,lcz} = 4180 + 4.396S + 0.0048S^2 \tag{5}$$

Furthermore, the effectiveness of the heat exchanger can also be determined according to Eq. 6 (Tundee et al., 2010) in Publication 1:

$$\varepsilon = \frac{T_{of} - T_{if}}{T_{LCZ} - T_{if}} \tag{6}$$

Where

T_{of} is the outlet temperature of the heat transfer fluid (°C)

T_{if} is the inlet temperature of the heat transfer fluid (°C)

T_{LCZ} is the LCZ temperature (°C)

In Publication 3 was carried out an economic analysis to define the savings involved the use of solar pond in the flotation process. For this, the fuel oil bill and the data obtained by monitoring the performance of the solar pond was compare

PUBLICATION 1

Alcaraz, A., Valderrama, C., Cortina, J., Akbarzadeh, A., Farran, A.
Enhancing the efficiency of solar pond heat extraction by using both lateral and bottom heat exchangers. "Solar energy", September 2016, vol. 134, p. 82-94.

doi.org/10.1016/j.solener.2016.04.025

ATTENTION¡¡

Pages 46 to 60 of the thesis are available at the editor’s web

https://www.sciencedirect.com/science/article/pii/S0038092X16300585

PUBLICATION 2

Alcaraz, A., Montalà, M., Valderrama, C., Cortina, J., Akbarzadeh, A., Farran, A.

Increasing the storage capacity of a solar pond by using solar thermal collectors: Heat extraction and heat supply processes using in-pond heat exchangers. "Solar energy", September 2018, vol. 171, p. 112-121

doi.org/10.1016/j.solener.2018.06.061

ATTENTION¡¡

Pages 62 to 72 of the thesis are available at the editor’s web

https://www.sciencedirect.com/science/article/pii/S0038092X18306121

PUBLICATION 3

Alcaraz,A., Montalà, M., Cortina, J.L., Akbarzadeh, A., Aladjem, C., Farran, A., Valderrama, C. *Design, construction, and operation of the first industrial salinity-gradient solar pond in Europe: An efficiency analysis perspective.* "Solar energy", April 2018, vol. 164, p. 316-326

doi.org/10.1016/j.solener.2018.02.053

ATTENTION¡¡

Pages 74 to 86 of the thesis are available at the editor's web

https://www.sciencedirect.com/science/article/pii/S0038092X18301865

PUBLICATION 4

Alcaraz, A., Montalà, M., Valderrama, C., Cortina, J., Akbarzadeh, A., Farran, A. ***T****hermal performance of 500 m^2 salinity gradient solar pond in Granada, Spain under strong weather conditions.* "Solar energy", September 2018, vol. 171, p.223-228

doi.org/10.1016/j.solener.2018.06.072

ATTENTION¡¡

Pages 88 to 94 of the thesis are available at the editor's web

https://www.sciencedirect.com/science/article/pii/S0038092X18306236

9. CONCLUSIONS

9. Conclusions

The use of renewable energies in industrial sector is a way to deal with environmental problems associate to the use of fossil fuels such as climate change, ozone layer depletion and air pollution. Furthermore, the substitution of fossil fuels represents an economic and environmental benefit for the industrial sector according to the current legislation. The European directive states that by 2020, 20% of energy production must come from renewable energy sources. This objective means that research into new technologies and increasing the efficiency of existing technologies will play a fundamental role in this new sustainable development.

In this PhD thesis, an industrial solar pond was designed, constructed, and operated during two periods (2014–2015) at the mining facilities of Solvay Minerales in Granada (Spain). This is the first industrial salinity gradient solar pond in Spain and its study is a starting point for the implementation of this type of systems in the industrial sector.

The use of this technology at industrial scale involves the evaluation of both its performance and its efficiency in order to optimize the operating parameters to provide the greatest amount of renewable energy to the industrial process. Since the construction of the Martorell solar pond in 2009, extensive research was carried out on this technology. All the knowledge acquired in the maintenance and operation as well as the results obtained on a pilot scale allowed to carry out the design and construction of the Granada solar pond on an industrial scale.

A new alternative method of heat extraction from the solar pond exhibited how the instantaneous efficiency of the solar pond increases when the heat extraction was performed by the lateral heat extraction regardless the weather conditions and compared with the traditional method of heat extraction from the bottom area. This behaviour during cold temperature conditions represents a substantial gain in instantaneous efficiency above 50% compared with the traditional method of heat extraction. In warm conditions, the lateral heat extraction reported a gain of approximately 30%. On the other hand, the use of both heat exchangers supposes a slight gain in the instantaneous efficiency of the solar pond compared with the efficiency obtained in the bottom heat extraction. The main advantage in the use of both heat exchangers in the heat extraction process is that the pond can deliver the same quantity of energy working at a lower flow rate. It means that the LCZ is capable of preserving more stored thermal energy using both heat exchangers than in the case of independent heat extraction.

Otherwise, seasonality affects the effectiveness of the heat exchanger showing effectiveness values of 60% during the colder months and about 80% during the warmer months.

The integration of other renewable energy sources such as solar collectors as an external energy source can be considered an appropriated solution to avoid a large decrease in the T_{LCZ} and T_{NCZ}, which would not only result in a significant improvement in energy efficiency but also increase the capacity of the solar pond to provide heat to an external application during the colder months, which are the most unfavourable in terms of solar radiation. The results obtained, in a cold month scenery, show that the heat supply process carried out with lateral and bottom heat exchangers is the most effective configuration present a value of up to 18%, representing 29% and 49% increases in efficiency compared when the test was performed independently.

When the heat supply process is combined with the heat extraction in summer conditions the efficiency shows the higher value when the process is carried out extracted the heat from the bottom area and supply heat from the lateral (18%) being twice the average efficiency of the solar pond and more than three times when there were no heat supply or extractions in the system.

The experience of the Granada solar pond proves that the main advantage of a solar pond is the capacity to store energy in the months with the highest solar radiation to provide a flux of heat to an external system during the whole year. Theoretical calculations based on solar radiation indicated that the use of the SGSP would reduce the annual fuel consumption by more than 50%, thus providing a significant improvement at both economic and environmental levels. Two months after the SGSP was established, in August 2014, the temperature in the storage zone of the SGSP reached approximately 90 °C.

During 2015, the salinity gradient began to deteriorate, increasing the height of the UCZ and LCZ and decreasing the height of the NCZ. In April 2015, the salinity gradient was considered to be technically destroyed. Notwithstanding, the system was able to provide the expected heat flow to the flotation unit for two more months, after which the solar pond stopped its operation. In September 2015, the solar pond was refilled using the water injection method and its operation was restarted.

In terms of energy efficiency, a yearly balance was suggested to obtain a reliable value of thermal efficiency and minimize seasonal effects. The overall efficiencies obtained after the first and second operation periods were 9.7 and 12.3%, respectively, with maximum values of 28 and 24% obtained during the first months of operation. In terms of the greenhouse gas emissions, 31.7 and 22.5 tn of CO_2 were avoided during the first and second periods of operation due to the heat supplied by the Granada solar pond.

Regarding the economic savings, the fuel oil cost of the flotation unit was reduced by a higher percentage than the fuel oil consumption, due to the decreasing tendency of fuel oil prices during 2014 and 2015. Reductions of 52 and 68% were obtained in the first and second periods of operation, respectively, when compared to 2013.

The study of this type of technology under non-favourable environmental conditions (low temperature and radiation) allows to know and predict the behaviour of the system in areas where the use of renewable energies is not common due to its climatological conditions. The study of the Granada solar pond during a snowfall showed how the system responded positively to weather variations, even those that are extreme and unusual, and that also confirms the fundamental role of the salinity gradient as a thermal isolation layer. It is important to note that salinity gradient and LCZ were not affected due to the snowfall and only the UCZ reported some temporary instability that lasted a week approximately. The stored energy during January 2015 was 13.3GJ and the weekly efficiency reached 10%. This analysis confirms that solar pond technology is able to store energy even under extreme weather conditions and it is of the greatest importance in terms of its operation as well as its capacity to supply energy to an external application.

10. ANNEXES

ANNEX I.AREA SALINITY GRADIENT SOLAR POND AND ECONOMIC SAVING

The first phase of the design of the Granada’s solar pond project is the sizing of the pond, considering the energy needs of the application and the environmental factors of the place. The aim of this project is pre-heating the working fluid of the flotation process using a solar pond as a thermal power source. The daily total volume of hot water needed for the application is 10000 L. Assuming that the temperature of the working fluid is at the same temperature as the LCZ, the monthly average values obtained in the Martorell solar pond during its operation is taken to calculate the energy required in the process. Take into account the total volume per day needs for the application, the average temperature of the tap water and the average temperature of the working fluid the total energy per month needs for the application is calculated as shows Table 3.

Table 3. Total energy per month needs for the flotation process

	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Days	**31**	**29**	**31**	**30**	**31**	**30**	**31**	**31**	**30**	**31**	**30**	**31**
flow rate [l/day]	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**
Temp av. tap water [°C]	**9**	**10,2**	**11,4**	**12,6**	**13,8**	**15**	**16,2**	**15**	**13,8**	**12,6**	**11,4**	**10,2**
Temp av. Process [°C]	**25**	**30**	**35**	**40**	**50**	**52**	**55**	**50**	**45**	**40**	**35**	**25**
ΔT [°C]	**16**	**19,8**	**23,6**	**27,4**	**36,2**	**37**	**38,8**	**35**	**31,2**	**27,4**	**23,6**	**14,8**
Energy required [GJ/day]	**0,7**	**0,8**	**1,0**	**1,1**	**1,5**	**1,5**	**1,6**	**1,5**	**1,3**	**1,1**	**1,0**	**0,6**
Total energy month [GJ]	**20,7**	**24,0**	**30,6**	**34,4**	**46,9**	**46,4**	**50,3**	**45,4**	**39,1**	**35,5**	**29,6**	**19,2**

Theoretically, a solar pond has an efficiency of 15 -20 %, that is, of the total solar radiation only this percentage is stored in form of heat in the system. Considering the monthly solar radiation, the theoretical area is calculated in different pond efficiency scenarios as shown Figure 19. Once the calculations have been made and taking into account that the efficiency of the pond will be around the theoretical value calculated in different studies, it is concluded that the smallest area necessary to meet the energy requirements of the application is 500 m^2.

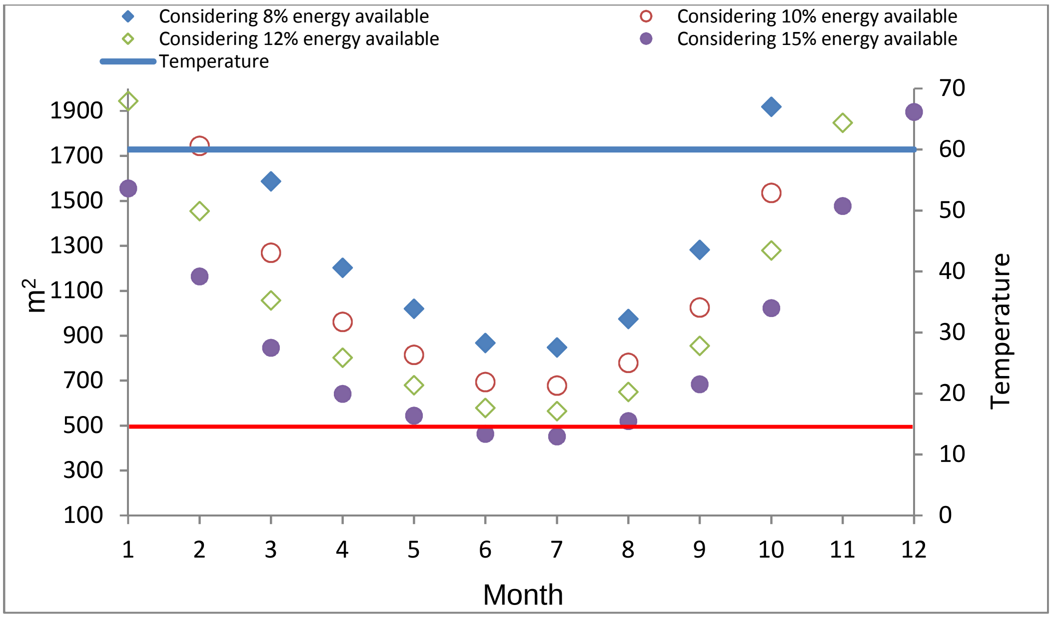

Figure 19. Calculation of the total area of the pond in different efficiency scenarios

On the other hand, the energy saving can be estimated taking into account that the average consumption of gas oil in the flotation process is 25000 l / year, therefore use of the solar tank as an energy source would result in an economic saving of approximately 50%.

ANNEX II. DESIGN HEAT EXTRACTION SYSTEM

II.1 Heat extraction system

The design of the heat exchanger was divided in two stages. First, the working flow rate was defined according the energy specifications of the process and also the solar pond capacity to supply energy. Second, the length of the heat exchanger is defined considering environmental factors, process needs and the previously defined working flow rate.

II.1.1 Definition of the working flow rate

The aim of this project is pre-heating the working fluid of the flotation process using a solar pond as a thermal power source. In the flotations process area there are two tanks of 5 m^3 each one which feeds the process. The flotation process consumes 5 m^3 in reagent tank (Tank 1) in approximately 16 hours. When the discharge of the Tank 1 is taking place the second reagent tank (Tank 2) start its charge. Independently of the flow rate of work, each tank will be charge once in a day, so the daily total volume of hot water will be 10000 L. On the other hand, depending on the flow rate, the duration of the charge of the tanks varies. For this reason, the fillings tanks time for the daily flotation process volume is calculated for different flow rates in order to check that the process of filling-emptying of the tanks is possible to different flow rates in the range of 0 - 100 L / min. Figure 20, 21 and 22 shows the process filling – emptying of the tanks. When increasing the flow, the filling of the tanks is faster, but it supposes a sudden cooling of the solar pond which can cause disturbances in the system and could destroy the thermal gradient.

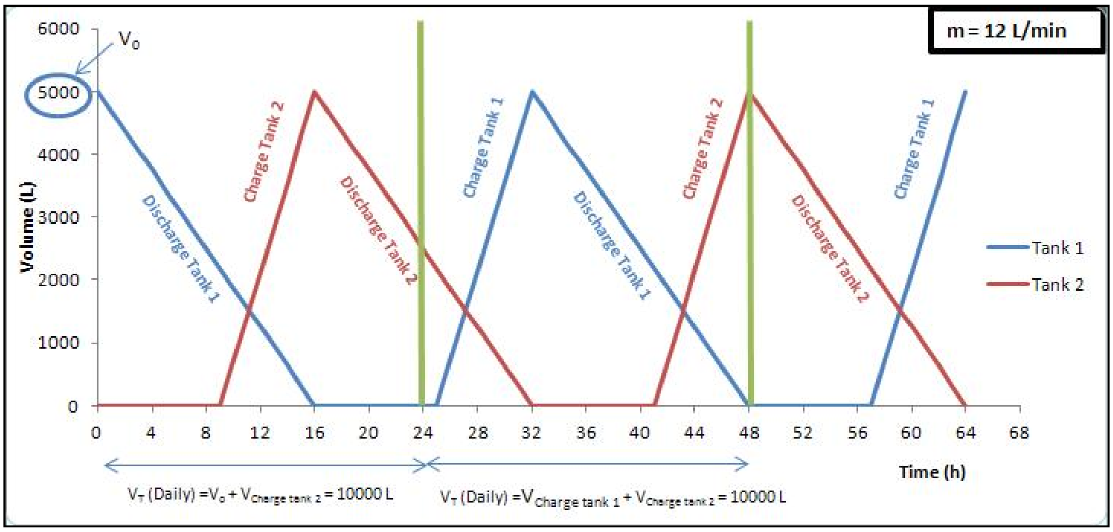

Figure 20. Charge-Discharge process for a flow rate of 12 L/min

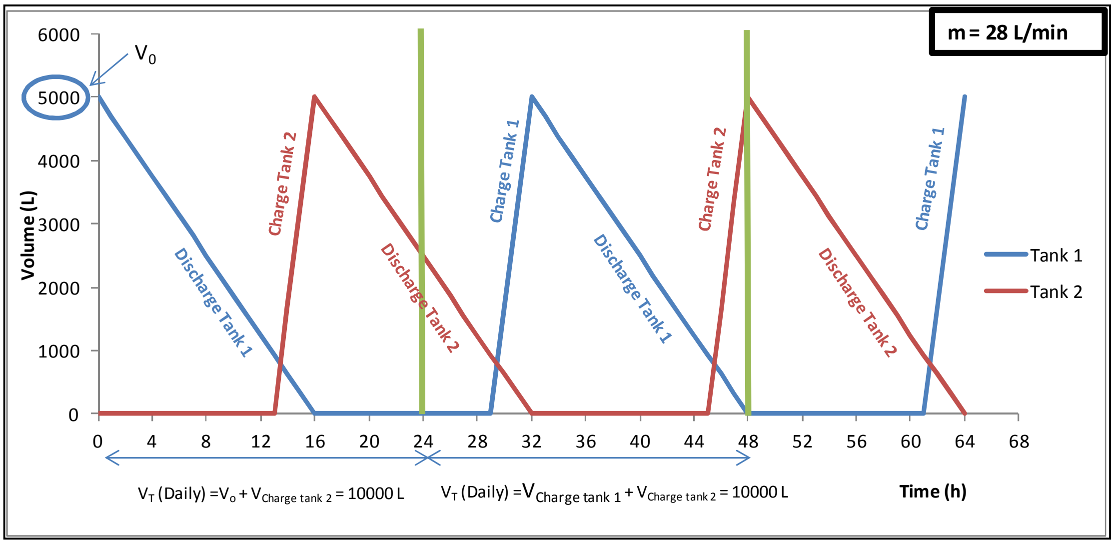

Figure 21. Charge-Discharge process for a flow rate of 28 L/min

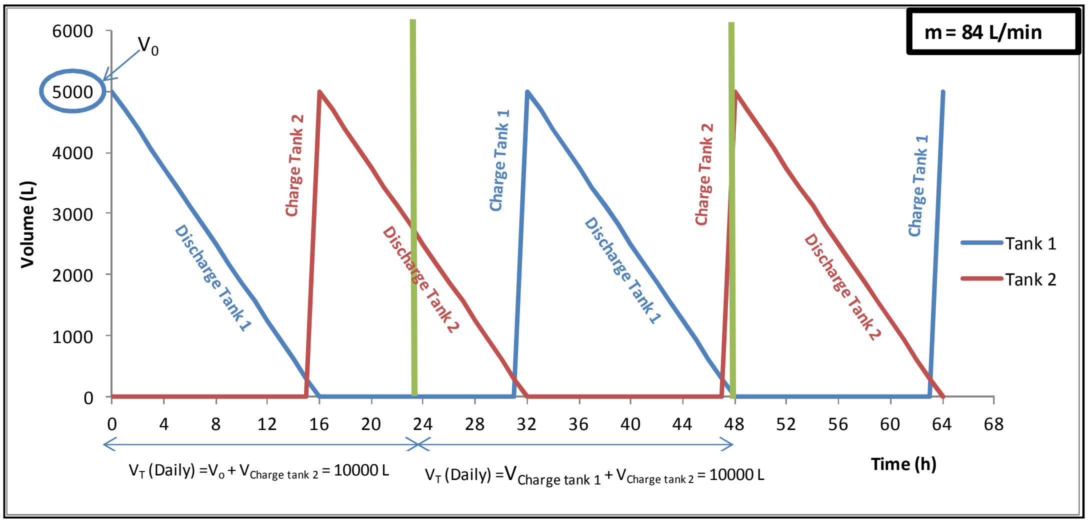

Figure 22. Charge-Discharge process for a flow rate of 84 L/min

Once the filling time of the tanks has been checked, the necessary length of the heat exchangers is calculated. Assume that the bottom of the pond is at 50 °C and the fresh water is at 15 °C it has been calculated with a mathematical model of heat extraction the outlet temperature of working fluid. Table 4 shows the main characteristics has been used.

Table 4. Working condition of the calculation of the length of heat exchanger system

Temperature LCZ (°C)	50
Temperature inlet cold water (°C)	15
Flow rate (L/min)	0 – 120

Longitude Heat exchanger (m)	1200
Average solar radiation daily (MJ)	10000
Vprocess flotation (L)	10000

Figure 23 shows the variation of the outlet temperature of working fluid and the efficiency of the solar pond depending on the flow rate of work. On one hand, the outlet temperature remains constant approximately of 55 °C (T_{LCZ}) for a flow rates below 40 L/min. When the flow rate increases above this value the outlet temperature of the working fluid decreases.

On the other hand, the pond efficiency is the thermal performance to store and delivered the heat and its value is in average of 15-20% (Wang and Akbarzadeh, 1982) and it can be calculated as the daily heat extracted regard the daily solar radiation at the surface of the pond. The rate of thermal energy extracted is given by equation 1 (Leblanc et al., 2011)

$$Q = m \cdot Cp \cdot (To - Ti) \qquad \text{(Equation 1)}$$

Where

Q is the rate of thermal energy extracted (W)

m is mass flow rate (kg/s)

Cp is the specific heat of water (J/kg °C)

To is the outlet temperature of the working fluid (°C)

Ti is the inlet temperature of the working fluid (°C)

Considering that the flotation process needs 10000 L every day, the daily rate of thermal energy extracted for each flow rate can be calculated by equation 2

$$q = Q \cdot t \qquad \text{(Equation 2)}$$

Where

q is the daily thermal energy extracted (J)

Q is the rate of thermal energy extracted (W)

t is the daily time to fill the reagents tanks to obtain 10000L (s)

Considering the daily solar radiation and the area of the pond, the pond efficiency it can be calculated by equation 3

$$\eta = \frac{q}{A \cdot H} \qquad \text{(Equation 3)}$$

Where

A is the area of the solar pond (m^2)

H is the daily solar radiation at the surface of the pond (J/m^2)

The Figure 23 shows that the efficiency for each flow rate has a value between 16.71 and 12.24 % that it is a reasonable value for salinity gradient solar pond performance.

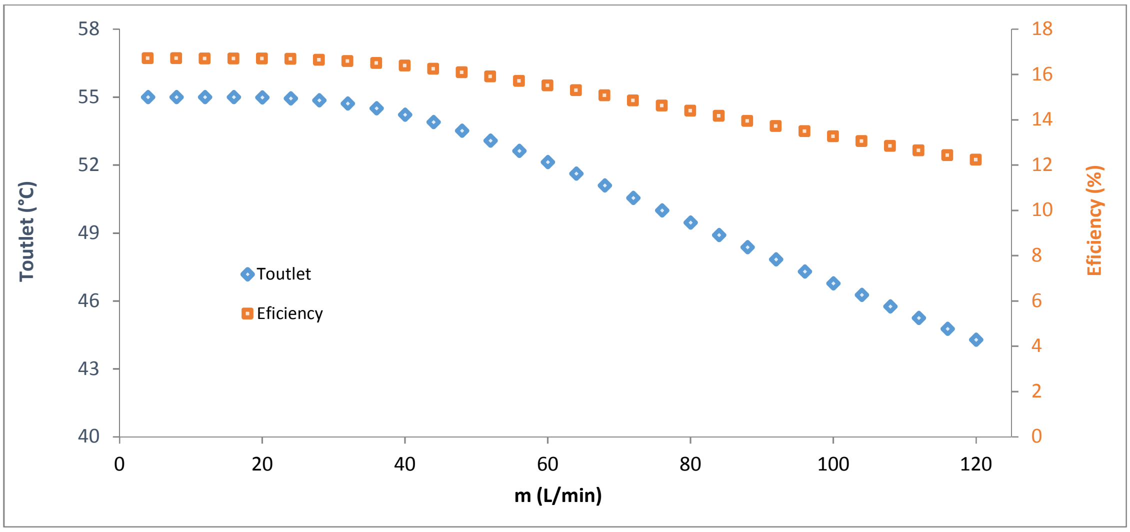

Figure 23. Effect of the flow rate on the outlet temperature of working fluid and efficiency of the solar pond

The effectiveness of heat exchanger is can be calculated by equation 4 (Tundee et al., 2010)

$$\varepsilon = \frac{T_{outlet} - T_{inlet}}{T_{LCZ} - T_{inlet}} \qquad \text{(Equation 4)}$$

Where

T_{oulet} is the outlet temperature of working fluid (°C)

T_{inlet} is the inlet temperature of working fluid (°C)

T_{LCZ} is the temperature of LCZ (°C)

It is noted from the Figure 24 that the effectiveness decreases when the flow rate increases. For flow rates below 40 L/min the effectiveness reached the higher values (approximately 100%) and then decreases to a value of 73.25 % for the higher flow rate (120 L/min).

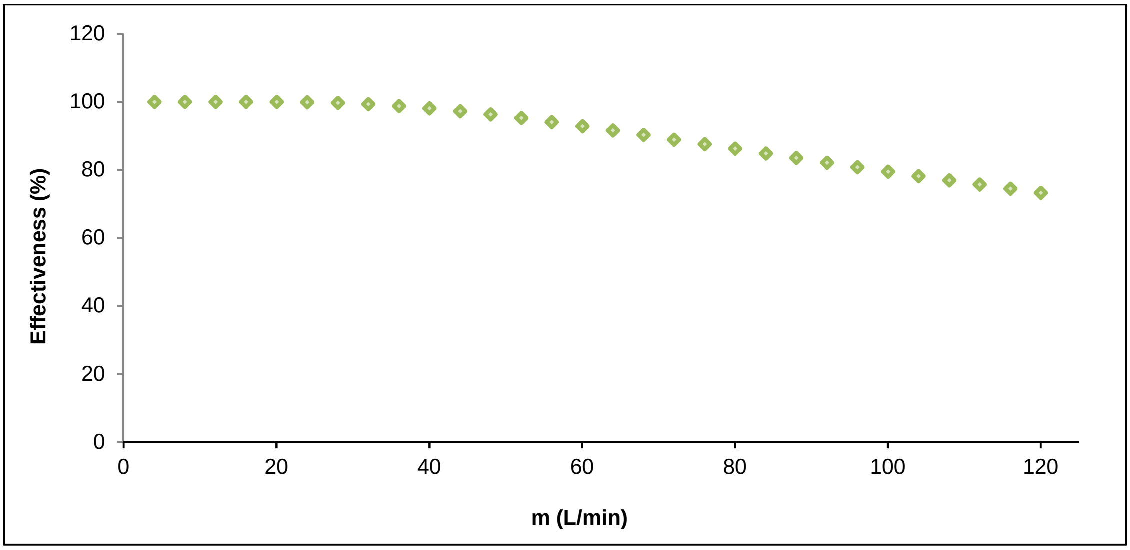

Figure 24. Effect of the flow rate on the heat exchanger effectiveness

The calculation carried out by mathematical model shows that to work with a flow rate above 40 L/min implies a decrease, on one side, in the outlet temperature of working fluid and, in the other side, in the effectiveness of the heat exchanger. Then, a flow rate of 40 L/min was set for the heat exchanger to ensure that the required amount of warm water was fed into the flotation unit.

II.1.2 Definition of the length of heat exchanger

The main characteristics used in the mathematical model are summarized in Table 5 and are defined by the pipe supplier (e.g ID and materials). Thus, the heat exchanger length was estimated by the pipe ID, the amount of heat stored in LCZ (predicted by the model), the tap water temperature and the amount of water needed in the reactive preparation (in terms of volume).

Table 5. Characteristic of the mathematical model

Material	D(m)	k (W/mk)	L_{spiral} (m)	e (m)	r_{inlet} (m)	r_{outlet}(m)	R_{pipe}(K/W)	R_{spiral} (K/W)
PE	0.016	0.43	20	0.002	0.0008	0.01	5.4E-05	4.1E-03

In order to evaluate the heat exchanger length and the influence of the weather (tap water temperature), the amount of heat delivered from the LCZ and the temperature of the heated water was estimated as can be seen in Figure 25 and 26 respectively for every season. The heat exchanger pipe was divided in spiral sections of 20 m length in order to calculate the heat and temperature variations.

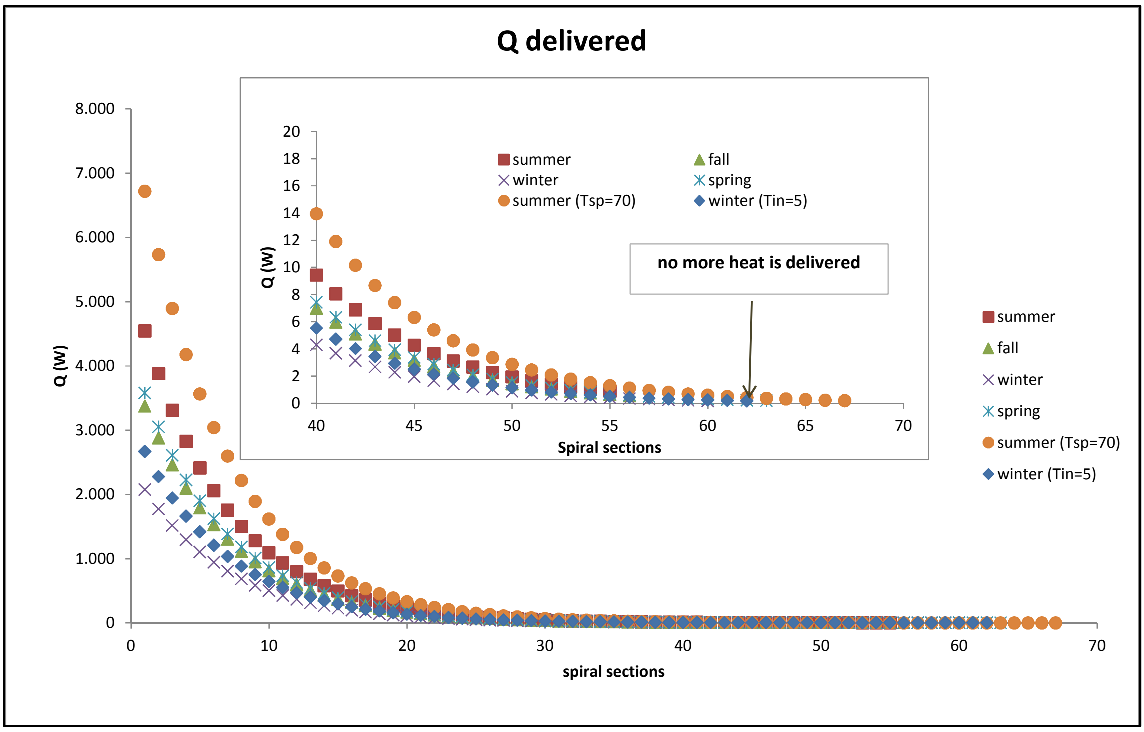

Figure 25. Heat delivered from LCZ for every season

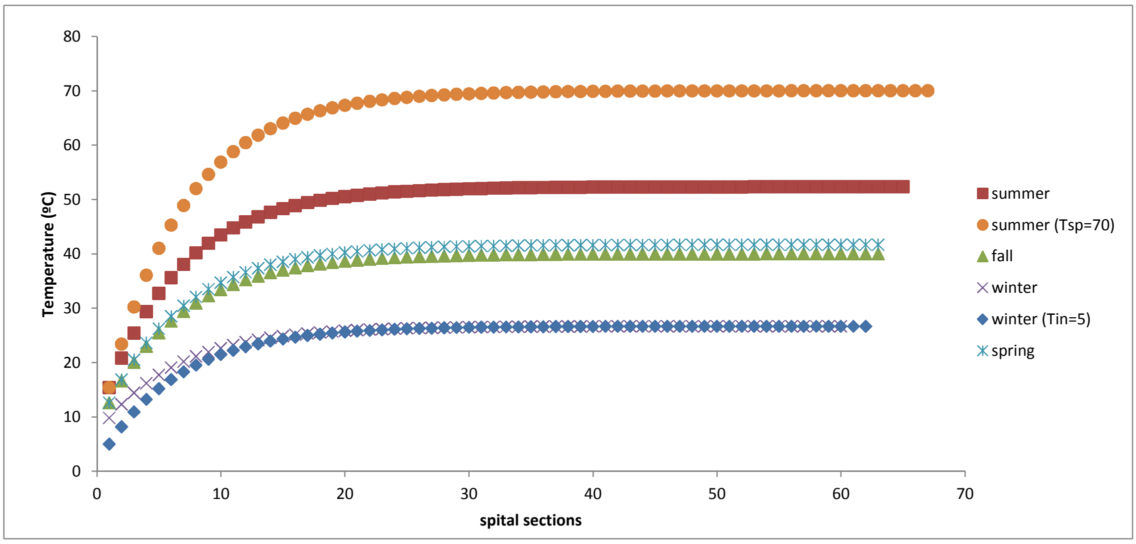

Figure 26. Temperature of the working fluid for every season

As can be seen after 60 spiral sections of the heat exchanger no more heat is delivered for every season and it corresponds to approximately 1200 - 1300 m.

II.1.3 Design of the configuration of the heat exchangers

The heat extraction system is designed to provide heat for use in reactive preparation in mine flotation process. Heat is extracted from the pond by circulating fresh water through a heat exchanger located in the bottom area, and then 150 m away to deliver heat to the application by feeding a tank. The layout in the bottom of the solar pond is able to take different configurations, which can be grouped in two groups:

- **Single module configuration**: Formed by a single pipe distributed across the bottom of the solar pond.

For this type of configuration, two designs are proposed. Firstly, a spiral single module (Figure 27) and secondly, parallel single module (Figure 28). The advantages that present these configurations are, on one hand, the flow rate will remain constant throughout the conduction and, in the other hand, the pipe is almost immersed in the storage area, only the outlet and the inlet are in the surface, so the heat losses are minimum. As a disadvantage the fact that a leakage in the pipe can occur so the extraction system has to be completely replaced.

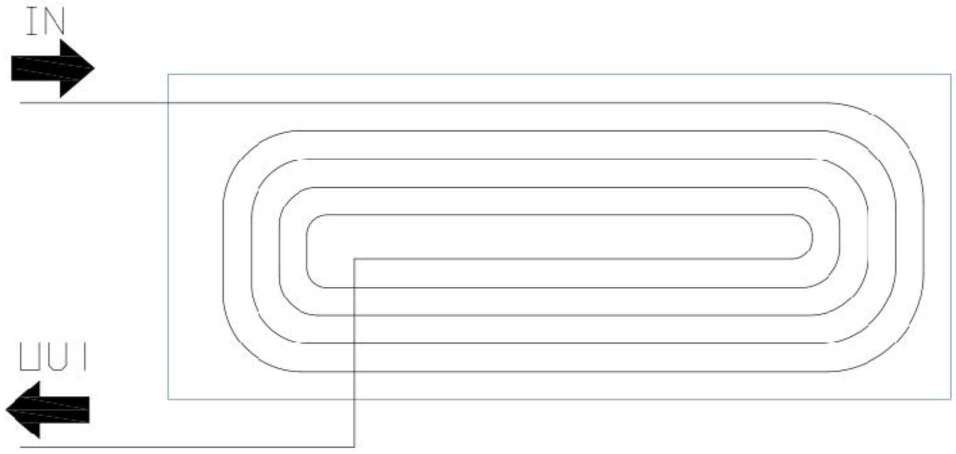

Figure 27. Spiral single module

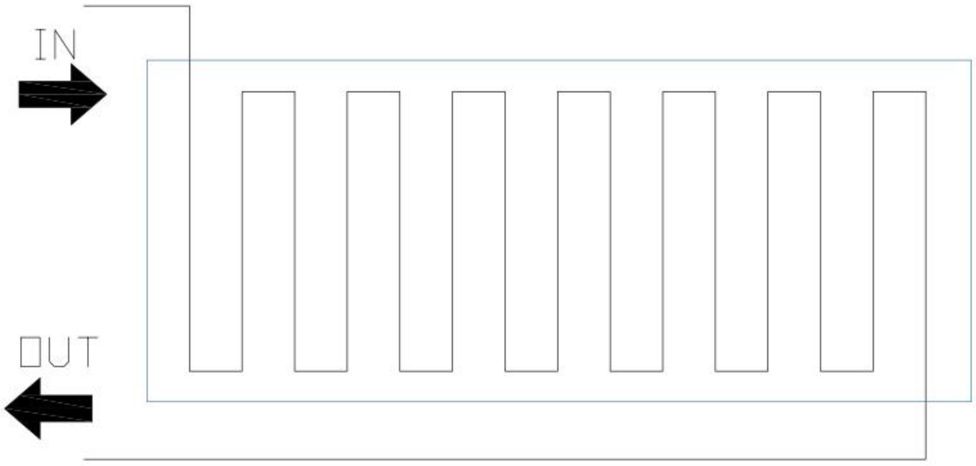

Figure 28. Parallel single module

- **Independent modules configuration:** Formed by individual pipes spread over different sectors of the bottom. All of them are independent of each other.

Three designs are proposed for this type of configuration. Firstly, serial spiral independent modules (Figure 29), secondly, parallel spiral independent modules (Figure 30) and thirdly parallel independent modules (Figure 31). The advantage that present these configurations is in the case of leakage, the module with the leak can be isolated. As for the disadvantages, it is impossible to assurance that the velocity of each module is the same and, on the other hand, a section of the pipeline of each module is located on the surface which causes heat loss. Similarly, heat loss also will occur when the pipe goes through HCZ and NCZ areas, due to their temperature are lower. This problem can be solved insolating the surface section of the pipes.

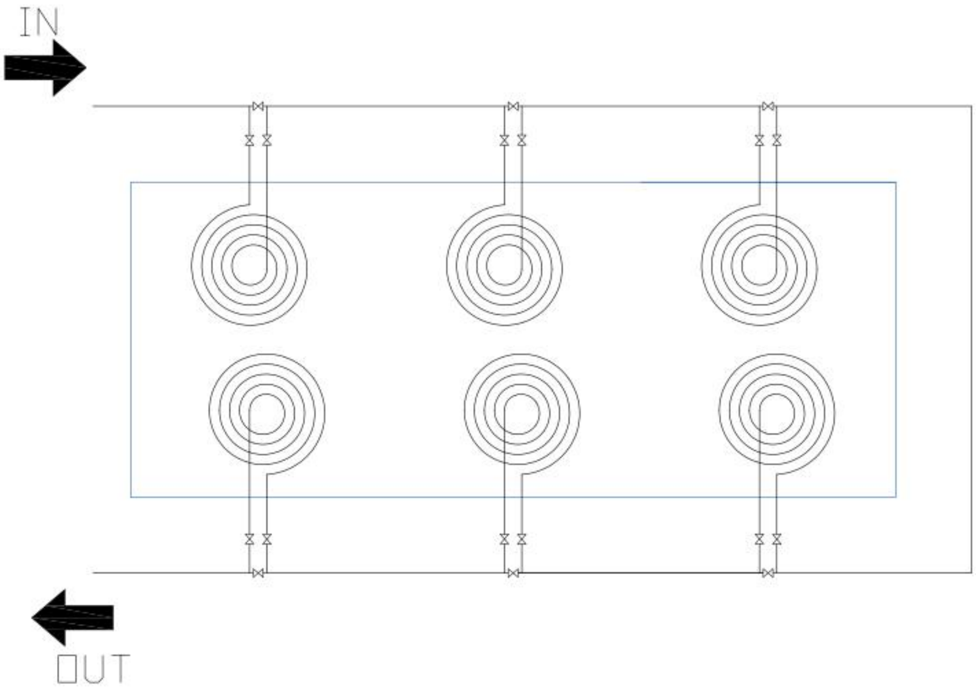

Figure 29. Serial spiral independent modules

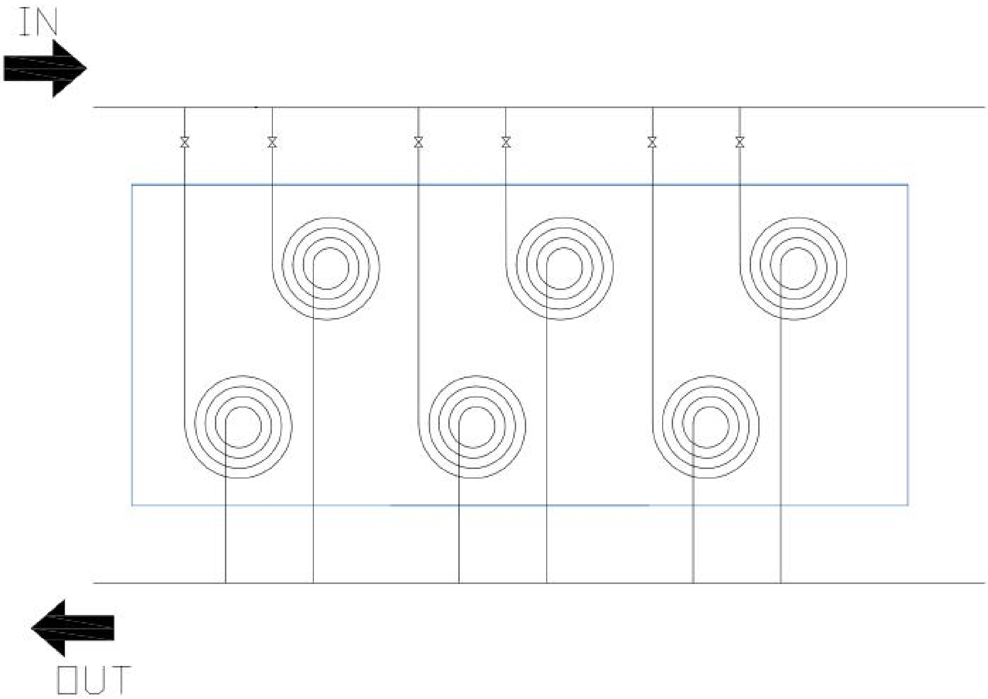

Figure 30. Parallel spiral independent modules

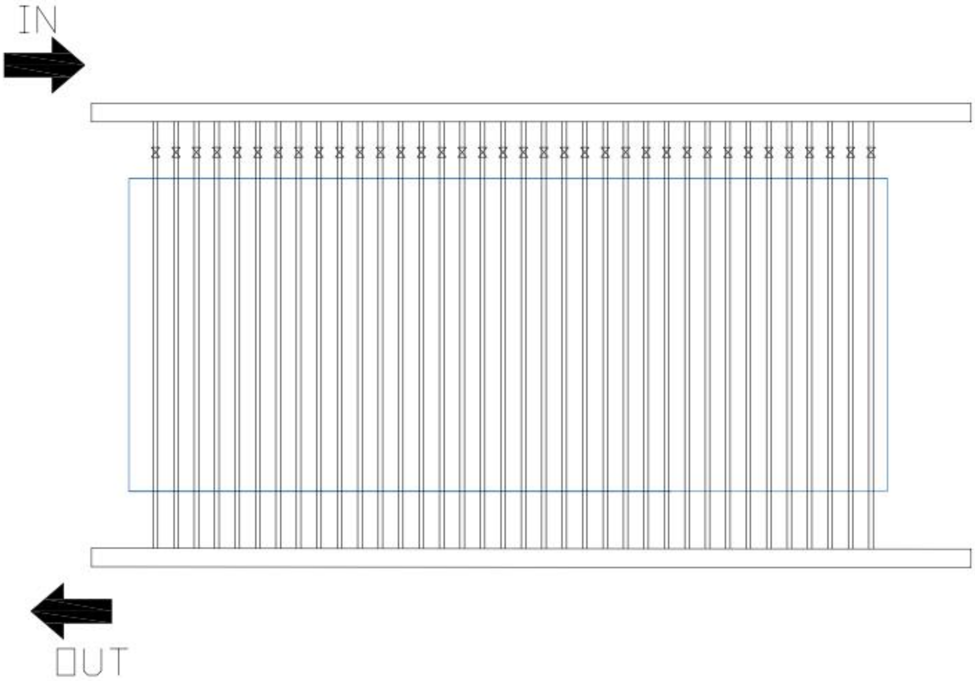

Figure 31. Parallel independent modules

The option that was carried out in the solar pond of Granada was the use of parallel spiral independent modules as it provided a simpler and more controllable work methodology.

The total length of the polyethylene heat exchangers pipes was determined to be 1200 m distributed in six individual spirals of 200m each one in all bottom area of the pond. Table 6 shows the characteristics of the heat extraction system. Figure 32 shows the final design of the distribution of the heat exchanger in the Granada solar pond.

Table 6. Characteristics of the heat exchanger of the Granada solar pond

Inner diameter (m)	0.028
Outer diameter (m)	0.032
Length of each roll (m)	200
Number of rolls	6
Material	PE100

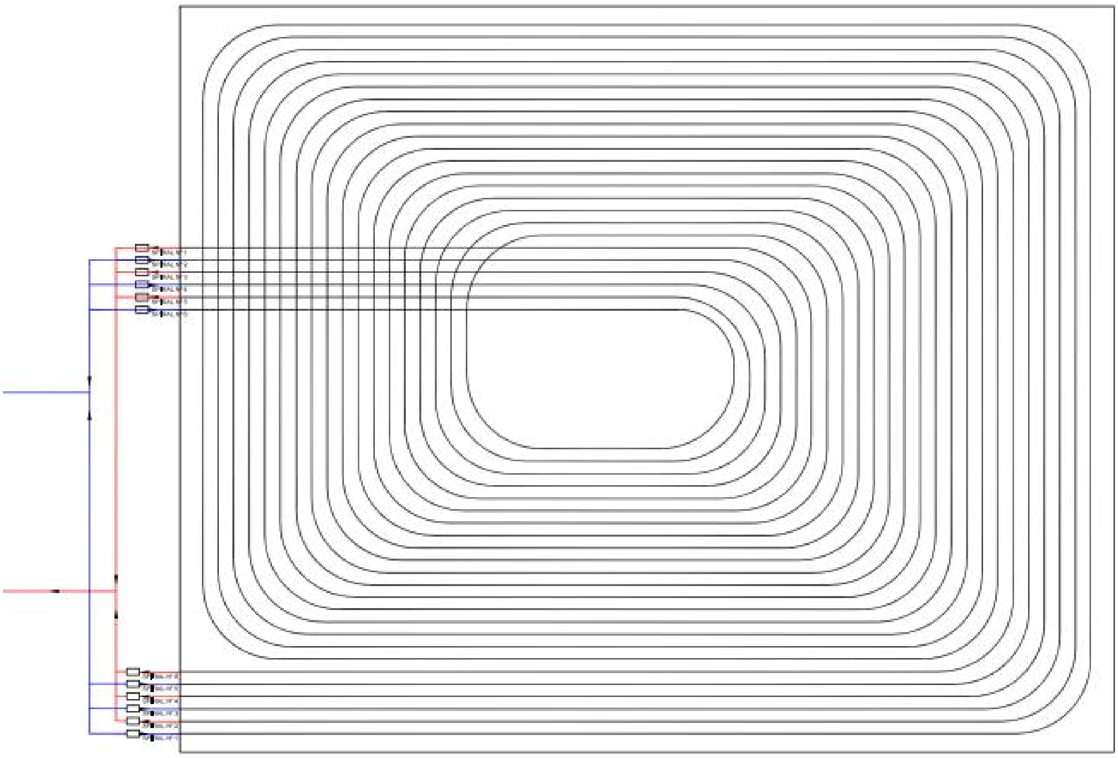

Figure 32. Final design of the heat exchanger in the solar pond Granada

ANNEX III. ESTIMATION OF WATER SUPPLY IN THE SOLAR POND AND SALT CONSUMPTION

In a saline gradient solar pond, salt diffuses from the storage zone (LCZ), which is at a saturation concentration of 25% (250000 mg / l), to the surface area (UCZ), which must be found at a concentration comprised between 0 - 4% (0-40000 mg / l), increasing the concentration in this area resulting in deterioration of the gradient. To guarantee the stability of the gradient zone, both the concentration of the storage area and the concentration of the surface area must be kept constant. For this, two maintenance actions must be carried out. On the one hand, salt must be added to the storage area, to ensure that it is at the saturation concentration and, on the other hand, fresh water must be added to the surface layer to drag the salt that has spread and also to compensate losses due to evaporation. To control the system, it must be quantified the consumption of fresh water that will lead to the use of the solar pond in the company Solvay Minerals as well as the management of the overflow water that will accumulate in the auxiliary pond.

The saline gradient solar pond has an area of 500 m^2 and a height of 2.5 m. The auxiliary pond has an area of 100 m^2 and a height of 1m.

Figure 33 shows a general scheme of the flows of matter that take place in the solar tank and the auxiliary pond

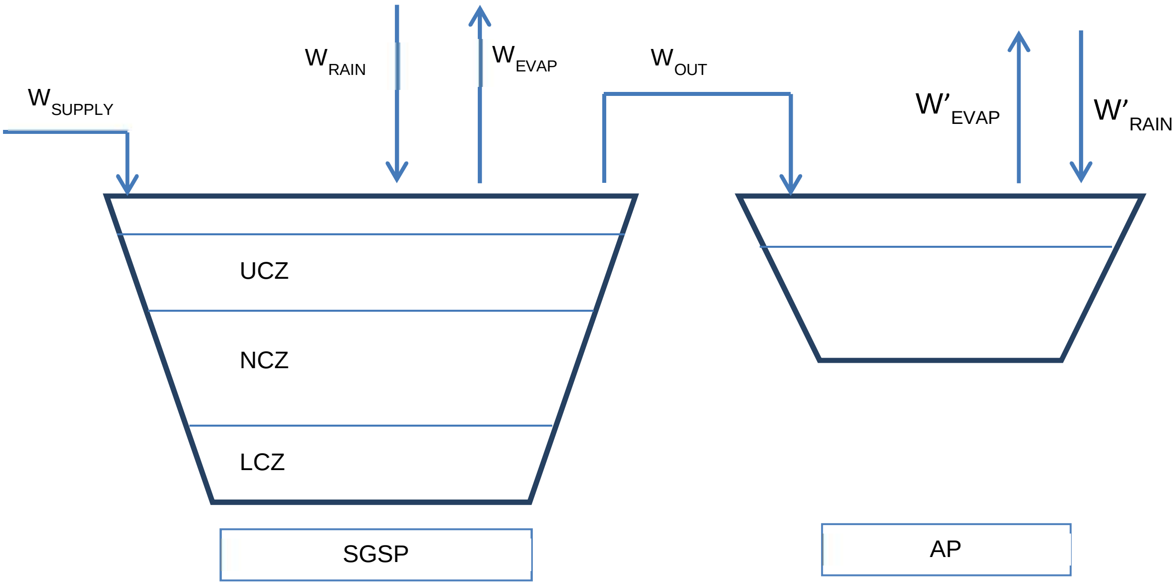

Figure 33. Flows of matter in the solar tank and the auxiliary pond

To quantify the consumption of fresh water in the system, a mass balance is made in the solar pond. Figure 34 shows the inlet and outlet flows.

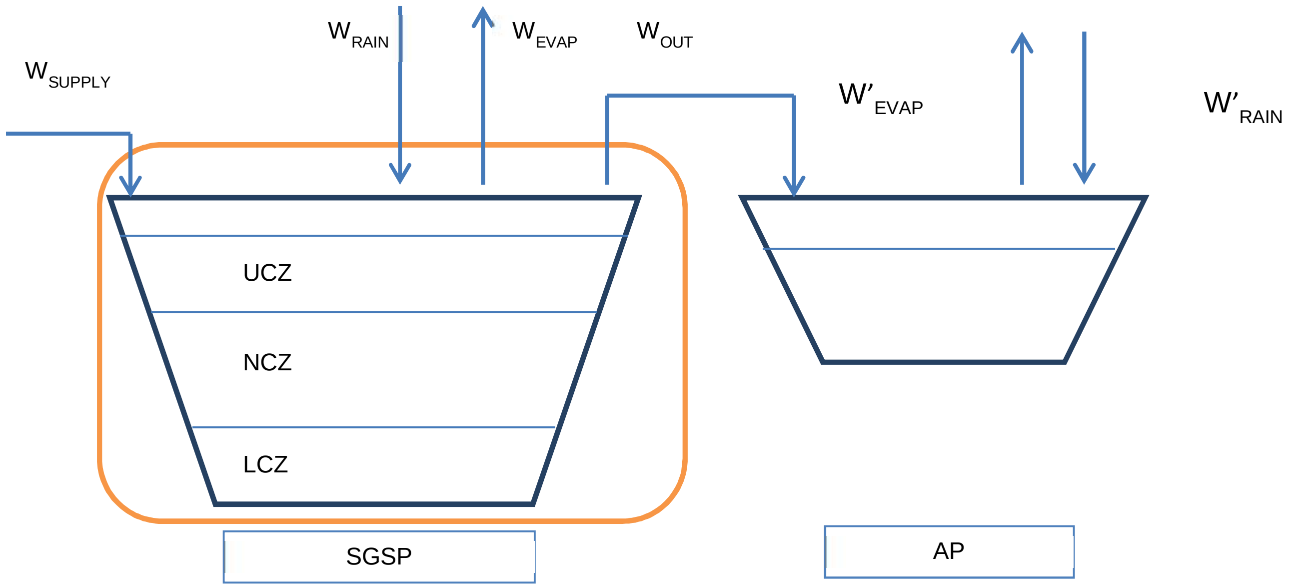

Figure 34. Mass balance in the solar pond

Equation 5 shows the mass balance in the solar pond:

$$W_{SUPPLY} + W_{RAIN} = W_{EVAP} + W_{OUT}$$ Equation 5

The volume contributed by the precipitations (Wrain) and the volume lost due to the evaporation that takes place in the surface layers of the pond (Wevap), are calculated taking into account the climatology of the area.

Table 7 shows the data of the precipitations in a place near Escuzar mine to quantify the water supply by the rain. This data come from the weather station located in Bermejales.

Table 7. Average monthly precipitation in Escuzar during the year

	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Precipitation (l/month m^2)	54.8	43.1	43.1	38.5	35.0	18.1	4.3	3.5	19.7	45.8	61.2	56.5

The calculation of the evaporation is done using equation 6 (Pancharatnam, 1972):

$$W = k_g(p^* - p_a)$$ (Equation 6)

Where

W Mass transfer between air and pond surface $\frac{lbH_2O}{h\cdot ft^2}$

Kg Mass transport coefficient $\frac{lbH_2O}{h\cdot ft^2\cdot mmHg}$

p^* saturation vapor pressure (mmHg)

p_a Partial pressure of water in air (mmHg)

For the calculation of each of the terms that form equation 6 equations 7, 8 and 9 defined in Perry's Chemical Engineers' Handbook (Perry and Green, 1997) are used:

$$k_g = 1.9 + (0.476 \cdot Vviento(mp\text{▯})) \cdot 0.001 \qquad \text{(Equation 7)}$$

$$p^* = 31.82 \cdot e^{\frac{17.421\cdot(T\ °F\ -86)}{T\ °F\ +460}} \qquad \text{(Equation 8)}$$

$$p_a = p^* \cdot \frac{Hr(\%)}{100} \qquad \text{(Equation 9)}$$

The values of the ambient temperature and the wind speed have been taken from the Bermejales weather station and Relative humidity from Ogijares weather station (Table 8). Both weather stations are near Escúzar mine

.Table 8. Average relative Humidity, ambient temperature and average wind spedd in Escuzar

	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Average Relative Humidity (%)	78.51	77.81	69.06	64.43	52.9	51.86	39.83	46.67	57.33	63.29	78.66	71.77
T ambient (ºC)	6.7	7.8	9.9	12	15.3	20.4	24.1	23.9	20.1	14.9	10.5	6.9
Average wind speed (m/s)	1.04	0.96	1.13	1.24	1.48	1.68	1.84	1.65	1.38	1.08	0.84	0.66

Figure 35 shows the values of the quantity of water evaporation and the water supply by the rain present in the mass balance for each month. It can be observed that in the period between the months of May to September, the evaporated volume is greater than the volume contributed by the precipitations, while from November to December, the precipitations are the majority.

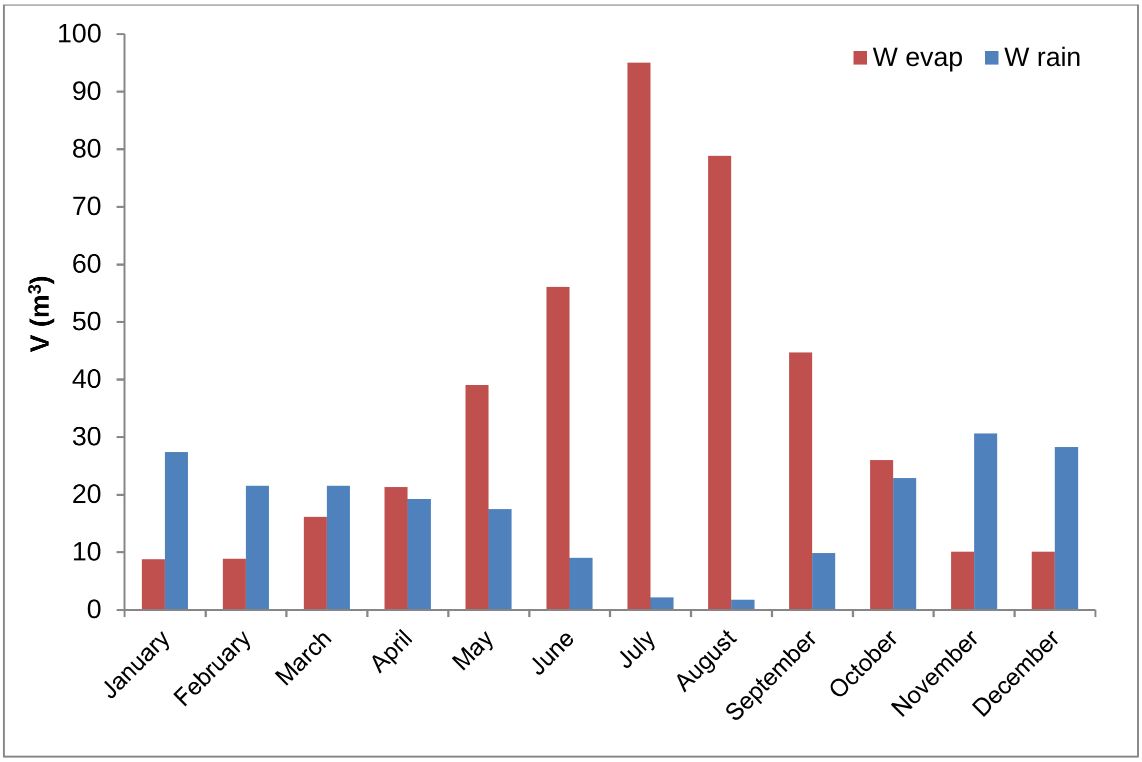

Figure 35. Precipitation and evaporation monthly volume in the solar pond

Once the volume corresponding to the climatological conditions has been quantified, it is only necessary to calculate the volume necessary to compensate the diffusion that takes place in the solar pond (Wout). For its calculation, the first Fick law of diffusion is used (Equation 10) that will provide the value of the mass diffusion speed ($\dot{m}$):

$$\dot{m}\ \frac{kg}{m^2\cdot año} = \propto\cdot\frac{\partial C}{\partial z} = \frac{C_{LCZ}-C_{UCZ}}{z} \qquad \text{(Equation 10)}$$

Where

C_{LCZ}	LCZ concentration (kg/m^3)
C_{UCZ}	UCZ Concentration (kg/m^3)
Z	NCZ height (m)
α	Diffusion coeficient (0.11-0.22 m^2/año)

Using equation 10 and the values of the diffusion coefficient of 0.11-0.22 m2 / year, values have been obtained for the mass diffusion speed of 20 and 40 kg / m^2 · year.

Table 9 shows the values of the mass diffusion speed used by different authors in order to compare whit the results obtained:

Table 9. Values of mass diffusion of different studies

Author	**Year**	$\dot{m}\ \frac{kg}{m^2 \cdot año}$
Agha et al.	2004	16.6
Ouni et al.	2003	20
Newell et al.	1994	12.5-25
Rabl and Nielson	1975	22-25
Tabor	1975	20-30
Weinberger	1964	20-30

In conclusion, the value of the mass diffusion speed used in this study has been chosen taking into account two aspects:

1. The range of values obtained by calculations made using equation 10 (20-40 kg / m2 · year).
2. Values used in research conducted on the operation of solar ponds.

According to these two premises, a value of 20 kg / m2 year is chosen because is an average of the values used by the different authors consulted. Taking into account the area of the solar pond (500 m^2) and the condition that in the surface area the concentration can have a maximum value of 4% (40000 mg / l), the volume of overflow will have a value around 250 m^3 / year, taking a constant monthly value for the Wout of 20.46 m^3 / month.

On the other hand, taking into account this mass diffusion coefficient, the average annual consumption of salt in the solar pond is estimated to be 10 Tn / year to keep the concentration in the LCZ.

Figure 36 shows the monthly values calculated for each factors of the mass balance (Equation 5). The outflows that correspond to evaporation water and water to compensate the diffusion are shown as a value:

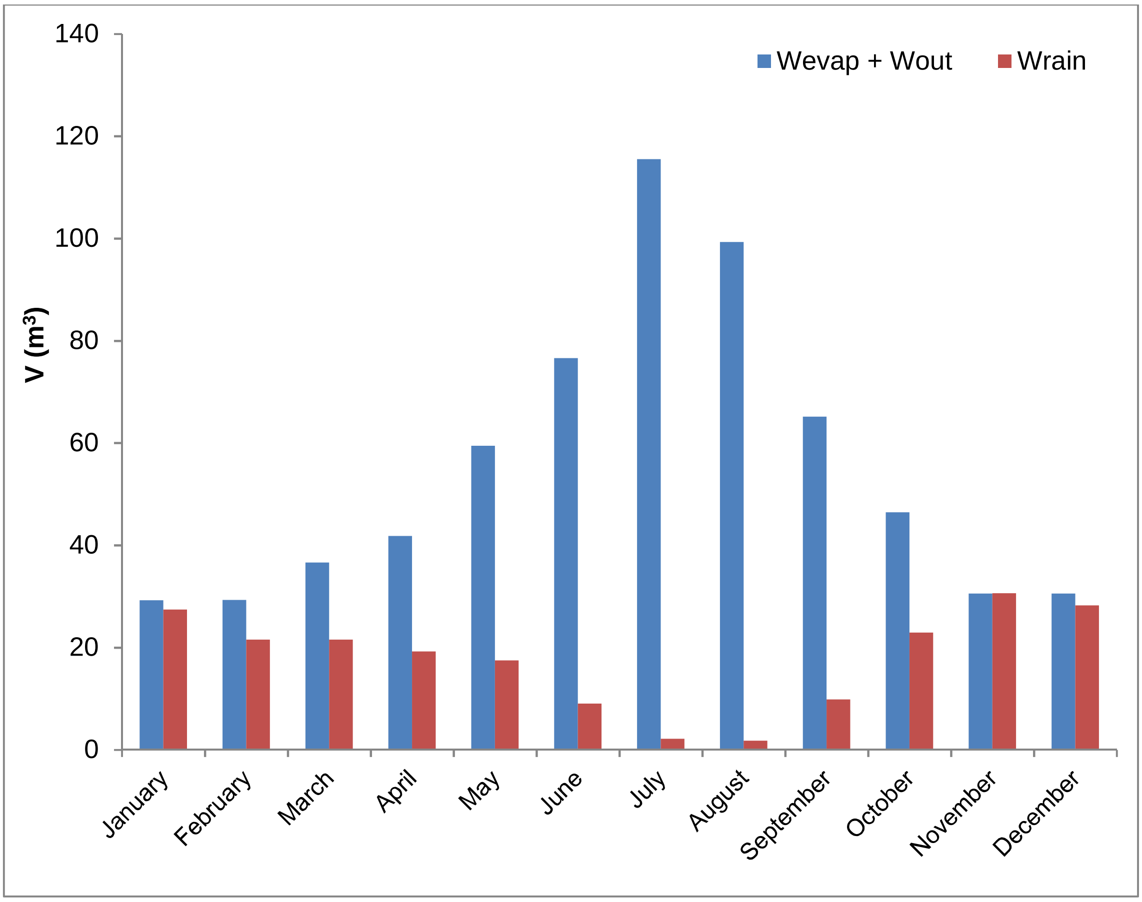

Figure 36. Precipitation, evaporation and outflow monthly volume in the solar pond

Figure 37 shows the value of the contribution water consumption required each month.

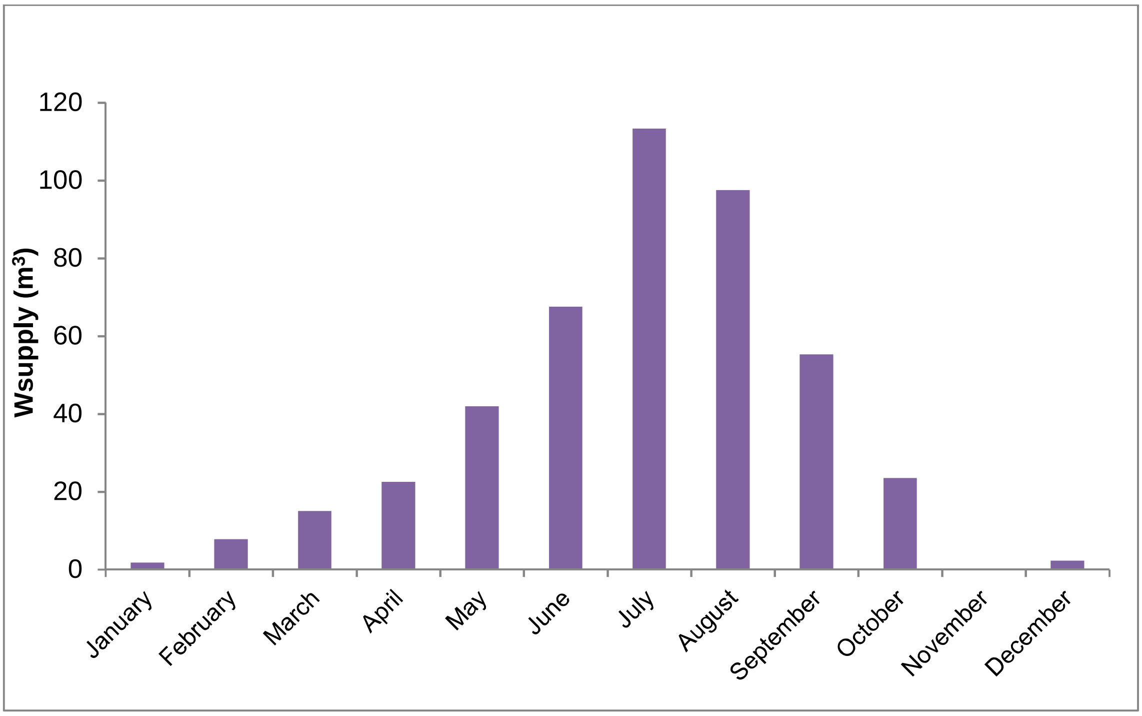

Figure 37. Water supply in the solar pond

If the monthly consumption of fresh water is added to achieve the correct functioning of the solar tank, the total annual consumption will be around 450 m^3.

The solar pond requires an auxiliary pond where the water from the overflow is accumulated. This overflow water is necessary to maintain a constant concentration in the surface layer and remove the possible dirt that accumulates on the surface, in order to allow the higher incidence of the sun rays.

For the calculation of the volume that will be stored in the auxiliary pond and the concentration of NaCl, a mass and component balance is made. Figure 38 shows a diagram of the outflows and the inflows that take place in the auxiliary pond.

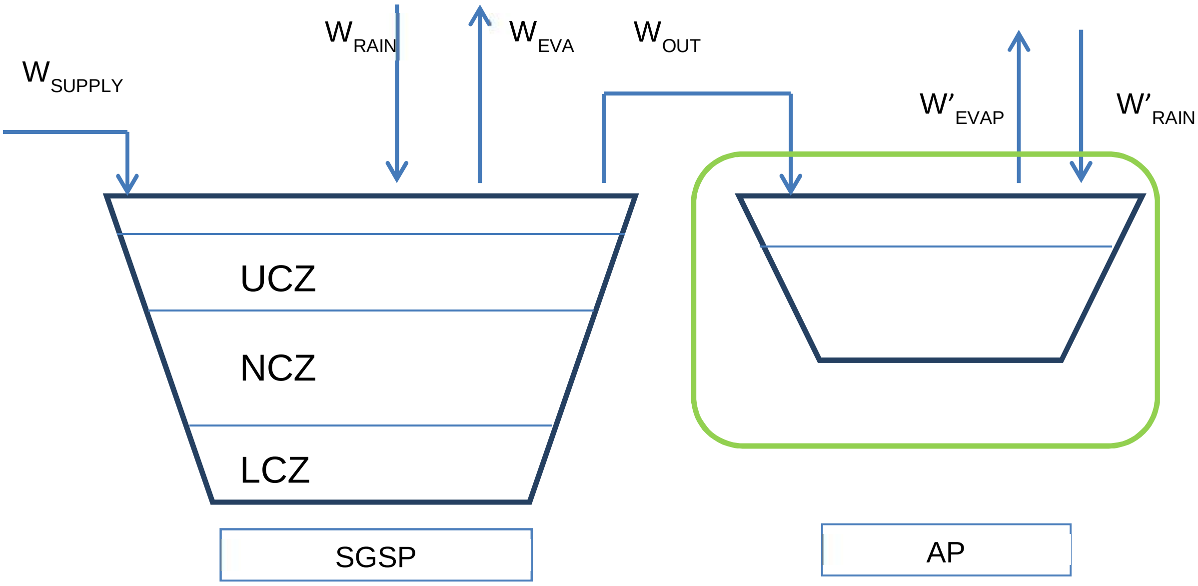

Figure 38. Mass balance in the auxiliary pond

Equation 11 shows the mass balance in the auxiliary pond:

$$V_{AP} = W'_{RAIN} + W_{OUT} - W'_{evap} \qquad \text{(Equation 11)}$$

The terms of the W'rain and the W'evap are calculated as was done in the case of the solar pond, taking into account now the surface of the auxiliary pondis 100 m^2. The meteorological data necessary for the calculation have been taken from the same sources as in the case of the solar pond calculation. The value of Wout is taken from the calculation made in the previous section for the calculation of the water necessary to compensate the diffusion, taking a constant monthly value of 20.46 m^3 / month.

Figure 39 shows the monthly values for each of the terms of the material balance (Equation 7):

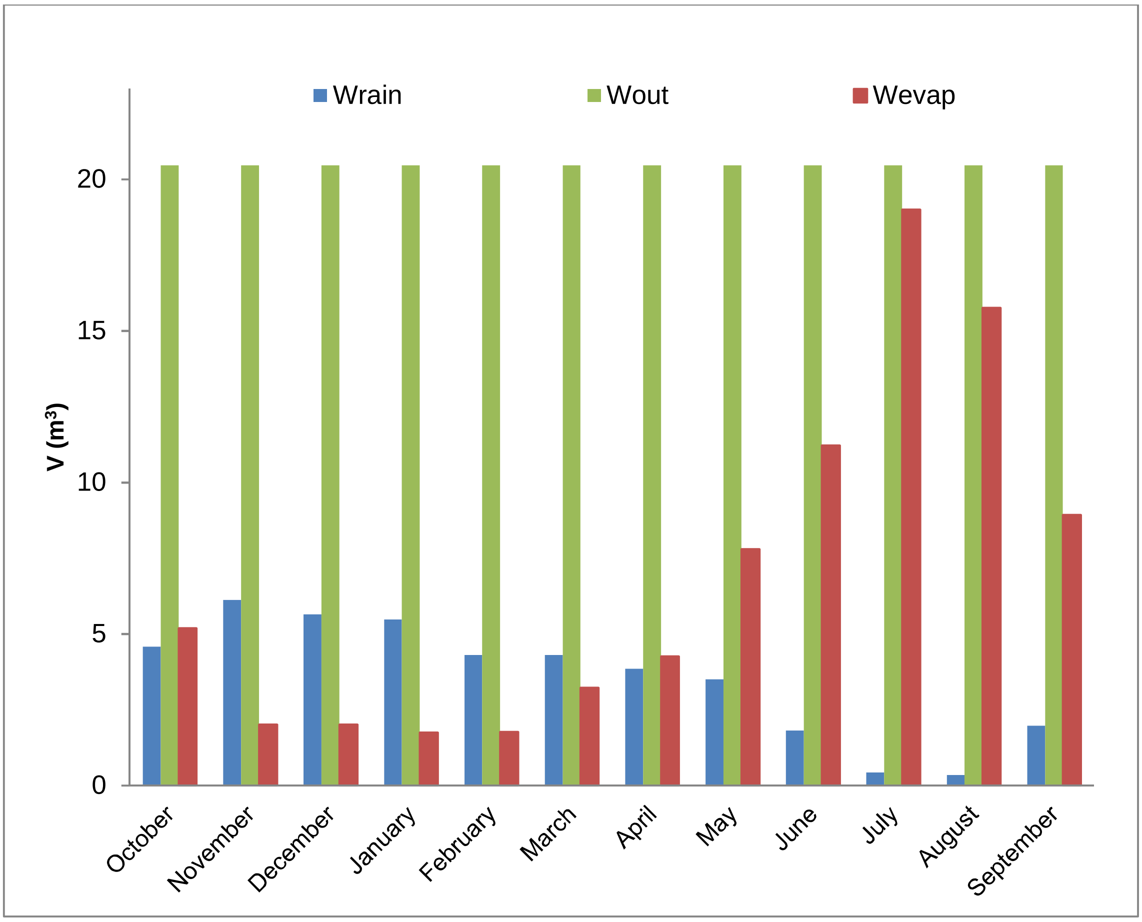

Figure 39. Values of the volumes calculated for evaporation water (Wevap), rainwater (Wrain) and water to compensate for diffusion (Wout) in the auxiliary pond

Assuming the auxiliary pond has a defined volume of 100 m^3 and it is empty in the month of October, equation 11 would be as follows:

- Mass balance October (first month):

$V\ (Oct) = W_{out}\ (Oct) + W_{rain}\ (Oct) – Wevap\ (Oct)$

Once the volume has been quantified for the first month, it is calculated for the subsequent months until the accumulated volume approaches the maximum volume of the auxiliary pool (100 m^3), at which time it will be emptied:

- Mass balance November:

$V\ (Nov) = V\ (Oct) + W_{out}\ (Nov) + W_{rain}\ (Nov) - W_{evap}\ (Nov)$

In general, the mass balance is defined for the first month (Equation 12) and the rest of months until reaching the volume of the auxiliary pond.

- Mass balance first month (or after emptying) (Equation 12):

$V(n) = W_{out}(n) + W_{rain}(n) - W_{evap}(n)$ (Equation 12)

- Mass balance month n (Equation 13):

$V(n) = V(n-1) + W_{out}(n) + W_{rain}(n) - W_{evap}(n)$ (Equation 13)

Figure 40 shows the volume of the auxiliary pond in each month using equations 12 and 13 for its calculation. As it is observed, three discharges would be made, one during the winter months, which depending on the meteorological factors would be carried out between the months of December to February; another in the summer months between the months of May to July and finally another discharge at the end of September, leaving the pond ready to start the cycle again.

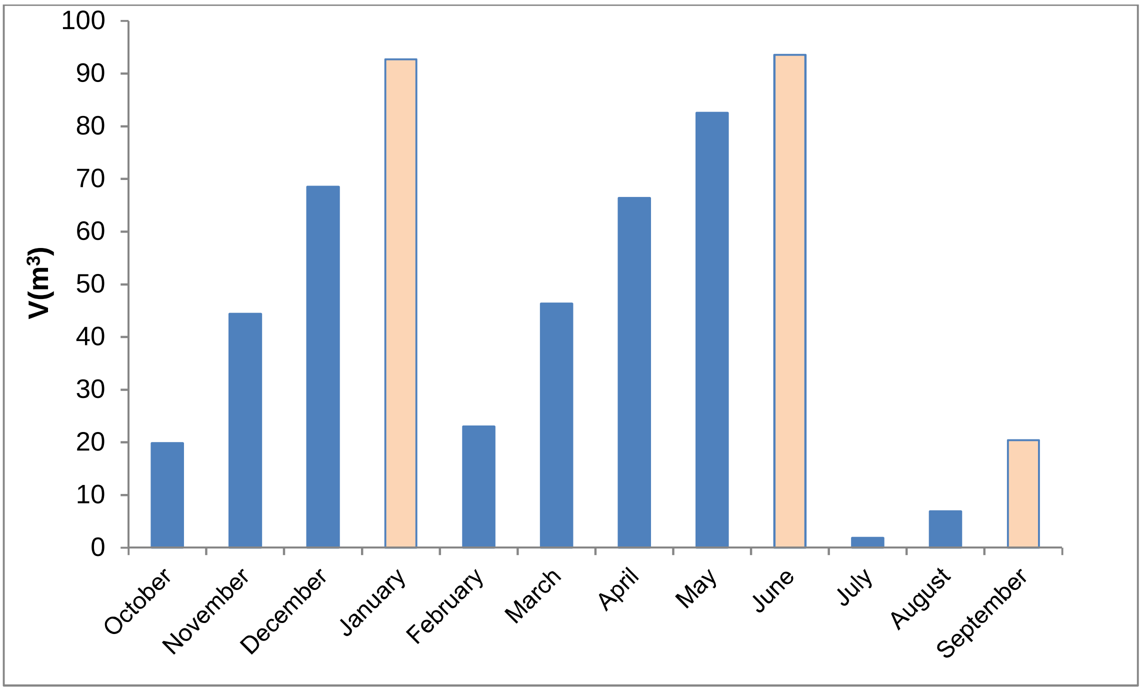

Figure 40. Water management in the auxiliary pond

The concentration present in the auxiliary pond is calculated by performing a component balance (NaCl).

- Component balance October (first month):

$V(Oct) \cdot C(Oct) = W_{out}(Oct) \cdot C_{out}(Oct)$

$C(Oct) = (W_{out}(Oct) \cdot C_{out}(Oct)) / V(Oct)$

- Component balance November:

$V(Nov) \cdot C(Nov) = V(Oct) \cdot C(Oct) + W_{out}(Nov) \cdot C_{out}(Nov)$

$C(Nov) = (V(Oct) \cdot C(Oct) + W_{out}(Nov) \cdot C_{out}(Nov)) / V(Nov)$

Generally, is defined the component balance for the first month (Equation 14) and the other month (Equation 15):

- Component balance first month:

$C\ (n) = (W_{out}\ (n) \cdot C_{out}\ (n)) / V\ (n)$ (Equation 14)

- Component balance month n:

$V\ (n) \cdot C\ (n) = V\ (n\text{-}1) \cdot C\ (n\text{-}1) + W_{out}\ (n) \cdot C_{out}\ (n)$

$C\ (n) = (V\ (n\text{-}1) \cdot C\ (n\text{-}1) + (W_{out}\ (n) \cdot C_{out}\ (n)) / V\ (n)$ (Equation 15)

Figure 41 shows the value of the concentrations over time in the auxiliary pond. During the discharges in winter and summer seasons, the concentration will be around values of 3.5-4.5% (35000 - 45000 mg / l), while in the last discharge in the month of September the concentration will be more elevated around a value of 12% (120000 mg / l). This is due during the summer the evaporation is higher than other seasons so the concentration increasing sine these values. The water discharged from the auxiliary pond is used to irrigate dirt roads to minimize dust in the mine facilities.

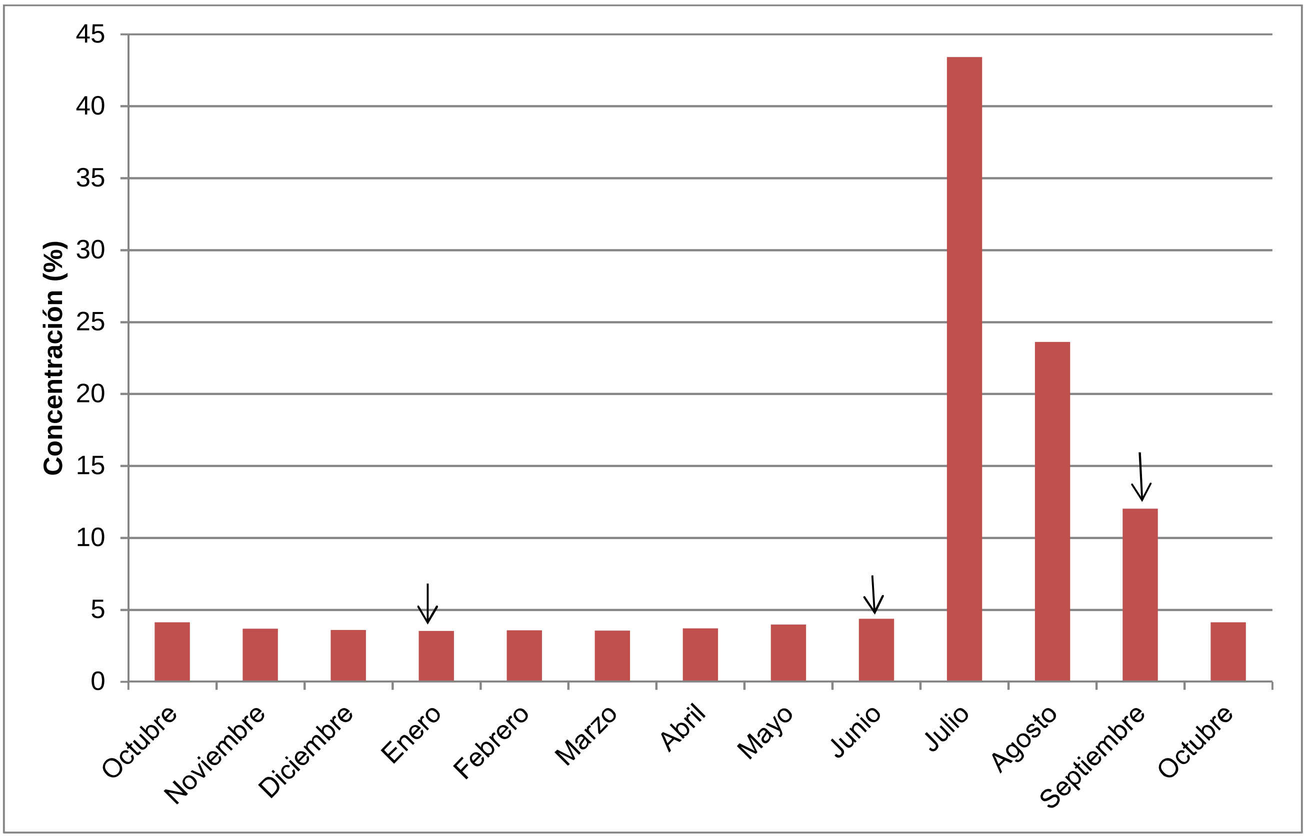

Figure 41. Concentration in the auxiliary pond during the year

Table 10 shows a summary of the volume and concentration during the discharge operations during the year.

Table 10. Summary of the study of volume and concentration in the auxiliary pond during the year

Discharge operation	**V auxiliary pond (m^3)**	**Concentration (%)**
December - February	∼ 90	3.5-4.5
May – July	∼ 90	3.5-4.5
September	∼ 20	12

ANNEX IV. ESTABLISHMENT OF THE SALINITY GRADIENT

The salinity gradient zone is the key element of salinity gradient solar ponds. The first major task of applying solar pond technology is determining how to construct a prescribed salinity distribution profile effectively and efficiently.

Before constructing the salinity gradient of the solar pond, a precalculated volume of saturated brine must be put into the pond. The level of brine required is governed by the depth of both the lower convective zone (LCZ) and the non-convective zone (NCZ). A saturated brine volume equal to the specified storage zone (LCZ) plus half of the gradient zone (NCZ) is the first step required.

To fill the pond, it is possible to use brine solution or to prepare a saturated salt solution. In this project it was decided to use brine coming from salt mines near the mine (Flusal S.A.). Table 11 shows the characteristics of the brine:

Table 11. Brine characteristic

Cl (g/l)	158
Cu (µg/l)	< 5
Pb (µg/l)	< 1
Dry residue (g/l)	231
(g/l)	110
pH	7,07
Density (g/l)	250 - 260

the initial volume of brine needed must be defined by equation 16:

$$V_{SB} = A_{sp} \cdot (h_{LCZ} + ½ h_{NCZ}) \qquad \text{(Equation 161)}$$

Where,

V_{SB} is volume of saturated brine (m^3)

A_{sp} is the total area of solar pond (m^2)

h_{LCZ} is the height of LCZ (m)

h_{NCZ} is the height of NCZ (m)

In the case of the Escùzar solar pond, the volume of saturated brine will be 662.5 m^3 with a total height of 1.32 m.

The Froude number, Fr, is a critical parameter for the fixed level injection process. The Froude number is a dimensionless number representing the ratio of the kinetic energy to the gravitational potential energy of the injected fluid. The correct Froude number can be calculated using the following equation (3) (Zangrando 1991).

$$\boldsymbol{Fr} = \frac{\rho * v^2}{\Delta\rho * g * \boldsymbol{B}}^{\frac{1}{2}} \qquad \textbf{(3)}$$

Where **ρ** is the density of the surrounding saline fluid (**kg/m^3**), **v** is the injection velocity at the diffuser outlet (**m/s**), **g** is the acceleration due to gravity (**m/s^2**), **Δρ** is the density difference between the injected fluid and the surrounding fluid (**kg/m^3**) and **B** is the gap width of the diffuser (**m**).

It has been found that the Froude number needs to be maintained at a constant value of approximately 18 in order to achieve complete mixing at the injection diffuser level (Liao, Swift and Reid, 1988; Zangrado and Johnstone, 1988). For Froude numbers smaller than this value the injected fluid rises, by buoyancy, and mixes above the diffuser level. For Froude numbers larger than this value, the injected fluid entrains significant quantities of fluid from below the diffuser level (Leblanc, 2011).

To maintain the Froude number at a value of 18, it is necessary to change the design of the diffuser (Gap width) or the injection velocity of the process Both changes make the filling process more complex.

Experimental experiences (Leblanc et al., 2011, Valderrama et al., 2011) in the establishment of the gradient show that it is possible to work with a Froude number of approximately 18 or below to achieve complete mixing at the injection diffuser level and establish the salinity gradient successfully. To verify that the values of Fr number were in the optimum working range (≤ 18), the variation of the Fr number through the height of the solar pond was calculated for different flow rates (Figure 42). The flow rate that presents a Fr number within the optimum working range is 250 l / min. For the surface area it has a value of approximately 16 for the surface area and values of approximately 4 for the bottom zone. These values of Fr number are saving to establish the salinity gradient. The lower flow rate (200 l / min) would also be a good workflow but the filling time would increase. The higher flow presents values above 18 which can generate problems when establishing the salt gradient. Therefore, 250 l / min is established as the work flow.

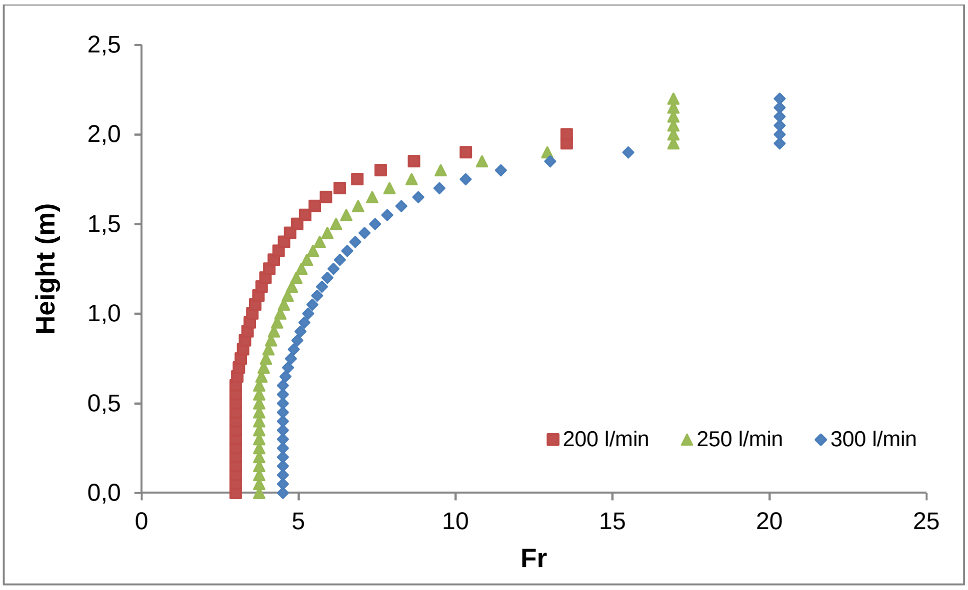

Figure 42. VAriation Fr number acros the height of the solar pond different flow rates

Figure 43 shows the design of the diffuser used in the establishment of salinity gradient profile in Granada solar pond. Table 12 shows the values defined for its construction.

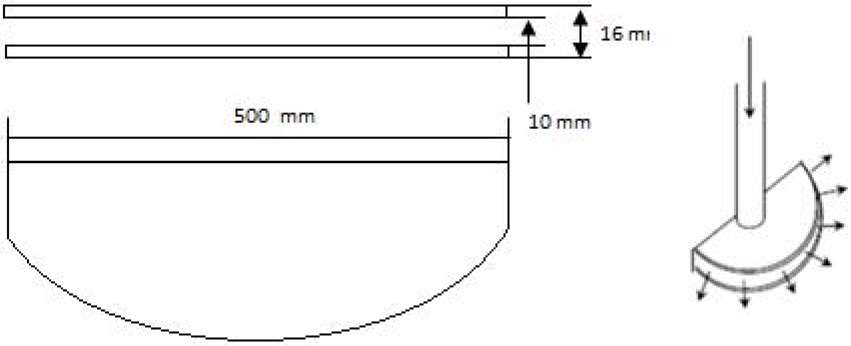

Figure 43. Scheme of the diffuser ued to set up salinity gradient

Table 12. Parameters of the diffuser used in the salinity gradient establishment of the Granada

Diameter (mm)	500
Gap width (mm)	10
Thickness (mm)	16
Pipe inlet diameter (mm)	50
Material	Stainless steel

Once the flow rate to fill the pond and the diffuser was defined, a procedure is designed to carry out the formation of the salt gradient and the necessary maintenance actions to ensure its correct operation.

Firstly, it fills the pond with saturated brine at a height of 1.3 m (h_{LCZ} + ½ h_{NCZ}). The transport of this brine to the mine will be done by trucks. The salt company has three trucks with a total volume of 24 m^3 each one. If the salt company does two trips per day, the pond will be filled in 5 days.

Once the pond is full with brine, the establishment of salinity gradient process starts. Firstly, the supporting vertical rod of the diffuser should be marked in intervals of 25 mm. With these marks is possible to control the distance between the plane of the diffuser and the water level at any time.

The injection process to establish the salinity gradient starts putting the diffuser at a height of 0.65 m from the bottom of the pond (NCZ-LCZ interface). The velocity of the injection will be of 250 L/min.

When the water level rises a height of 50mm the injection will be stop. With this flow rate, the injection process for each step will be about 1.67 hours. Then, it must wait for 30 minutes. To check the correct establishment of the salinity gradient a complete salinity profile will be taken. This should also take another 30 minutes. Therefore, every step will take approximately 3 hours.

When the salinity profile has been taken, the second step will be start. It has to move the diffusor 100 mm and it will get back to inject water. Accomplish this injection process until the pond water level reaches the boundary of NCZ and UCZ specified in the design. Therefore 13 injections steps will be required.

To finish, add fresh water into the pond surface through a Floating system to avoid mixing, until the pond level reaches the design value (2.2 m). The supply water system can be used to carry out this operation with a low flow rate approximately about 25 L/min.

Once the gradient is established it will be start the actions to control de system. On one hand, it will be necessary to take samples of the system to study the evolution and the stability of the salinity gradient every day in the week after the gradient establishment. Density, pH and turbidity will be measured to carry out this objective. On the other hand, it will be needed to add acid to decreases the pH between 3 to 4 to control de clarity of the system and to prevent the growth of the algae. The acid will be HCl and its concentration should be approximately 9% so it’s necessary to prepare the solution with this concentration and add to the system through the pipes of the acidification system. It’s recommended to add acid each day after the gradient establishment to decreases the pH in several steps for not disturb the system using 200 L of acid solution approximately in each supply operation. It must supply acid to the system until the pH shows values between 3 to 4. In the schedule it can be seen that the operation of supply acid will be one week. If the system reaches the needed pH before it will stop the supply operation.

Once time the pH of the system will be stable, the study of the stability and the evolution of the system will be carried out once a week. If the pH increases it would be necessary to add acid to the system again.

Simultaneously the treatment of data must be carried out. The salinity and temperature profiles, the water, salt and acid consumptions and the weather parameters will be study to have an overview of the system.

The establishment of the salinity and thermal gradient can be seen in Figure 44 a and b respectively.

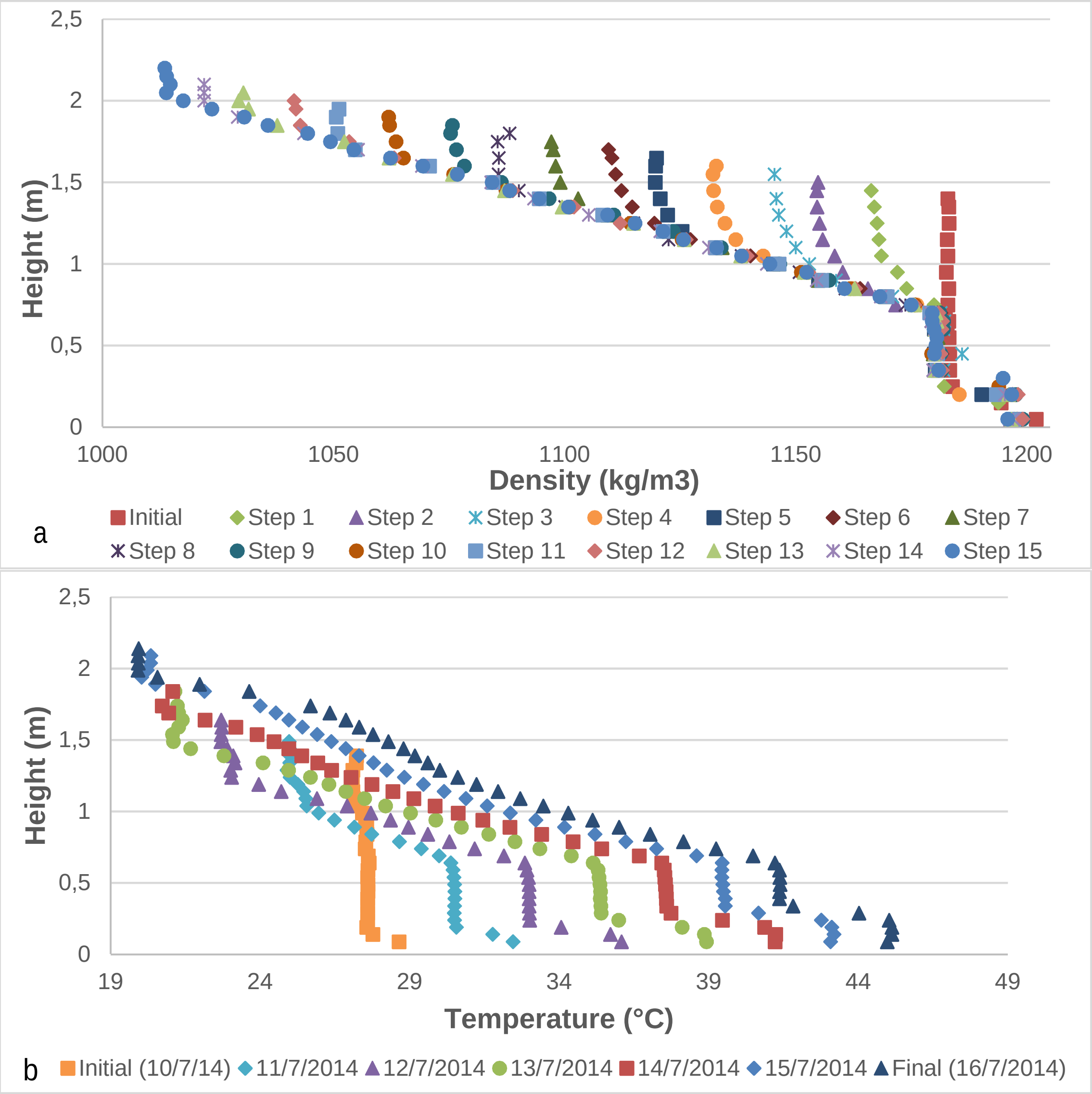

Figure 44. a) Settling of salinity gradient and b) evolution of the temperature gradient during the process of establishing the salinity gradient at the Granada solar pond in July 2014.

ANNEX V.CONSTRUCTION GRANADA SOLAR POND

V.1 Construction

During the month of May 2014, the construction of the solar pond began at the Solvay Minerals facilities in Granada. The construction of the pond was carried out in different phases. In this section, the different phases will be explained chronologically.

V.2 Earth movement

Before beginning the excavation process, it was necessary to move some freshwater pipes that were in the construction area of the solar pond (Figure 45 and 46).

Figure 45. Initial location of the freshwater pipes in Solvay Minerales facilities

Figure 46. New location of the freshwater pipe

After this relocation of the pipes, the excavation of the land began. First the ground was prepared with a bulldozer (Figure 47) and all the plaster was removed from the construction zone (Figure 48).

Figure 47. Preparation of the ground

Figure 48. Removal of rock

Then the compaction of the land was carried out. First, the soil was leveled and then compacted using a drum compactor machine (Figure 49). The goal was to get a surface as uniform as possible.

Figure 49. Compaction of the ground

The area of the solar pond was marked using a total station to measure the perimeter for the solar tank as a measurement tool (Figure 50).

Figure 50. Perimeter measurement with a total station

The excavation process was formed by two parts (Figure 51). Firstly, the excavation of the volume of rocks, without taking into account the walls of the pond (Figure 52). Secondly, the excavation process on the walls, to ensure greater stability (Figure 53). It was decided that the walls of the solar pond should have a certain inclination so that, when the earth gets wet in the winter and autumn seasons, periods with a higher proportion of rain, the plaster rocks that can be loose, cannot fall and damage the coating of the pond.

Taking into account this observation, the first stage of excavation was not carried out until the end of the marked perimeter to execute it in a second stage, taking into account the certain inclination of the walls of the pond. Once both phases were completed, the surface material was removed, and the earthwork phase was completed (Figure 54).

Figure 51. Start of excavation process

Figure 52. First phase of the excavation process

Figure 53. Second phase the excavation process

Figure 54. End of the excavation process

Once the excavation of the land and the walls of the solar pond was completed, the surface finishing phase began. This phase was divided in two parts, first at the base and then the walls of the pond as the excavation process. The objective of this operation is to prevent leaks and achieve a uniform finish.

For this, a level was placed at the base of the pond with the idea of measuring the uniformity of the land (Figure 55) and adding material in the areas where the desired uniformity is not achieved (Figure 56 and 57).

Figure 55. Land leveling on the base of the pond

Figure 56. Addition of material on the walls of the pond

Figure 57. Addition of material on the base of the pond

V.3 Overflow system

The solar pond was connected to the auxiliary pond by an overflow system. This system is a canal with a length of 0.8 m and a height of 0.3 m (Figure 58 and 59). Through this system the rainwater and the water supply, used to maintain constant the concentration of the UCZ, is accumulated in the auxiliary tank. To construct the channel concrete pieces were used as show Figure 60.

Figure 58. Canal to connect solar pond with auxiliary pond 1

Figure 59. Canal to connect solar pond with auxiliary pond 2

Figure 60. Concrete piece used in construction of the overflow system

V.4 Thermal insulation installation

Once the entire surface of the base and walls had been sealed and the overflow system of the solar pond had been completed, the surface was waterproof and thermally insulated. This insulation was made to reduce the heat losses of the pond with the soil and walls. The waterproof was done with a layer of concrete (Figure 61).

Figure 61. Concrete layer on the walls to waterproof the system

The internal insulation is composed of several layers of insulating material. For the first layer two options of insulation were proposed: the ChovAFOAM 300 meters and the second one was THERMOPLAN. Both are good thermal insulators that adapt perfectly to the conditions of the project, but ChovAFOAM 300 has been chosen because was more resistant to work at higher pressures.

Table 13 y 14 shows the characteristics of each of the thermal insulators considered.

Table 13. Characteristics of ChovAFOAM 300 M (50mm)

ChovAFOAM 300 M (50 mm)		
DESIGN CRITERIA	**Score (0-5)**	**REASON**
Affordability	5	~ 6 € / m^2
Thermal conductivity	4	Good thermal conductivity (0.034 W/mK)
Maximum pressure able to withstand	5	Can withstand ≥ $300\ KPa$ of pressure
Maximum temperature able to withstand	4	$0℃ \le T \le 65℃$

Table 14. Characteristics of TERMOPLAN (8mm)

TERMOPLAN (8 mm)		
DESIGN CRITERIA	**Score (0-5)**	**REASON**
Affordability	5	~ 6 € / m^2
Thermal conductivity	5	Good thermal conductivity (0.034 W/mK)
Maximum pressure able to withstand	0	Can withstand ≥ $300\ KPa$ of pressure
Maximum temperature able to withstand	5	$-20\square \leq T \leq +80\square$

The material was prefabricated strips of 1250 mm x 600 mm x 50 mm (Figure 62). The installation was done on the base of the pond and up to a height of 0.80 m from the walls. It took approximately three days to be placed on the base and walls of the solar pond (Figure 63 and 64).

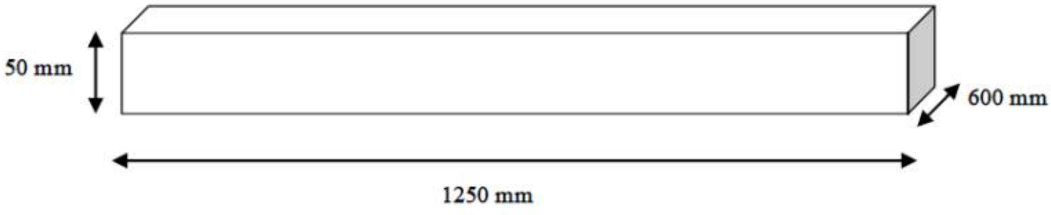

Figure 62. Dimensions of insulation ChovAFOAM 300 M 50

Figure 63. Start of the thermal insulation installation process

Figure 64. End of the process of placing the first layer of insulation

The second layer of thermal insulation is composed of expanded clay (Arlita). This layer ensures thermal insulation layer protection in the case the temperature reaches 65°C in the LCZ (Figure 65). At the end of the process of placing the second layer of insulation, the coating of the walls is continued with the thermal insulation ChovAFOAM 300 meters (Figure 66).

Figure 65. Laying the extended clay layer

Figure 66. Laying the ChovAFOAM material on the walls.

Once placed the insulation ChovAFOAM 300 M 50 mm and expanded clay (Figure 67), began the placement of the third layer. This layer of thermal insulation was composed by a geo-textile layer. It is a material composed mainly of polypropylene and polyester, to separate the different layers of thermal insulation and ensure that there is no contamination between the different materials (Figure 68).

Figure 67. End of the process of placing the second layer of insulation

Figure 68. Laying the geotextile layer

To finish, two layers of primary coating insulation with a thickness of 1 mm and secondary coating were placed. The primary coating is composed of vinyl polychloride (PVC), a material characterized by ductile and tenacious, with dimensional stability and environmental resistance. In addition, it is a great thermal insulator, a very necessary condition for this type of technology (Figure 69 and 70).

Figure 69. Placement of PVC on the geotextile layer

Figure 70. End of the process of placing the third layer of insulation

The secondary coating, the last layer of thermal insulation, is composed of high density polyethylene (PE), with high chemical resistance, very favourable as a waterproof barrier, to ensure that there are no leaks (Figure 71).

Figure 71. End of the process of placing the quarter layer of insulation

The use of both coatings is to provide a double layer of protection for the solar pond. To detect possible leaks, between the PVC and PE coverings, a PE pipe connecting the base with the surface of the pond and a sensor that indicates the existence of water between these two layers of insulation was installed.

Figure 72 shows a schematic of the insulation layers of the system

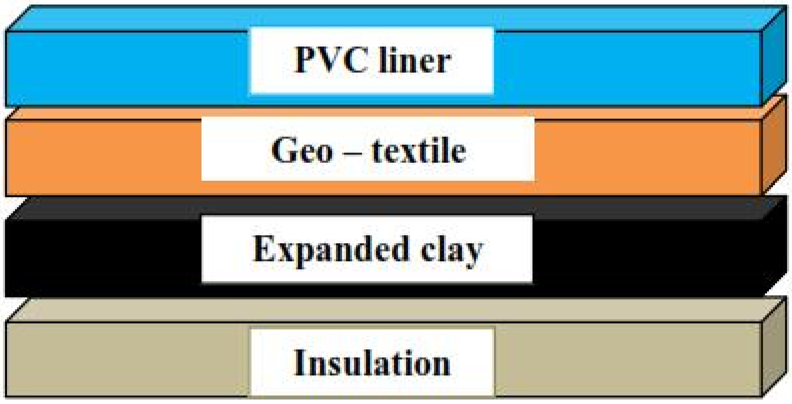

Figure 72. Scheme of insulation layers of the systems

V.5 Catwalk and instrumentation room

The next step was the construction of an access platform to the solar pond and an instrumentation room (Figure 73). In this catwalk several instrumentations were installed. On one hand, the two salt chargers were installed to feed the LCZ with NaCl in order to maintain a constant saturation concentration (Figure

74 and 75). On the other hand, a sampler was installed to control the salt gradient as well as the temperature and pH of the system at different heights (Figure 76). Also, 42 termoresistences was installed over the height to control the temperature of the system. These sensors were distributed at intervals of 5 cm, starting 0.5 cm from the bottom and installed in plastic supports (Figure 77). Finally, pipes system was installed to add hydrochloric acid to the system at different heights in order to conserve the water clarity (Figure 78). Figure 79 shows all the instrumentation placed on the catwalk.

Figure 73. Catwalk and instrumentation room

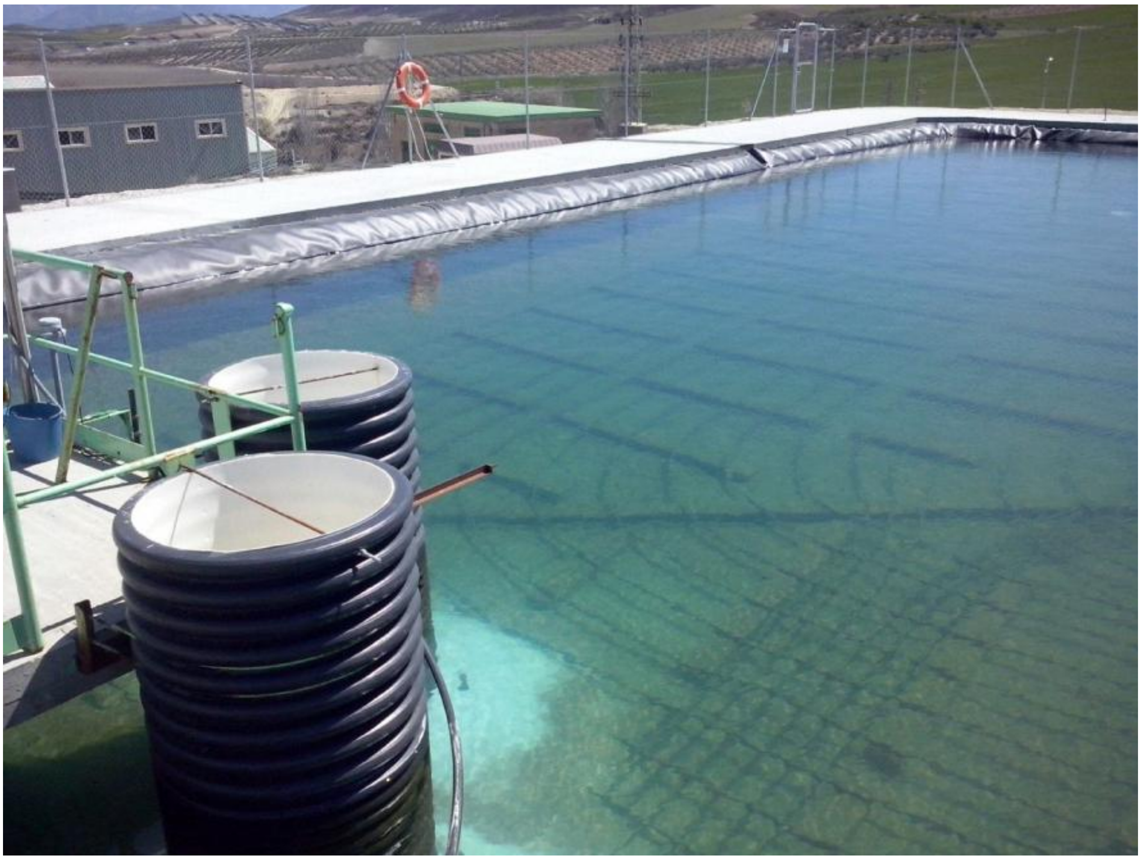

Figure 74. Salt chargers

Figure 75. Loaded salt charger

Figure 76. Sampling mechanism to take samples at different heights

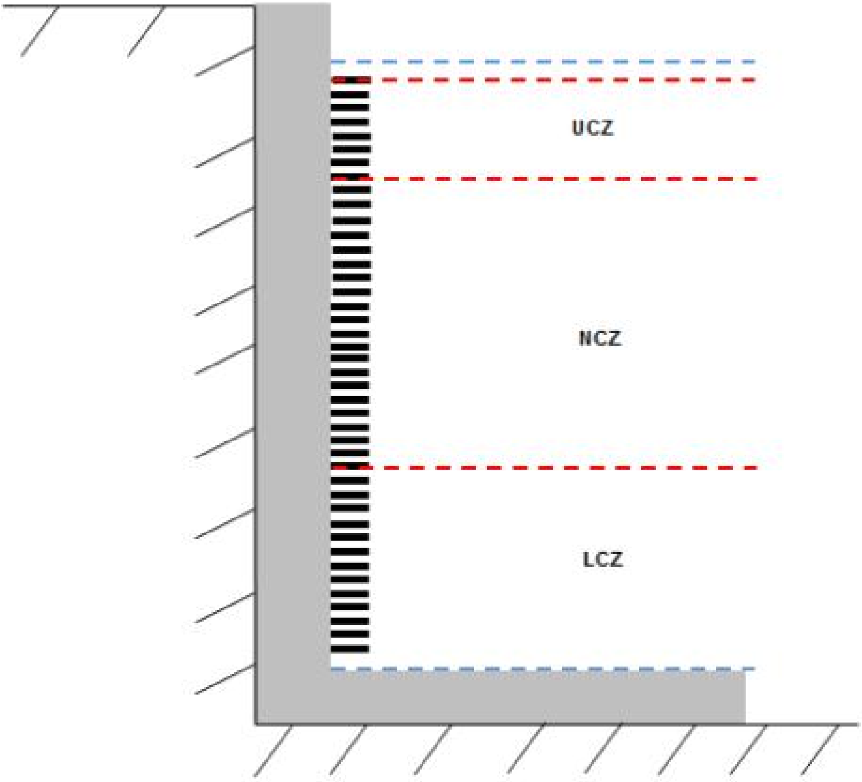

Figure 77. Disposition of temperature sensors in the solar pond

Figure 78. Pipe system to add acid in the system at different heights

Figure 79. Salt charger, temperature sensors, system of pipes and diffusor on the catwalk

The instrumentation room is used to install all necessary instrumentation to control the heat extraction process of the system and the fresh water supply system. A flow meters (SMC) to mesure the inlet flow rate and thermal sensors (PT100) were installed to measure the inlet and outlet temperature of the working fluid. To ensure that the inlet flow rate in each spiral was the same, a rotameter was installed in each of the individual spiral heat exchangers. A valve to regulate the flow rate is also intalled (Figure 80)

To mesure the parameters of the fresh water supply system a flow meter and a temperature sensor were installed (Figure 81).

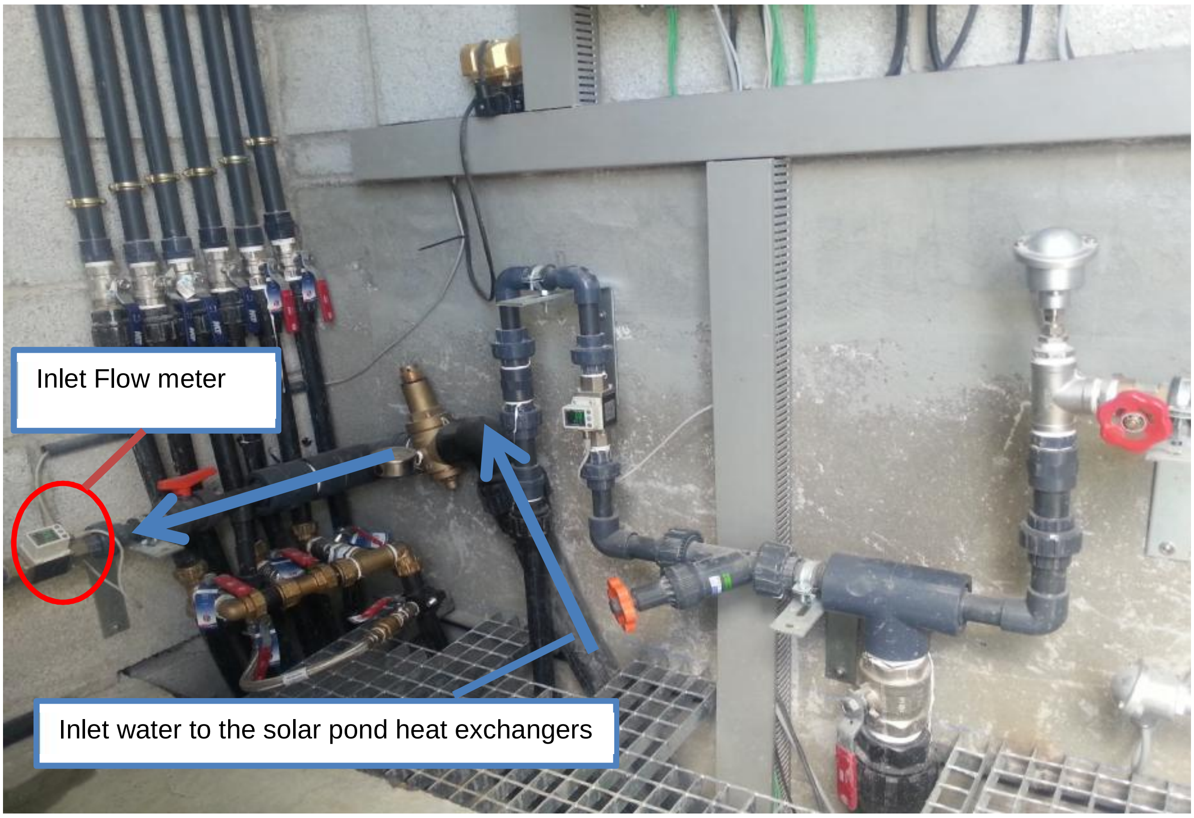

Figure 80. Fresh wàter System

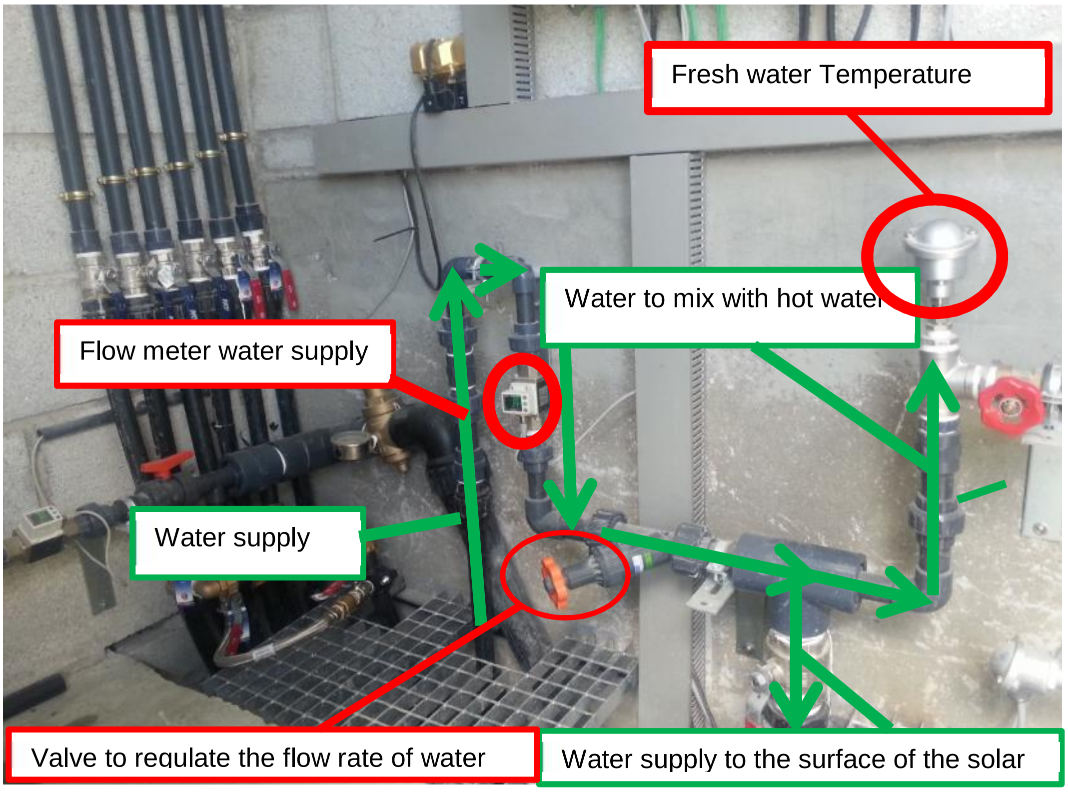

Figure 81. Water supply system

On the other hand, a thermostat valve were installed to achieve a constant temperature of 60 °C. When the temperature of the outlet flow is higher than 60 °C this thermostate valve open a circuit to mix with fresh water (Figure 82). Firstly, the decrease in the temperature of the outlet flow was obtained, but the thermostatic valve didn’t work correctly because couldn’t regulate the temperature in a stable way, so it was decided to work without it. Consequently, the outlet flow from the heat exchanger goes directly to the industrial process (Figure 83).

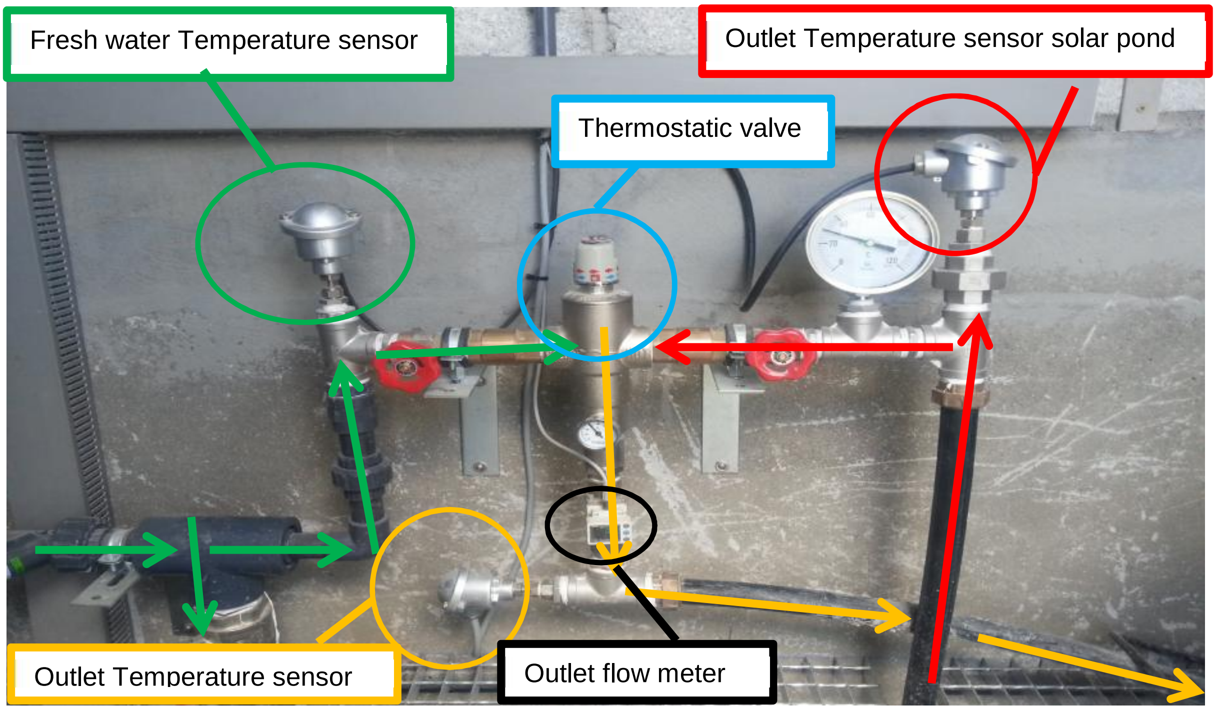

Figure 82. Initial outlet flow rate to the industrial application with thermostatic valve

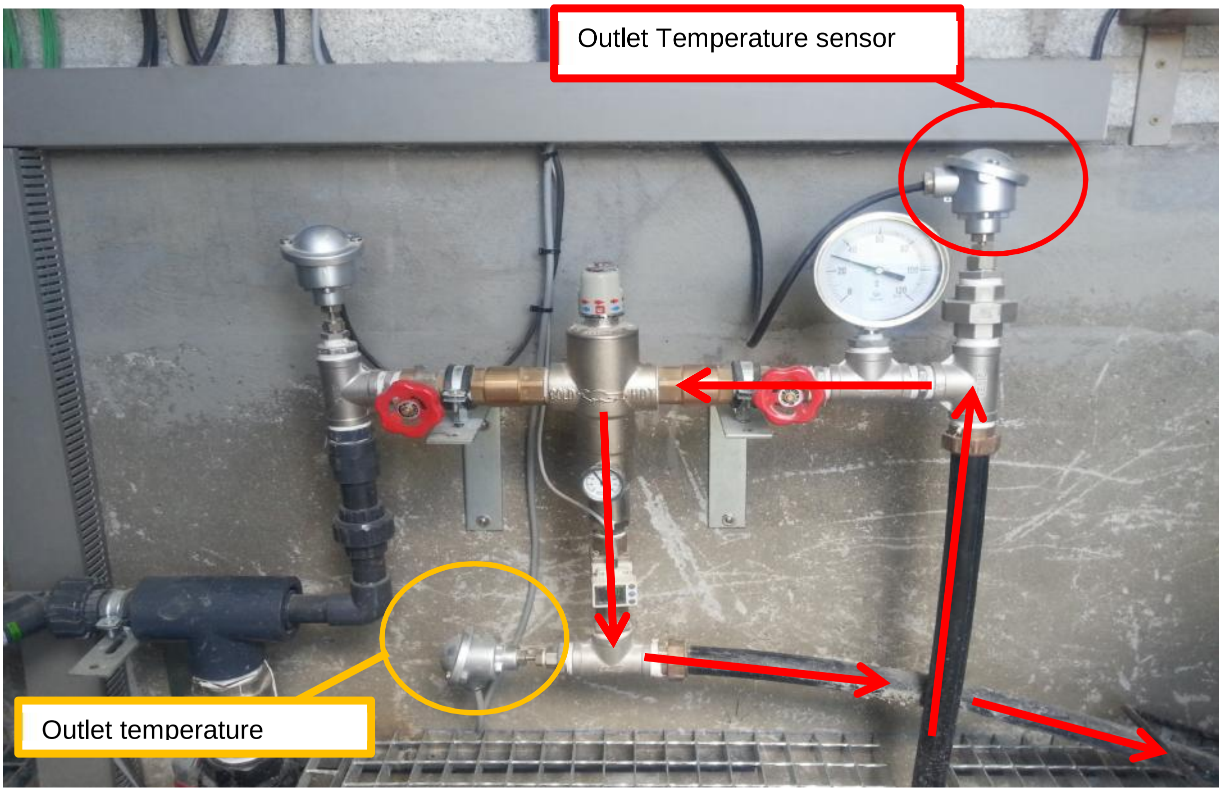

Figure 83. Final system of the outlet flow rate to the industrial application

V.6 Auxiliary pond

The auxiliary pond was built parallel to the solar pond. Both are connected by the overflow system. The function of this pond is to store the excess water from the solar pond. This water comes from rainwater as well as the water supply used to keep the concentration on the surface constant. It has a volume of 134.4 m^3 and an area of 96 m^2 (Figure 84).

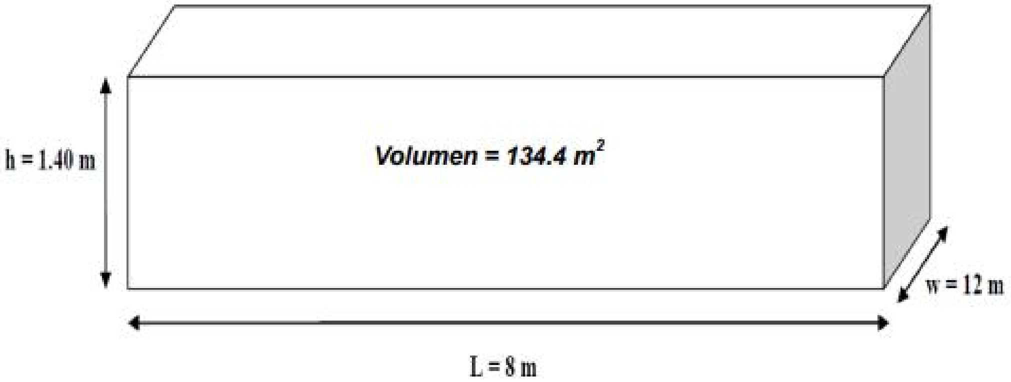

Figure 84. Dimensions of the auxiliary pond

The auxiliary pond is not buried. For its construction, firstly, the ground was cleaned and smoothed so that the surface was as uniform as possible (Figure 85). Secondly, the structure of the side walls was built (Figure 86). Thirdly, the side walls were raised to a height of 1.40m using blocks (Figure 87). This auxiliary raft was isolated to prevent leaks to the ground with two layers, one of geotextile and another of PVC (Figure 88 and 89). Finally, both ponds are joined by the overflow system (Figure 90).

Figure 85. Preparation of the ground of the auxiliary pond

Figure 86. Structure of the auxiliary pond

Figure 87. Construction of the walls of the auxiliary pond

Figure 88. Laying the geotextile layer

Figure 89. Laying the layer second layer of PVC

Figure 90. Final aspect of the auxiliary pond and union with the solar pond (red)

V.7 Installation heat exchangers system

The heat exchanger was placed at the bottom of the solar pond. The material that was used to manufacture the heat exchanger were polyethylene pipes (PE100) of 32 mm and 28 mm of outer and inner diameter respectively. The use of metallic pipes would provide a greater heat transfer but could lead to corrosion problems due to the high salinity of the water in the pond. According to the design, the exchanger would be formed by 6 independent pipes of 600 m each one placed in a spiral shape to occupy the entire lower area of the tank. To place them, a structure made up of concrete blocks was used to separate the tubes from the pond floor (Figure 91). The heat transfer occurs in the entire lateral area of the pipes. Once this structure was placed, each of the spirals forming the heat exchanger was placed (Figure 92).

Figure 91. Structure of the concrete blocks in the bottom of the solar pond

Figure 92. Final location of the heat exchanger

V.8 Meteorological station

The meteorological station CR1000 Measurement and Control System (Campbell Scientific, Barcelona, Spain) was installed on the roof of the instrumentation room to measure the environmental parameters (Figure 93). The station was programmed to measure and store data (Datalogger CR1000) from the different meteorological sensors with high accuracy, as follows: rain (52202/52203, 2% up to 25 mm / h); solar radiation (CS300, ± 5% for daily total radiation); wind speed (03002, ± 0.5 m / s); relative humidity (CS215, ± 2%, 10-90% RH); barometric pressure (CS106, ± 0.6 mb, 0-40 ° C), and air temperature (CS215, ± 0.4 ° C, over +5 to +40 ° C). The sensors take measurements every 10 s, and the hourly average is recorded as well as the daily average (24 h). The monthly average ambient temperature is determined by averaging the values recorded daily.

Figure 93. Meteorological station

ANEXX V