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EXPERIMENTATION OF AN EVAPORATION-CRYSTALLIZATION PROCESS OF SOLAR SALT FROM MEROUANE CHOTT (SOUTH-EAST ALGERIA)

Purpose. To optimize the phenomenon of salt crystallization at Merouane Chott (Algeria) by solar energy using mirror reflection of solar radiation.

Methodology. In this work, experimental studies were carried using test facilities for evaporating brine equipped with a mirror and installed near the Merouane Chott. The test results were compared to the data obtained while applying the same facilities, yet without a mirror.

Findings. According to the test results obtained using test facilities with a mirror, the evaporation rate and the crystallization thickness of the salt are very significant compared to the control pan, probably due to the surface of the reflecting mirror; the time of crystallization of the brine by solar energy is proportional to the dimensioning of the mirrors.

Originality. The study site of the Merouane Chott is located in the region of El Oued (South East of Algeria) which is characterized by an intense solar flux. To benefit from this renewable energy source, a flat mirror was installed to accelerate the salt crystallization process and optimize the residence time of salt brine by natural evaporation.

Practical value. The optimization of the salt crystallization process by solar energy with the use of plane mirrors installed on the salt pans and the presence of a favorable organic environment present sources of sustainable development assets of the salt industry based on its evaporation driven by solar energy, as well as the development of a region rich in fauna, flora and geo-tourism.

Keywords: *Algeria, Merouane Chott, crystallization, experimental studies, mirror, salt, solar energy*

Introduction. Sodium chloride (NaCl) or salt, as it is generally called, occurs in nature either in solid or liquid forms: rock salt and brine. Salt is also found in seawater. Rock salt is extracted from the deposits with classical mining methods by rock cutting either mechanically or by blasting. Spoils are delivered to the processing plant to be subjected to mechanical processing (crushing, sieving, dedusting and others), followed by enrichment, depending on the mineral's designation (e.g. table salt with potassium iodide, road salt with anti-caking agents). Brine is collected either from the places of its natural occurrence or after it is generated by the rock-mass leaching process. Evaporated salt is obtained through brine evaporation. Evaporated salt can be enriched similarly to rock salt. In the case of seawater, salt extraction relies on natural evaporation. The process takes place in special ponds, or salt pans, where seawater is subjected to sunlight. In high temperature, salt crystallizes with evaporation. Regardless of the salt production method, salt can be used for the following purposes:

- edible salt is designed for the food industry and used as condiment for consumption (table salt);
- industrial salt is applied e.g. in power engineering, chemical and paint industries, chemical household products, or electrolysis processes;
- road salt is used for defrosting and winter road maintenance [1].

Algeria has considerable salt potential thanks to very favorable climate conditions for the production of solar salt in chotts or lakes of the North, chotts or lakes of the highlands and high plains and chotts or vast depressions of the Saharan platform. These latter environments (chott, lake and depression) in Algeria have rarely been the subject of detailed studies [2].

The brine represents an important source of mineral salts suitable for domestic and industrial uses. The salts are composed of mainly halite mixed with other impurities such as carbonates, bicarbonates, and sulfates of sodium and potassium, respectively. Thermodynamic calculations based on Pitzer's ion interaction model indicate that the lake brine is under-saturated with respect to the major dissolved mineral salts [3].

Solar energy is an important energy resource for salt precipitation from lake [4]; it is one source of free energy that is inexhaustible in supply and use. Many processes in the mining and mineral processing industry, such as fractional crystallization and leaching lend themselves to solar applications.

This study aims to optimize the crystallization process at the Merouane company to meet consumer demand. To achieve these objectives, our study is conducted on a development of a plane mirror facility which will be used, firstly, to reflect solar radiation on the surface of brine in the salt pans and, secondly, to optimize the crystallization process.

The Merouane Chott is characterized as being from a hyper-arid to arid region, in which exploitation of salt is based on solar energy. The method includes pumping the brine from the chott. The pumped volume decreases substantially with the evaporation; thus, it is necessary to maintain the level of brine in salt pans. After crystallization by solar energy and under effect of winds, the harvest of crystallized layers starts from the month of June. Salt is transported by trucks to the washing station to eliminate harmful residues; the purified salt is stored in camels.

Behavior analysis of hydrogeological, geochemical and mineralogical features of Merouane Chott. Melghair Chott (34° 15′ N, 06° 17′ E) and Merouane Chott (34° 10.63′ N, 6° 17.32′ E) are the largest salt lakes in Algeria. These Chotts are located in the northeast of the northern Sahara and are part of the Melghair chott basin in southeastern Algeria covering large areas of 551 500 to 337 700 ha. The altitude of these Chotts is considered the lowest in northern Africa and in some places is 31 m below sea level. The Melgair and Merouane chotts constitute a vast strip that extends from southern Tunisia to the Atlas Mountains in northern Algeria. The evaporation of the Chott, especially during the dry season, gives rise to salt crystals composed mainly of sodium chloride, which varies from 0 to 10 cm deep, which makes the zone an important salt mineral. Other minerals identified on the surface of Chott include gypsum, calcite, and clays. Due to the combined effect of evaporation and incoming water, the Merouane Chott experiences annual cycles of lake filling and complete evaporation. It is fed by three main water sources, namely, the Oued Righ Canal, which also drains local urban water, groundwater from the terminal complex aquifer and precipitation. The 150 km long canal drains the waters up to Chott Merouane. The total amount of water drained through the Oued Righ Canal was estimated at $131.5 \cdot 10^6$ m^3 during 1994. It is fed by collector water on baths and oases. The annual share of the groundwater supplying the Merouane Chott was estimated at $62 \cdot 10^6$ m^3. During the contribution of precipitation, the supply of the Chott was estimated by the meteorological station of Touggourt to a volume of $4.9 \cdot 106$ m^3 [5].

Further to the water balance assessment study, the calculation of the mass balance and mineralogical identification of Merouane Chott precipitated salts in the geochemical cycle was performed [6]. The results obtained show that the major elements (HCO_3^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}) are stable and retain the same geochemical behavior; the mass balance shows an indigenous enrichment salt production through the years. During complete evaporation of brine waters of Merouane Chott an evaporation sequence of salt-bearing minerals in geochemical cycles rush over the whole surface of Chott, depending on their degree of solubility. According to their mineralogical composition, minerals are rushing in the following order: calcite, sulfides, antraticite, halite, epsomite, blodeite, bichovite and sylvite.

The motivation of our study is the saline systems in Southern Tunisia such us El Jerid Chott, sabkhas El Melah–Zarzis and Oum El Khialate [7]. Geological, hydrogeological and geochemical research showed that these regions contain very significant natural brine reserves. In the case of Oum El Khialate, the total reserves of mirabilite are about 16 million tons. The deposit contains thenardite ($NaSO_4$) and mirabilite ($NaSO_{10}H_2O$). In addition, the results of studying salt lake of Katwe reveal that the raw materials contain substantial amounts of salt, which can be commercialized to enable an optimum production. The brines are highly alkaline and rich in Na^+, K^+, Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^-. Moreover, they contain trace amounts of Mg^{2+}, Ca^{2+}, Br^- and F^-. The lake is hydro-chemical of a carbonate type with the brines showing an intermediate transition between Na–Cl and Na–HCO_3 water types. Also, the evaporation-crystallization is the main mechanism controlling the lake brine chemistry. These evaporites are composed of halite mixed with other salts such as hanksite, burkeite, trona and others, but with a composition that varies considerably within the same grades. The laboratory isothermal extraction experiments indicate that various types of economic salts such as thenardite, anhydrite, mirabilite, burkeite, hanksite, gypsum, trona, halite, nahcolite, soda ash, and thermonatrite exist in the brine of Lake Katwe. In addition, the salts were found to crystallize in the following sequence: sulfates, chlorides, and carbonates [8].

The solar flux of El Oued region and the hydroclimatic parameters. The region of El Oued is characterized by a high level of solar potential. It has an average annual solar flux of 4.85 kWh/m^2 with a total sunshine period of 3900 h/year. Therefore, the winter has less solar potential with average daily solar radiation varying between 3.17 and 3.77 kWh/m^2. In addition, it becomes very important between April and September when the average daily solar radiation varies from 4.93 to 7.54 kWh/m^2 [9].

With a relative humidity ranging from 30 to 65 %, wind regimes are very intermittent with speeds up to 2.5 at 4 m/s, annual rainfall of 0 to 20 mm, evaporation rate going to a minimum in the winter period of 100 mm/month and going to a maximum of 400 mm/month in the summer period, the ambient temperatures ranging from 10 to 35 °C coupled with an insolation of 230 hours/month to 350 hours/month, which is 3900 hours/year. With an average annual solar flux of 4.85 kW h/m^2, the place is hot and dry unlike other equatorial climates which are hot and humid. The chott is at an altitude of –31 m, with an area of 337700 km^2. With a depth of mineralization ranging from 0 to 10 cm [10].

Materials and Methods. Solar energy does not need advanced technology for its use; it is clean rather than polluting, available across the globe, though, obviously with different intensity, sustainable and inexhaustible. In this study, two (02) tests in situ were carried out near the Merouane Chott during the months of May and June 2015. This period was chosen due to the existence of brine in the lake and very stable climatic conditions with clear skies.

Equipment for measuring. Densimeter: The accuracy of measure is ±0.001 g/ml. Weather station (anemometer, hygrometer, and thermometer): The accuracy of the integrated sensor suite of the weather station for measuring each climatic variable was ±6 % for wind speed, ±4 % for relative humidity, and 0.5 °C for ambient temperature.

Test 1: brine pan with a mirror. In situ the tests carried out were programmed for the period from 10/05/2015 to 31/05/2015. Brine pans with size of 1m*1m (a surface of 1 m^2 each) are used; they are made of stainless steel, the pan bottom consists of two layers, the lower layer is in clay and the other is against salt, its external walls of anticorrosive material are covered by the timber to prevent heating by solar radiation (Fig. 1). These test benches are installed near the chott which is filled with brine, its salt concentration is 400 g/l and the brine thickness in pans is 200 mm each. The first pan has a flat mirror with a surface of 30 cm height and 35 cm width that to say 0.12 m^2 (3.3 % of the pan area), the second is the witness pan, the mirror installed captures solar radiation and is reflected towards the surface of the brine. During the test period, sampling measurements of air temperature and evaporation of the brine were taken for two pans.

Test 2: brine pan expansion with mirror surface. During the second test in situ, measures were taken as those of the first test but with an increase in the mirror surface 70 cm*70 that is 0.49 m^2 (the mirror surface represents 49 % of that of the pan). Samples and measurements are made during the period from 25/05/2015 to 12/06/2015.

Solid-liquid equilibrium calculations. According to thermodynamic principles [8], the solubility of a hydrated salt in a concentrated electrolyte solution at a given temperature and pressure can be calculated if the

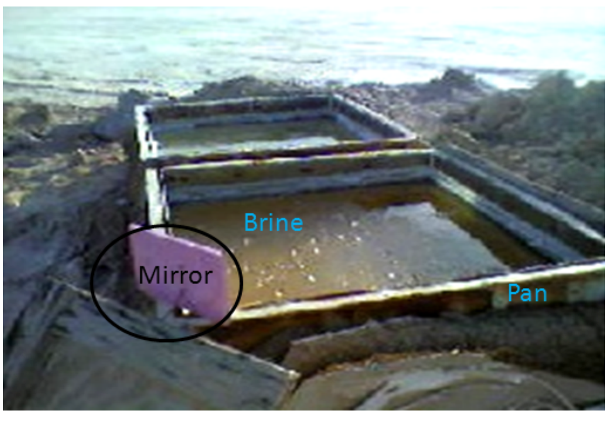

Fig. 1. Photography of two Brine pans

solubility equilibrium constant k_{sp} of the salt is known and if the activity coefficients of the electrolytes can be conveniently obtained. Considering a hydrated salt $Mv_M Xv_X \cdot v_O H_2O(s)$, the equilibrium constant at the definite temperature and pressure for the dissolution reaction is

$$Mv_M Xv_X \cdot v_O H_2O(s) = V_M M^{+ZM} + V_X X^{-ZX} + V_O H_2O. \quad (1)$$

It can be expressed by the following relationship

$$\ln K_{sp} = V_M \ln\left(m_M \gamma_M\right) + V_X \ln\left(m_X \gamma_M\right) + v_O \ln v_O \ln a_{H_2O}, \quad (2)$$

where m_i and γ_i represent the concentration (mol/kg) and the activity coefficient of the hydrated ions in the solution, respectively.

The activity of water is related to the osmotic coefficient φ by the equation

$$\ln a_{H_2O} = -\varphi\left(\frac{M_w}{1000}\right)\sum M_i, \quad (3)$$

where M_w is the molar mass of water with the sum that covers all solute species. The activity coefficients, γ_i and the osmotic coefficients, φ can be calculated using Pitzer's ion-interaction model (Pitzer, 1973; Harvie et al., 1984). Hence, the solubility of any mineral of interest can be determined.

Results and discussion. The influence of temperature during the month of May, generated by the reflection of solar rays on the plane mirror onto the surface of the brine in the pan witch has the daily average of the evaporated water 8.888 mm ±2.541, shows an increase in the evaporation rate of 1.61 mm compared with the witness pan, which also has the daily average of the evaporated water 7.272 mm ±3.149. A similarity between the curves in the period from 15/05/2015 until 17/05/2015 is probably due to the cloudy weather (hidden solar radiation). The amount of water in the brine of the pan with a mirror finishes its evaporation on 27/05/2015; on the contrary, the witness pan continues its evaporation until 31/05/2015.

Formation of a layer of crystallized salt prepared to harvest took about 21 days from 10/05/2015 to 31/06/2015 for brine directly exposed to solar radiation (the witness pan) and 18 days for the brine exposed to rays reflected by the plane mirror resulting in a profit of 4 days, a rate of crystallization optimization process 22 %. The test results are shown in curves (Fig. 2).

Measurements of the second test are performed in the same way as in the first test except for the fact that in this test the surface of the plane mirror is 4 times larger than the surface of the mirror in the first test. This geometric enlargement of the mirror reveals significant results of one part by an evaporation difference of 3.41 mm (Fig. 3) between the evaporation curve of the pan with a mirror, which has the daily average 12.307 mm ±3.544 of the evaporated water, and that of the witness pan, witch also has the daily average 8.888 mm ±2.517 of the evaporated water; on the other hand, the time of the final crystallization of salt took 19 days (25/05/2015 to 10/06/2015) as the total duration of the test; 5 days gained makes an optimization of rate by 38 %. The low-

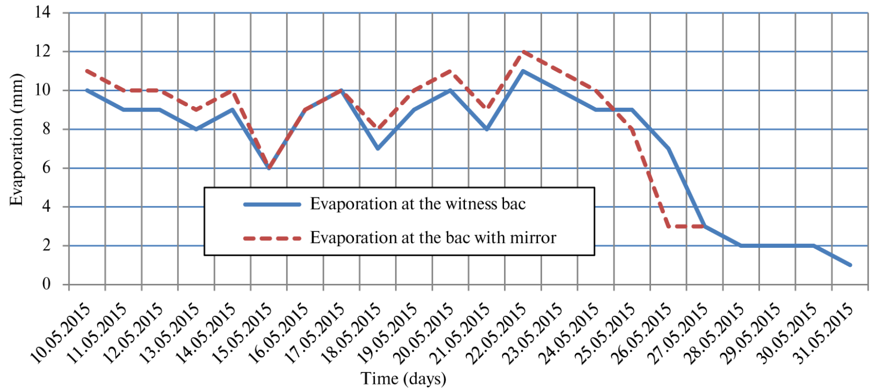

Fig. 2. Influence of the evaporation period (10 May to 31 May, 2015) on the crystallization of brine by solar energy

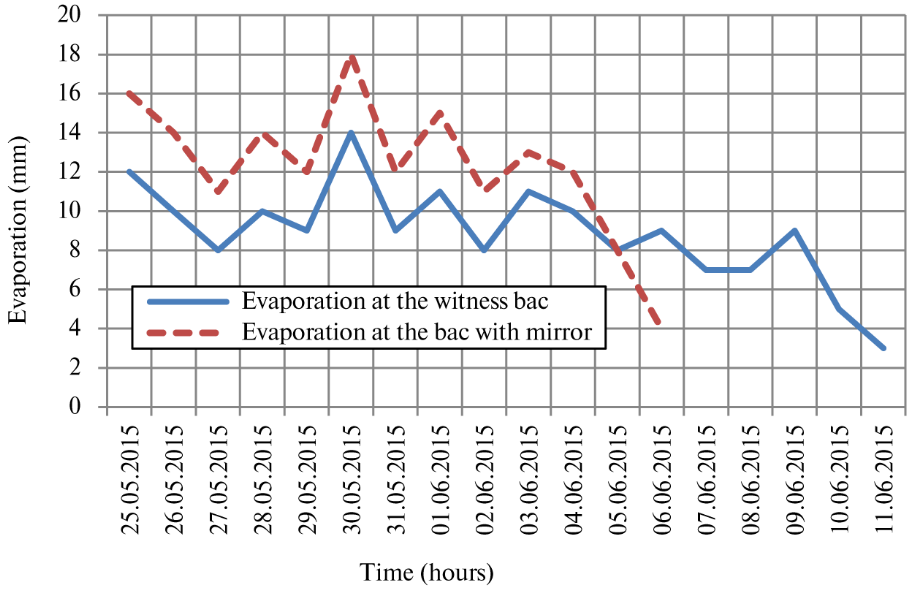

Fig. 3. Effect of the evaporation period (25 May to 10 June, 2015) on the crystallization of the brine by solar energy

Table 1

The hourly monitoring of brine and air temperatures, humidity, and wind speed and meteorological observation

Time (hour)	Brine temperature of the pan with mirror, °C	Brine temperature of the witness pan, °C	Air temperature, °C	Humidity, %	Wind, m/s	Meteorological observation
7 : 00	20	20	30	30	6	Clear sky
8 : 00	23	22	30	41	4	Clear sky
9 : 00	27	24	33	42	2	Clear sky
10 : 00	30	27	37	29	5	Clear sky
11 : 00	32	29	38	31	1	Clear sky
12 : 00	33	31	40	30	2	Clear sky
13 : 00	34	32	43	32	3	Clear sky
14 : 00	36	34	42	33	2	Clear sky
15 : 00	36	34	42	30	2	Clear sky
16 : 00	36	34	42	29	2	Clear sky
17 : 00	35	33	41	32	7	Clear sky
18 : 00	33	31	40	29	4	Clear sky

er curves for the two tests to the lowest values of 2 to 1 mm is due to the evaporation rate which regresses as it approaches the final crystallization of the salt [7]. According to the study, the average evaporation flux from the traditional system [4] is about 0.02 kg/m^2-hr while that of the enhanced system is about 1.68 kg/m^2-hr, corresponding to a brine temperature increment from 30 to 50 °C. The results show that the evaporation of the brine is increased with the implementation of parabolic solar concentrator as compared to the natural process. The increment in the evaporation flux implies a decrease in the number of days for the crystallization process thus improving the productivity.

In the second test, during the day of 29/05/2015, we conducted measurements of meteorological parameters every hour from 07 : 00 am to 18 : 00 pm; the results are shown in Table 1. With a maximum humidity of 42 % and an average wind speed of 3.33 m/s (Fig. 4), it turns out that this day represents a favorable climate for evaporation. Temperatures of the brine pan with a mirror and that of the witness pan reveal a gap with an average of 2 °C, this increase is caused by the influence of the solar radiation that the flat mirror reflects towards the surface of brine, this elevation is according to an increase in the air temperature.

Conclusion. Near the Merouane Chott, preliminary tests are carried out in May and June on brine pans with and without a mirror (witness pan) and show promising results in time of crystallization of the brine by solar energy. The geochemical evolution of evaporating chott

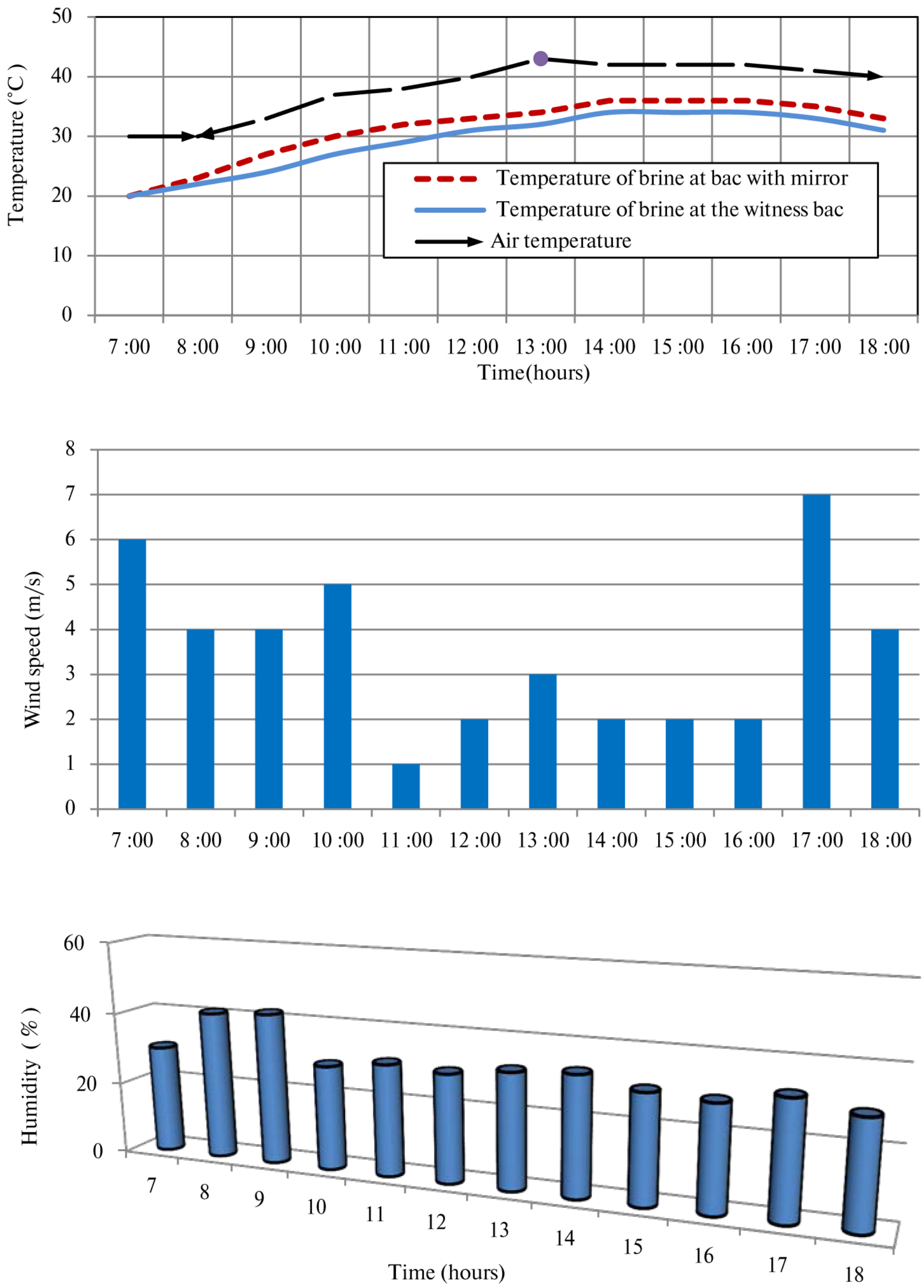

Fig. 4. Effect of climate conditions (temperature, wind speed and air humidity) on the crystallization of brine by solar energy

systems is directly related to the climatological parameters, especially the evaporation, relative humidity, air temperature and wind speed.

The ENASEL Company has eleven salt pans of 250 m width and 275 m in length or an area of 68 750 m^2 each, the mirror surface used in the second test is 49 % of the pan surface. To apply the idea of this work, to accelerate the crystallization process in situ, it is, therefore, necessary to develop a system of plane mirrors reflecting solar radiation to a total area of 30.937 m^2, which is difficult to achieve on an industrial scale. For this reason, research studies will be done later always based on the optimization of the crystallization process of the salt by the solar energy in order to achieve the realization on the ground.

The variations of chemical elements in the brine during the lifetime of Merouane chott are fairly good due to a salt quality; however, thanks to the mirror reflection during the selected months of the solar radiation towards the evaporating surface of brine in the salting table rich in Halite and low in undesirable salts especially the Mg, we were able to obtain a good quality of salt. Also, it gave us an early crystallization of the layer of salt; on the one hand, the latter represents a favorable climate for the harvest (a layer of soft salt for the harvesters); on the other hand, there is a possibility to multiply production by a different operation (from pumping to harvesting).

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Експериментальне дослідження процесу випаровування-кристалізації солі із Шотт Меруан (Південно-Східний Алжир)

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Мета. Оптимізувати явище кристалізації солей у Шотт Меруан (Алжир) сонячною енергією за допомогою дзеркального відбивання сонячної радіації.

Методика. У даній роботі були проведені експериментальні дослідження з використанням випробувальних установок для випаровування розсолу солі, оснащених дзеркалом і встановлених недалеко від Шотт Меруан. Результати тестування порівнювалися з даними, отриманими при використанні таких самих установок, але без дзеркала.

Результати. Згідно з результатами тестування, отриманим за допомогою випробувальних установок із дзеркалом, швидкість випаровування й товщина шару кристалізованої солі значні в порівнянні з контрольною ємністю, ймовірно, завдяки поверхні дзеркала, що відбиває; час кристалізації розсолу за рахунок сонячної енергії пропорційний розмірам дзеркал.

Наукова новизна. Дослідницький центр Шотт Меруан розташований в області Ель Уед (Південно-Східний Алжир), що характеризується інтенсивним потоком сонячної енергії. Щоб використовувати переваги даного джерела поновлюваної енергії, було встановлено пласке дзеркало, що прискорює процес кристалізації солі та оптимізує час випаровування розчину солі природним шляхом.

Практична значимість. Оптимізація процесу кристалізації солі за рахунок сонячної енергії із застосуванням пласких дзеркал, встановлених на сольових піддонах, і наявність сприятливого органічного середовища являють собою джерела стійкого екологобезпечного розвитку промисловості отримання солі, заснованої на випаровуванні її під сонцем, а також розвиток регіону з багатою фауною, флорою та геотуризмом.

Ключові слова: *Алжир, Шотт Меруан, кристалізація, експериментальні дослідження, дзеркало, сіль, сонячна енергія*

Экспериментальное исследование процесса испарения-кристаллизации соли из Шотт Меруан (Юго-Восточный Алжир)

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Цель. Оптимизировать явление кристаллизации солей в Шотт Меруан (Алжир) солнечной энергией с помощью зеркального отражения солнечной радиации.

Методика. В данной работе были проведены экспериментальные исследования с использованием испытательных установок для выпаривания рассола соли, оснащенных зеркалом и установленных недалеко от Шотт Меруан. Результаты тестирования сравнивались с данными, полученными при использовании таких же установок, но без зеркала.

Результаты. Согласно результатам тестирования, полученным с помощью испытательных установок с зеркалом, скорость испарения и толщина слоя кристаллизованной соли значительны по сравнению с контрольной емкостью, вероятно, благодаря поверхности отражающего зеркала; время кристаллизации рассола за счет солнечной энергии пропорционально размерам зеркал.

Научная новизна. Исследовательский центр Шотт Меруан расположен в области Эль Уэд (Юго-Восточный Алжир), характеризующейся интенсивным потоком солнечной энергии. Чтобы использовать преимущество данного источника возобновляемой энергии, было установлено плоское зеркало, ускоряющее процесс кристаллизации соли и оптимизирующее время испарения раствора соли естественным путем.

Практическая значимость. Оптимизация процесса кристаллизации соли за счет солнечной энергии с применением плоских зеркал, установленных на солевых поддонах, и наличие благоприятной органической среды представляют собой источники устойчивого экологобезопасного развития промышленности получения соли, основанной на выпаривании ее под солнцем, а также развитие региона с богатой фауной, флорой и геотуризмом.

Ключевые слова: *Алжир, Шотт Меруан, кристаллизация, экспериментальные исследования, зеркало, соль, солнечная энергия*

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