Thermal performance of 500m^2 salinity gradient solar pond in Granada, Spain under strong weather conditions

A. Alcaraz [1], M. Montalà [1,2], C. Valderrama [1,2], J. L. Cortina [1,2], A. Akbarzadeh [3], A. Farran [1,2]

[1] Chemical Engineering Department, UPC-BarcelonaTECH, 08930 Barcelona, Spain

[2] Barcelona Research Center for Multiscale Science and Engineering, 08930 Barcelona, Spain

[3] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Australia

*Correspondence should be addressed to: César Valderrama

Departament d'Enginyeria Química, Universitat Politècnica de Catalunya-Barcelona TECH

C/ Eduard Maristany, 10-14 (Campus Diagonal-Besòs), 08930 Barcelona, Spain

Tel.: 93 4011818

Email: cesar.alberto.valderrama@upc.edu

Abstract

In this study, an experimental investigation of temperature performance and efficiency of an industrial solar pond during strong winter conditions is presented. Several temperature sensors connected to a data logger were used to measure the temperature gradient in a 500 m^2 solar pond. During the winter 2015 there was a snowfall in the solar pond of Granada (Spain), reaching a minimum air ambient temperature of -2.4 °C. The temperature of the storage zone in Granada solar pond remained constant (around 40 °C) indicating the system responds positively to weather variations and confirming the fundamental role of the salinity gradient as a thermal insulation layer. The stored energy during January 2015 was 13.3 GJ,

the weekly efficiency reached 10% and finally, the solar pond was able to provide 247.1 MJ to the flotation unit during the week of the snowfall.

Keywords: solar energy; energy efficiency; snowfall; industrial solar pond; mineral flotation

1. Introduction

World is now facing challenges in meeting its energy demand through burning fuels. Elevated level of CO_2 in the atmosphere is contributing to climate change. Therefore, there is an urgent need to conserve energy and move towards clean and renewable energy sources. Thermal energy storage is a key function enabling energy conservation across all major thermal energy sources, although each thermal energy source has its own unique context. Absorbing and storing the solar energy is the most important challenge in this field. Different collectors can be used for absorbing the solar energy for different purposes such as power generation, desalination, water heating, space heating, etc. A solar pond is a low cost solar collector for collecting and storing the thermal energy for a long period of time (Khalilian, 2017; Swift et al., 1987) .

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. In broad terms, a solar pond is a large body of water that collects and stores solar energy in the form of heat.

A typical salinity gradient solar pond (SGSP) consists in three distinct zones (Zangrando 1980; Tabor & Weinberger 1981). 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 air 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 consisting of 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 content), 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.

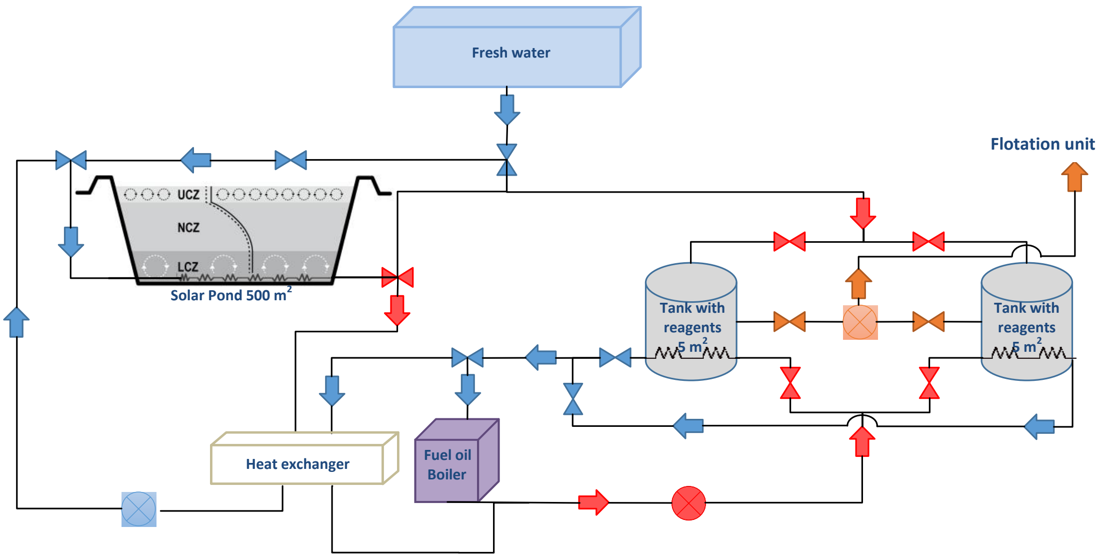
In the last years, several studies have been carried out to analyse and evaluate the performance of salinity gradient solar ponds and to increase their overall performance. Experimental studies have focused on i) alternative applications (Zhang et al., 2016; Rahaoui et al., 2017; Ziapour et al., 2017; Karakilcik et al., 2018); ii) the addition of heat from external sources (Ganguly et al., 2017); iii) the performance analysis to enhance the overall efficiency (Sayer et al., 2108; Simic and George, 2017; A.A.Abdullah et al., 2017; Torkmahalleh et al., 2107; Bozkurt and Karakilcik, 2015a); and iv) the analysis of exergy efficiencies (Njoku et al., 2017; Khalilian, 2017a, 2017b; Bozkurt and Karakilcik, 2015b).

The weather conditions determine the performance of any solar pond facility and can affect its long-term storage capability. Solar radiation, wind, heavy rain can cause instability in the system and make its efficiency decrease. The aim of this study is to evaluate a 500-m^2 industrial solar pond in Granada (Spain) during an event of extreme weather conditions of snowfall during the winter of 2015. The present note studies the influence of the weather conditions on the storage capacity and on the thermal efficiency of the solar pond. The rationality of the analysis is to evaluate if the technology of solar ponds is able to store energy even in extreme weather conditions and continue to provide the energy required in the flotation unit of the mining facility. This is of great interest in terms of the operation, as well as the ability to supply energy to an external application under unfavourable environmental conditions.

2. Materials and methods

In 2014, a salinity gradient solar pond was constructed in the Solvay Minerales facilities in Granada (South Spain). The solar pond design, construction and operation was described by (Alcaraz et al., 2018): The solar pond was constructed to deliver the heat needed to preheat the water (> 60 °C) used in the mineral flotation unit. Some features of this solar pond are: the total area of the pond is 500 m^2 (20 × 25 m) with a depth of 2.2 m. The thickness of the LCZ, NCZ and UCZ was 0.6 m, 1.4 m and 0.2 m, respectively. The heat extraction was carried out through a heat exchanger (PE pipe with an internal diameter of 28 m) located at the LCZ with a total length of 1200 m, which was divided into six independent spirals of 200 m. The solar pond is installed in a mine facility devoted to produce celestine ($SrSO_4$). The processed rock, with a celestine content of 30-50%, is milled and then concentrated up to a content of 90% by using a flotation stage. The aqueous solution containing the reagents should be heated to 60-65ºC. Before the installation of the solar pond, this was carried out using a boiler fed with gasoil. The solar pond was integrated with the flotation unit by connecting a pipe from the freshwater tank that travels through the LCZ of the solar pond and joins the existing pipe line. A view of the experimental solar pond in Granada is shown in Figure 1.

a



b

Figure 1. Schematic view showing: a) the integration of the solar pond in Solvay facilities and b) view of the 500 m^2 solar pond at Solvay Minerales facilities (Granada, Spain)

3. Thermal efficiency of a salinity gradient solar pond

The solar energy can be collected and stored by the salinity gradient solar pond as follows, when solar radiation is incident on the solar pond, part of the radiation is reflected away from the top surface while most of the incident sunlight is transmitted down through the top surface of the UCZ. A fraction of the transmitted radiation is rapidly absorbed in the surface layer. However, this absorbed heat is lost to the atmosphere by convection and radiation heat transfer. Some of the remaining radiation is absorbed in the middle NCZ before the rest of the radiation reaches the bottom of the pond. In the LCZ, the absorbed solar energy is converted to heat and stored as sensible heat in the high concentration brine (Valderrama et al., 2016). The efficiency of the solar pond has been defined in different ways, for instance: i) the thermal energy stored in the system relative to the incident radiation up on the pond (Nie et al., 2011; Bozkurt and Karakilcik, 2015; Karakilcik et al., 2006; Dehghan et al., 2013; Erden et al., 2017); or ii) the heat extracted from the system relative to the incident solar radiation (Andrews and Akbarzadeh, 2005; Leblanc et al., 2011). Both methods underestimate the solar energy storage capacity over the months with high solar radiation. Alcaraz et al., (2018) defined a different approach to estimate the thermal efficiency of a solar pond supplying heat to an external system throughout the year:

$$\eta = \frac{\sum_i Q_{stored_i} + \sum_i Q_{extracted_i}}{\sum_i Q_{incident_i}} \quad (1)$$

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, if any, during day i and is estimated according to (Leblanc et al., 2011), and Q_{stored} represents the part of the solar radiation that the system is capable to store in the LCZ along period i. The temperature in the LCZ may decrease in some days, therefore, the system losses its capability to store energy due to unfavorable solar radiation conditions, consequently, Q_{stored} is assumed to be zero. Thus, Q_{stored_i} and $Q_{extracted_i}$ are calculated as follows:

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

(2)

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

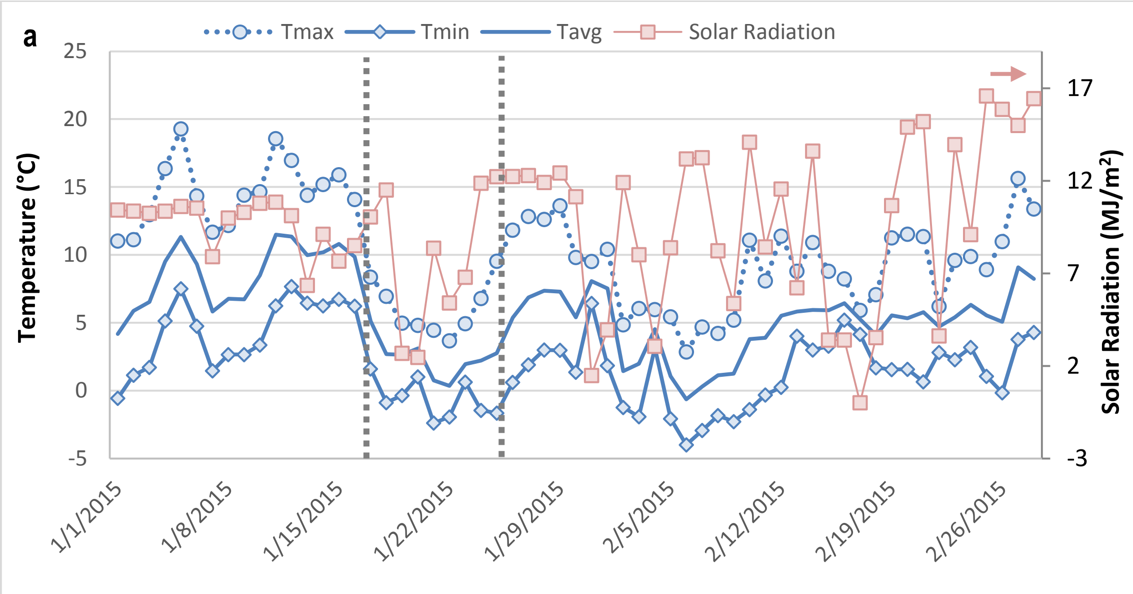
(3)

T_{LCZ} is the temperature measured by the sensors installed in the LCZ, ρ is the density measured by routinely control of the density profile, V_{LCZ} is the volume of the LCZ calculated using ρ and the geometry of the system, $\dot{m}$ is the mass flow rate through the heat exchanger, T_{out} and T_{in} are the outlet and inlet temperatures of the heat exchanger, $time$ is the period of time while heat is extracted from the system and C_p is water heat capacity, calculated considering the density and temperature.

The performance of solar pond need to be analyzed in long-term perspective due to its capacity to provide heat stored throughout year. Alcaraz et al., (2018) proved that efficiencies for short periods are not representative due to the variability of weather conditions from one period to another. However, to analyze the impact of snowfalls on the operation of Granada solar pond, weekly efficiencies have been used in order to compare the performance before, during and after the snowfall. The values obtained cannot be in any case assumed as solar pond overall efficiencies.

4. Results and discussion

During the night of 21/01/2015 a snowfall took place in the facilities of the solar pond of Granada. Low temperatures favoured this unusual phenomenon reaching a minimum temperature of -2.4°C. Figure 2a shows the evolution of average, minimum and maximum air ambient temperatures and incident solar radiation during January and February of 2015.


a
Tmax
Tmin
Tavg
Solar Radiation
Temperature (°C)
25
20
15
10
5
0
-5
Solar Radiation (MJ/m²)
17
12
7
2
-3
1/1/2015
1/8/2015
1/15/2015
1/22/2015
1/29/2015
2/5/2015
2/12/2015
2/19/2015
2/26/2015

1

b

2

3

Figure 2. a) Evolution of the Maximum (Tmax), minimum (Tmin) and average (Tavg) air ambient temperature and incident solar radiation evolution during January and February 2015 and b) photos after the snowfall on 21/01/2015 in the Granada solar pond facilities.

As for the solar radiation an average value of 8.4MJ/m^2 was recorded during the snowfall. Although neither the minimum incident solar radiation nor the minimum temperature were reached the days around snowfall, the combination of both environmental conditions were clearly unfavourable for the operation of the solar pond as can be seen in some photos of the Granada solar pond facilities after the snowfall (Figure 2b). Despite the low temperatures and heavy snowfall, the surface of the pond did not freeze. The thermal gradient before, during and after the snowfall is shown in Figure 3. As was expected, the most affected zone was the UCZ by creating a sub-gradient due to the lower temperatures at the pond surface. Then, one week after the snowfall, the profile of the UCZ recovered its normal pattern with a constant temperature in the layer. The NCZ remains practically at the same temperature for each height regardless of the low temperatures. The storage zone remains almost constant while the air ambient temperature reached values approaching to 0°C. The density gradient was not measured constantly. However, considering the measurements made in January (Figure 3b), it can be seen that there were no significant variations in the density of the NCZ. On January 31st, the surface decreased slightly, but the system was able to recover the initial values only 6 days later.

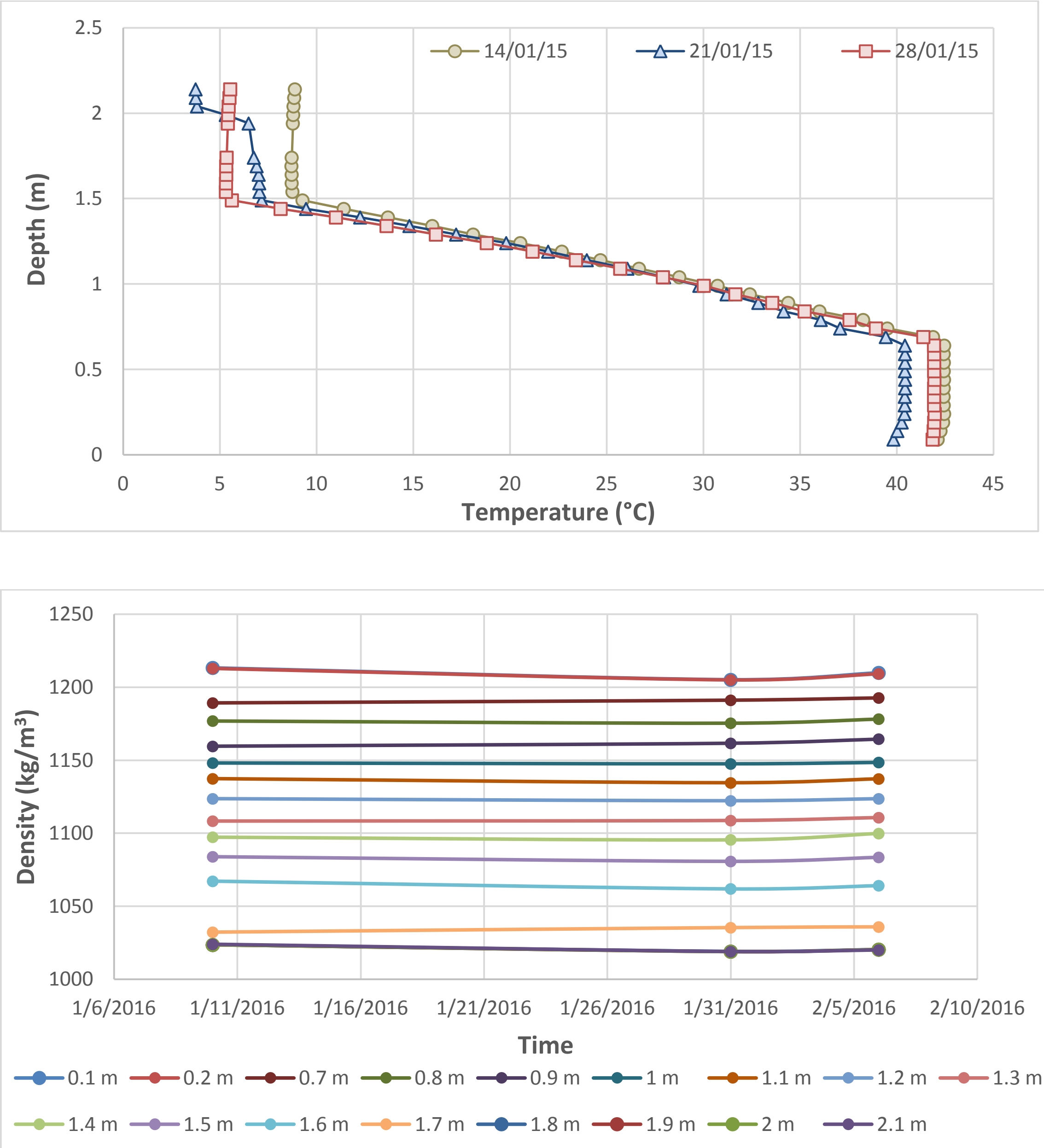


Figure 3. a) Thermal gradient before, during and after the snowfall (15/01/2015) and b) the density gradient evolution in NCZ of the Granada solar pond (January 2015).

Despite the adverse environmental conditions and the heat extracted, the LCZ average temperature was kept around 40 ºC, as can be seen in Figure 4.

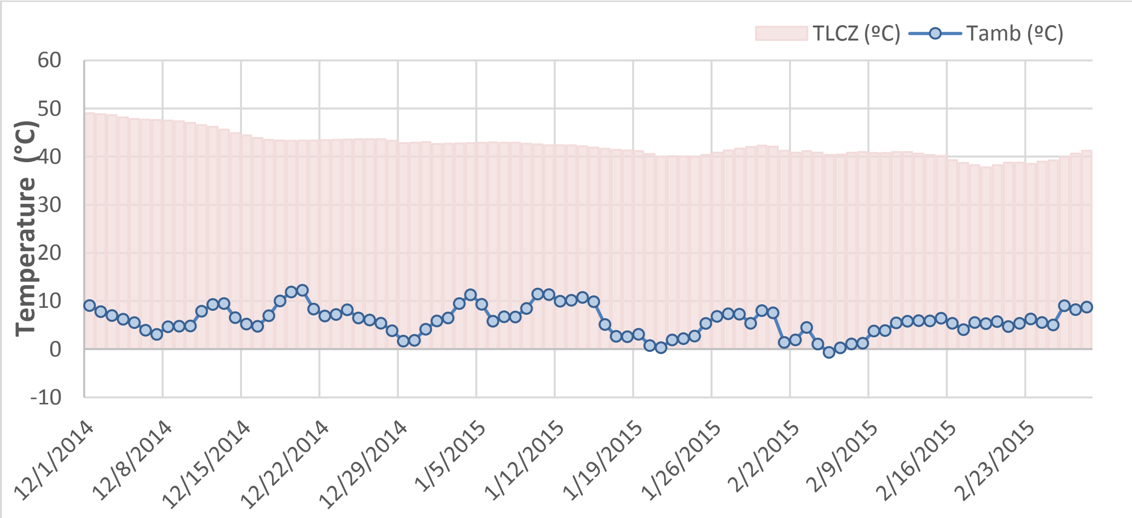


Figure 4. Air ambient and LCZ temperatures during the snowfall (SGSP Granada).

From 1st December 2013 to 28th February 2014, the solar pond was able to provide 10493 MJ of heat to the flotation unit, the amount of heat extracted per day and the evolution of the LCZ average temperature are shown in Figure 5. The amount of heat extracted from the solar pond is quantified using the data measured by the temperature sensors installed in the pond, the inlet and outlet water temperature of the system and the mass flow rate of the working fluid (Eq. 3). The day of the snowfall, the average ambient temperature was 0.3ºC and 12.2 MJ of heat were extracted from the system. The day before, the average ambient temperature was slightly lower, 0.8ºC, and the solar pond was able to provide 235 MJ of heat. From 1st January until the day of the snowfall, 3142.6 MJ were extracted from the system, which added to the unfavourable weather conditions, resulted in a decrease of 2.6ºC in the LCZ average temperature. After the snowfall no heat was extracted from the solar pond during 20 days which allowed an increase of 1 ºC in the average LCZ temperature.

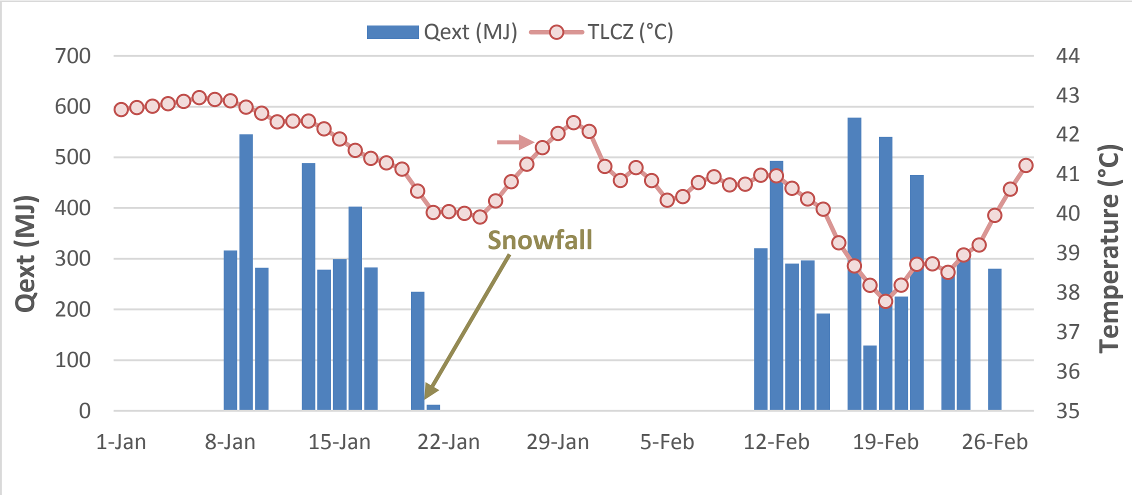


Figure 5. Heat extracted and LCZ average temperature during January and February 2015 (SGSP Granada).

It is worth to mention that the amount of heat extracted depends only on the energy needs in the flotation unit. Finally, the weekly efficiencies, calculated using Eq. 1, of solar pond of Granada are depicted in Figure 6. The minimum weekly efficiency (3.8%) is achieved during the snowfall week. However, despite the adverse environmental conditions, the solar pond was able to provide 247.1 MJ to the flotation unit. The minimum average air ambient temperature was achieved the first week of February (4.6%, efficiency), despite the low temperature the system was able to partially store part of solar radiation in some periods (Figure 5) partially thanks to the fact that not heat extractions were performed from the solar pond.

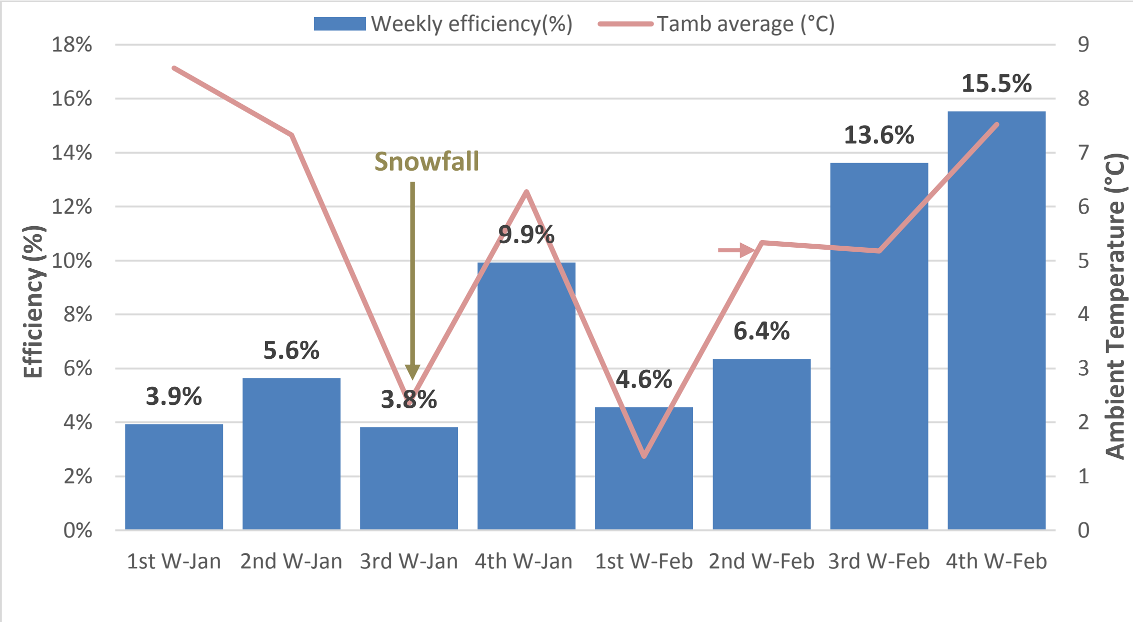


Figure 6. Weekly efficiency and weekly average ambient temperature during January and February 2015 (SGSP Granada).

5. Conclusions

The energy storage capacity of a solar pond can be affected by the weather conditions and the amount of heat extracted. This note analyses the behaviour of the solar pond technology under low temperatures and the performance of the system when it is exposed to a snowfall. The temperature of the storage zone in the Granada solar pond remained constant, which indicates that the system responds 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 by 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 greatest importance in terms of its operation as well as its capacity to supply energy to an external application.

Acknowledgments

The authors gratefully acknowledge personnel from Solvay Minerales and Solvay Martorell facilities for practical assistance, especially to M. Gonzalez, C. Gonzalez, C. Aladjem, J.L. Ochando and M. Giménez for their valuable cooperation. This research was financially supported by the Ministry of Science and Innovation (MICINN, Spain) WASTE2PRODUCT project and the Catalan Government (Project Ref. 2017SGR312).

References

Abdullah, A.A., Fallatah, H.M., Lindsay, K.A., Oreijah, M.M., 2017. Measurements of the performance of the experimental salt-gradient solar pond at Makkah one year after commissioning. Sol. Energy 150, 212–219. doi:10.1016/j.solener.2017.04.040

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

Andrews, J., Akbarzadeh, A., 2005. Enhancing the thermal efficiency of solar ponds by extracting heat from the gradient layer. Sol. Energy 78, 704–716. https://doi.org/10.1016/j.solener.2004.09.012

Bozkurt, I., Karakilcik, M., 2015a. The effect of sunny area ratios on the thermal performance of solar ponds. Energy Convers. Manag. 91, 323–332. https://doi.org/10.1016/j.enconman.2014.12.023

Bozkurt, I., Karakilcik, M., 2015b. Exergy analysis of a solar pond integrated with solar collector. Sol. Energy 112, 282–289. doi:10.1016/j.solener.2014.12.00

Dehghan, A.A., Movahedi, A., Mazidi, M., 2013. Experimental investigation of energy and exergy performance of square and circular solar ponds. Sol. Energy 97, 273–284.

https://doi.org/10.1016/j.solener.2013.08.013

Erden, M., Karakilcik, M., Dincer, I., 2017. Performance investigation of hydrogen production by the flat-plate collectors assisted by a solar pond. Int. J. Hydrogen Energy 42, 2522–2529. https://doi.org/10.1016/j.ijhydene.2016.04.116

Ganguly, S., Jain, R., Date, A., Akbarzadeh, A., 2017. On the addition of heat to solar pond from external sources. Solar Energy 144, 111-116.

Karakilcik, M., Dincer, I., Rosen, M.A., 2006. Performance investigation of a solar pond. Appl. Therm. Eng. 26, 727–735. https://doi.org/10.1016/j.applthermaleng.2005.09.003

Karakilcik, M., Erden, M., Cilogulları, M., Dincer, I., 2018. Investigation of hydrogen production performance of a reactor assisted by a solar pond via photoelectrochemical process. International Journal of Hydrogen Energy 43, 10549-10554.

Khalilian, M., 2017a. Assessment of the overall energy and exergy efficiencies of the salinity gradient solar pond with shading effect. Solar Energy 158, 311-320

Khalilian, M., 2017b. Exergetic performance analysis of a salinity gradient solar pond. Sol. Energy 157, 895–904. https://doi.org/10.1016/j.solener.2017.09.010

Leblanc, J., Akbarzadeh, A., Andrews, J., Lu, H., Golding, P., 2011. Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency. Sol. Energy. https://doi.org/10.1016/j.solener.2010.06.005

Nie, Z., Bu, L., Zheng, M., Huang, W., 2011. Experimental study of natural brine solar ponds in Tibet. Sol. Energy 85, 1537–1542. https://doi.org/10.1016/j.solener.2011.04.011

Njokua, H. O., Agashia, B. E., Onyegegbu, S. O., 2017. A numerical study to predict the energy and exergy performances of a salinity gradient solar pond with thermal extraction. Solar Energy 15, 744-761

Rahaoui, K., Ding, L .C., Tan, L. P., Mediouri, W., Mahmoudi, F., Nakoa, K., Akbarzadeh, A., 2017. Sustainable membrane distillation coupled with solar pond. Energy Procedia 110, 414 – 419.

Sayer, A. H., Monjezi, A. A., Campbell, A. N., 2018. Behaviour of a salinity gradient solar pond during two years and the impact of zonal thickness variation on its performance. Applied Thermal Engineering 130, 1191–1198.

Simic, M., George, J., 2017. Design of a system to monitor and control solar pond: A review. Energy Procedia 110, 322 – 327.

Swift, A.H.P., Reid, R.L., Sewell, M.P., Boegli, W.J., 1987. OPERATIONAL RESULTS FOR A 3355 m**2 SOLAR POND IN EL PASO, TEXAS., in: Solar Engineering. pp. 287–293.

Tabor, H., Weinberger, Z., 1981. Non-Convecting Solar Ponds.

Torkmahalleh, M. A., Askari, M., Gorjinezhad, S., Erog, D., Obaidullah, M., Habib, A. R., Godelek, S., et al., 2017. Key factors impacting performance of a salinity gradient solar pond exposed to Mediterranean climate. Solar Energy 15, 321-329.

Valderrama, C., Luis Cortina, J., Akbarzadeh, A., 2016. Solar Ponds, in: Storing Energy: With Special Reference to Renewable Energy Sources. pp. 273–289. doi:10.1016/B978-0-12-803440-8.00014-2

Zangrando, F., 1980. A simple method to establish salt gradient solar ponds. Sol. Energy 25, 467–470. https://doi.org/10.1016/0038-092X(80)90456-9

Zhang, G., Wu, Z., Cheng, F., Min, Z., Lee, D. J., 2016. Thermophilic digestion of waste-activated sludge coupled with solar pond. Renewable Energy 98,142-147.

Ziapour, B.M., Saadat, M., Palideh, V., Afzal, S., 2017. Power generation enhancement in a salinity-gradient solar pond power plant using thermoelectric generator. Energy Conversion and Management Volume 136, 283-293.