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Design and experimental study of systems for the regeneration of aqueous $CaCl_2$ solutions using solar energy

Diseño y estudio experimental de sistemas de regeneración de soluciones acuosas de $CaCl_2$ mediante energía solar

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Abstract

Desiccants are capable of extracting or releasing water vapor from the air, in relatively large quantities. It is important from the economic point of view the recovery by thermal regeneration of these desiccants. Therefore, the development of a technique for the regeneration of this type of substance is of technical and economic interest. For this reason, in the present work, two equipments for the regeneration of calcium chloride in aqueous solutions were designed, built and experimented with, one with a flat surface and the other with a stepped surface assisted by solar energy as a heating medium. This process was monitored through various temperature and humidity sensors to know the operating conditions inside the regenerators, as well as the environmental conditions throughout the experiments through a climatic and solarimetric station. During the study it was observed that the materials and dimensioning of both equipment are adequate. When comparing the temperatures and amount of water evaporated during the test period, a better performance was obtained in the regenerator with an inclined plane, than in the stepped type, which was corroborated by evaluating the relative density of the solutions.

Aqueous desiccant, Variable monitoring, Regeneration

Resumen

Los desecantes son capaces de extraer o liberar vapor de agua del aire, en cantidades relativamente grandes. Es importante desde el punto de vista económico la recuperación por regeneración térmica de estos desecantes. Por lo anterior, el desarrollo de una técnica para la regeneración de este tipo de sustancias resulta de interés técnico y económico. Por ello, en el presente trabajo se diseñaron, construyeron y se experimentó con dos equipos para la regeneración de cloruro de calcio en soluciones acuosas, uno de superficie plana y otro escalonado asistidos por energía solar como medio de calentamiento. Este proceso fue monitoreado mediante diversos sensores de temperatura y humedad para conocer las condiciones de operación dentro de los regeneradores, así como las condiciones ambientales a lo largo de los experimentos mediante una estación climática y solarimétrica. Durante el estudio se pudo observar que los materiales y el dimensionamiento de ambos equipos son adecuados. Al comparar las temperaturas y cantidad de agua evaporada durante el periodo de pruebas se obtuvo un mejor desempeño en el regenerador con plano inclinado, que en el tipo escalonado, lo cual se corroboró mediante la evaluación de la densidad relativa de las soluciones.

Desecante acuoso, Monitoreo de variables, Regeneración

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Introduction

In the last decades, in the field of air conditioning of spaces, the industrial sector has focused on the control of environmental humidity, this due to the repercussions that it has on the industrial processes of pharmaceuticals, food drying, among others, and air conditioning. of spaces, such as hotels, houses and shopping malls. This has caused a growing demand for air conditioning equipment which in turn generates a greater demand for primary energy resources.

The air conditioning equipment operates under heat transfer mechanisms, carrying out operations of evaporation and condensation of water from the ambient air, in such a way that they can control the temperature, air quality and humidity in closed environments.

This is how the need to partially or totally eliminate water vapor from the air (a process called dehumidification) is created, in order to achieve optimal operating conditions. Currently there are several methods for dehumidification, among which are mainly dehumidification by cooling and dehumidification using desiccants. The first method consists of bringing humid air below its dew point temperature, which causes condensation of water in the air, simultaneously obtaining cooling and dehumidification. The second method is based on the use of absorbent or adsorbent desiccant materials in solid and liquid state (absorbents and adsorbents), which retain a certain amount when they come into contact with water vapor, increasing their temperature due to the heat of dissolution. Currently, there are several systems that operate with this method (desiccant dehumidification). Which have great potential for improvement in the dehumidification process, since under the right conditions they could increase the speed and facilitate the process of moisture retention.

Within the absorbers and adsorbers used for these processes, silica, alumina, zeolites, activated carbon, etc. are used as solid materials, and for liquid absorbents, solutions of inorganic salts are used, such as LiCl and $CaCl_2$, among others. These desiccants can be regenerated through conductive and/or convective and radiative heating processes derived from conventional energy sources (electrical and from fossil fuels) and renewable energies such as solar energy, geothermal energy and biomass.

In recent years, several techniques have emerged where solid and liquid salts are regenerated using conductive and convective heating, both for conventional heating systems and for systems that operate with renewable energies, however, it is unknown if the solar energy available in the Central- Northern Mexico is sufficient to carry out regeneration processes of hygroscopic salts in a liquid state with the climatic conditions of the state of Zacatecas.

At present, a large part of the industrial processes such as the manufacture of medicines, pharmaceuticals, the treatment and preservation of wood, textiles, the storage of post-harvest products and the drying of food depend on environmental conditions, mainly on temperatura and environmental humidity, whose high values favor the generation of molds, the decomposition of products, the corrosion of metals or simply achieving an undesirable climatic environment [I].

Mexico is a country with a wide diversity of climatic conditions with areas where the weather varies throughout the year. This highly changing environment generates environments with high humidity contents in most of the country, especially in the April-August season, which makes it difficult to control the conditions in the processes. Figure 1 shows two maps of the national territory that show: a) the annual maximum relative humidity and b) the maximum relative humidity values for the month of July [II].

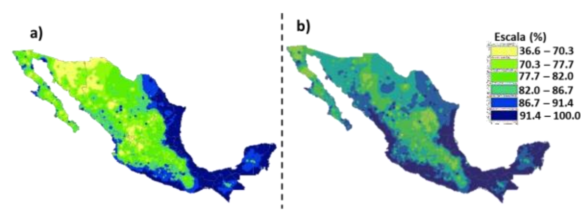

Figure 1 Relative humidity: a) annual average 2018, b) maximum month of July 2018

Therefore, it is important to achieve air conditioning in the processes to facilitate and optimize the processes by reducing the moisture content and controlling the temperature. There are air conditioning systems that cover these needs, such as mechanical vapor compression (SCV) systems that, according to research carried out by the International Institute of Refrigeration in Paris, present a problem due to their high energy consumption.

According to this study, the proportion of energy used by air conditioning systems in homes and buildings represents almost 45% of the electricity consumption in this sector, which represents almost 15% of the total energy consumption in the world [III]. In addition, in developing countries, refrigerants with a high environmental impact such as chlorofluorocarbons (CFCs) are still used, which deplete the ozone layer and equipment that generates large amounts of CO_2, being a problem for the environment [V]. Hence, the need arises to look for new alternatives to satisfy the air conditioning conditions and reduce the environmental impact due to the high electrical consumption of the equipment. As well as new alternatives to recycle and regenerate the chemical substances involved in said air conditioning equipment.

Kyshore et al (2013), conducted an experimental analysis of a hybrid liquid desiccant dehumidifier system. Air dehumidification is performed in a randomly packed packed column in which air and desiccant solution flow countercurrently to exchange heat and moisture and after heating and mass transfer is circulated through the regenerator where it is reconcentrated. The desiccant chosen for the analysis is aqueous calcium chloride solution [VI].

Seenivasan et al. (2018), studied the effects of input parameters on the performance of liquid desiccant dehumidifiers with and without an indirect evaporative cooler or intercooler (IDEC) between one and two stage dehumidifier. They conclude that the double stage desiccant dehumidifier with indirect evaporative cooler has a better performance [VII].

Cho et al. (2019), found that in a liquid desiccant desiccant desiccant, the direction of airflow to the solution plays an important role in desiccant performance and the physical size of the desiccant tower. The assertion was with the results when using the liquid desiccant in counterflow and crossflow. They concluded that the crossflow liquid desiccant dehumidifier would provide relatively stable dehumidification performance, regardless of changes in operating parameters [VIII].

Chen et al (2020), in their article, present a bibliographic review of air conditioning and dehumidification systems using liquid desiccants. In addition, they present various types of dehumidifiers and their integration with the liquid desiccant dehumidification system. They have also grouped and compared the combination of liquid desiccant dehumidification system with solar collector, vapor compression systems, heat pump systems, CHP systems, etc. [IX].

Bhowmik (2021), proposed a hybrid method by combining solar evacuated tube collectors as a regeneration source to drive the liquid desiccant system in a closed loop. They made the overall energy balance between the ambient air and the liquid desiccant. Similarly, they analyzed the effects of independent parameters on the performance parameters of the dehumidifier-regenerator. In addition, they developed Adaptive Neurofuzzy Inference System (ANFIS) prediction models to predict system performance based on system-independent parameters. The model results exhibited good agreement with the experimental results [X].

Sarukasan et al. (2022), carried out a theoretical-experimental analysis of $CaCl_2$ regeneration using solar energy. The dehumidifier used was a vertical film connected to a flat collector. Among their results, they verified that the regeneration performance increases as the temperature of the solution increases, the massive evaporation increases by 50%. Since solar energy is used, the total energy of the system is reduced and the emissions are also reduced [XI].

Passamani et al. (2023), used concentrated $CaCl_2$ solutions for the dehumidification of humid air. The work carried out was in order to acquire the necessary experience for the design of systems of this type, they built an experimental prototype lighting artificially, in order to collect information on the parameters that define the evaporation process and obtain experience on construction details and materials to use [IV].

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Gado et al. (2023), comprehensively present the operating principles of atmospheric water collection technology. Subsequently, they carry out a detailed evaluation of state-of-the-art sorption materials, such as activated carbon fiber, zeolite, silica gel, organometallic structures, calcium chloride with various host materials and hydrogels, where their isotherms and adsorption kinetics are examined. They also summarize and classify numerous solar-powered atmospheric water collector designs, including fixed and mobile installations. They demonstrated the viability of these systems is also demonstrated in different weather conditions. Finally, the obstacles and limitations that hinder its use and future research directions are explored [XIII].

Kumar et al (2023), their study offers an overview of the advances associated with the incorporation of liquid desiccant technologies in VCS units to date. Various dehumidifier configurations and hybrid technology. This review article is beneficial. to researchers as it identifies research gaps and explores prospective future research techniques to further improve the performance of hybrid vapor compression-liquid desiccant systems [XIV].

Shah et al. (2023), evaluated the advantages of providing internal cooling and the effect of LD concentration, as well as environmental conditions. They proposed two new efficiencies, one based on ambient wet bulb temperature and the other on LD crystallization temperature to give due credit to the higher moisture removal potential available in the internally cooled dehumidifier. At 40% LD concentration, dehumidifier effectiveness at wet bulb temperature was 67% for the adiabatic dehumidifier, but could be increased to 95% using an internally cooled dehumidifier [XV].

Xie et al. (2023), comprehensively reviewed and compared the state of the research on several different adsorbents, such as zeolite, silica gel, and organometallic structures. They conducted in-depth research on the synthesis processes, characterization, and adsorption characteristics of various adsorption composite materials. The purpose of this study was to provide a reference for researchers engaged in the development of new adsorption materials in various applications and conditions [XVI].

Methodology

The current design methodology in terms of spatial dimensions of the equipment was raised based on a bibliographic review, in addition, parameters such as environmental conditions and properties of the chemical substances involved such as corrosivity, density and solubility were taken into account.

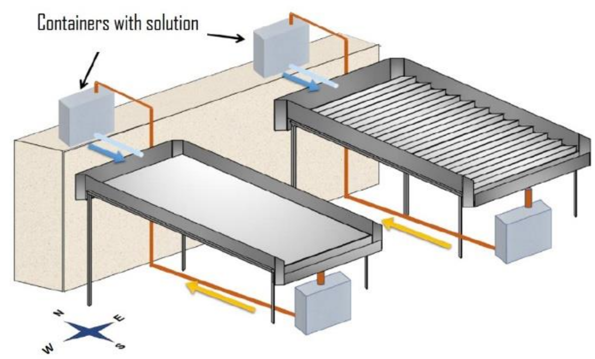

Figure 2 Equipment assembly diagram

For the climatic parameters of the place of installation, the climatological database registered by the UNAM was used as: "Database are Meteorological Information (Irradiation, Ambient Temperature, Relative Humidity and Wind Speed) for all the populations of Mexico of more than of 10,000 inhabitants registered in 2011", with registration number 03-2012-112811530700-01. Obtained with the FORDECYT 190603 project. And to the Zacatecas_04 Solarimetric Station of the National Solarimetry System located in the E6 building of the Siglo XXI campus at the Autonomous University of Zacatecas (Latitude: 22.77 ° N, Longitude: 102.64 ° W, Height: 2,440 snm) Figure 3, from which the historical data recorded in this area were obtained and processed, which are reported in Table 1. And based on which it was decided to carry out experimentation in the third quarter of the year since historically it is where the most suitable conditions for the operation of the regeneration systems are recorded.

Month	T_a (°C)	$T_{mín}$ (°C)	$T_{máx}$ (°C)	HR (%)	V_{air} (m/s)	Radiation (MJ/m^2 day)
January	11.1	4.8	17.3	52.9	4.33	15.35
February	12.2	5.5	19.0	45.5	4.36	18.46
March	14.6	7.5	21.7	33.8	4.51	21.52
April	16.8	9.7	23.8	32.6	4.16	22.57
May	19.1	12.0	26.2	38.1	3.44	24.03
June	19.0	12.5	25.4	62.3	2.78	22.30
July	17.2	11.5	23.0	71.6	2.77	21.52
August	17.2	11.5	23.0	69.7	2.54	21.16
September	16.8	11.2	22.3	72.8	3.12	18.23
October	15.7	9.6	21.8	69.0	3.42	16.84
November	13.9	7.4	20.4	63.4	3.86	16.93
December	11.9	5.8	18.1	56.5	4.08	14.16

Table 1 Averaged historical climatological data for Zacatecas

Figure 3 Zacatecas_04 Solarimetric Station of the National Solarimetry System

Results

Preliminary tests were carried out to know the behavior of the solutions, the regeneration equipment and the monitoring during the dehumidification process. The qualitative results that were found were used to improve the previously established methodology. The aspects analyzed correspond to the flow velocity in the solution, the orientation of the equipment and its elevation angle with respect to the sun, the monitoring data recording intervals, as well as the optimal intervals for the recirculation of the solutions.

Regarding the flow of the solution, it started with low values between 0.5-0.75 l/min, observing the formation of canals in certain areas in the regeneration equipment, which indicates a waste of the available heat exchange area of the equipment.

In flows equal to or greater than 2 liters/min, low and insufficient temperature increases in the solution were observed due to the short residence time of the solution in the equipment. In addition, it was necessary to recirculate the solution many times.

The results indicated the need to operate the generators in a flow domain between 0.8 and 1.8 l/min to reduce the effect of the canalizations, a more adequate recirculation and have a better use of the available area.

In addition, a test was carried out in the staggered equipment with an inlet flow of 1.0 l/min, where different inclinations were tested with 5° increments with respect to the floor starting at 23°, this to determine the influence of the inclination with respect to the increase in temperature by the angle in which the equipment receives solar radiation, in addition to determining the variation of the velocity of the fluid throughout the equipment, from which it was observed that inclinations greater than 45° contact time of the solution with the plate which is reflected in low temperature increases. It was possible to verify that the optimal range of inclination is from 23° to 38° of inclination, which depends on the solar declination, that is, on the day of the test. During this test the recording intervals on the loggers were set to 0.5 seconds for the arduino. Regarding recirculation, in order to protect the equipment from damage due to an operation without flow, it was decided to recirculate the solutions until all the solution had circulated through the regeneration equipment. Regeneration of salts and calculations of solar and thermal energy used

For the first regeneration test, 50 liters of solution were prepared with $CaCl_2$ whose mass fraction was 0.20. The solution was distributed in two 25-liter drums and was taken to the experimental site after evaluating its properties (temperature, relative density, and weight and volume). Prior to the regeneration test, the solar declination and solar noon were calculated and the equipment was tilted at the appropriate angle and operated with a flow of 1.2 l/min. Measurements began and every minute was monitored with the help of sensors and arduino.

According to the data obtained by processing the information from the data collectors, the environmental temperature was plotted, the temperatures of the saline solution as a function of time both in the overflow and at the end at the end of the equipment and the profiles of the temperature increases in the solution for the flat type equipment and the stepped one (Figure 4).

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The temperatures reached by the solution at the beginning and end of its passage through the equipment throughout the regeneration test, in addition to the solar radiation received. The solution that reached the highest temperature is the one treated in the inclined plane equipment, with a value of up to 52.12 °C registered at 1:50 p.m., in contrast to the solution treated by the stepped equipment, the maximum temperature was 40.47 °C registered at 13:46 civil time.

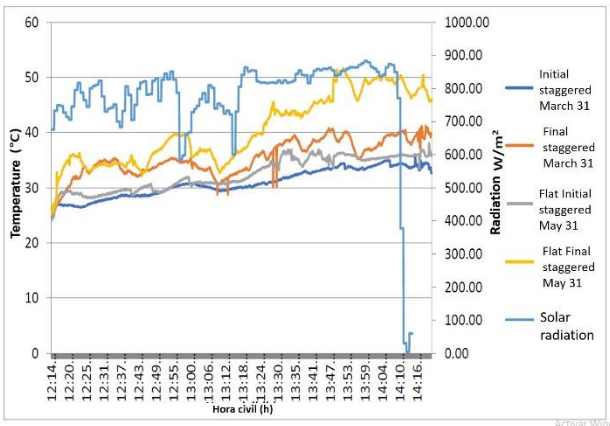

Figure 4 Temperature increase in $CaCl_2$ regeneration equipment

Regarding the amount of water removed, the relative density at the beginning and that obtained at the end of the test was recorded.

For the determination of the change of the concentration of the solutions, the mass fraction of $CaCl_2$ in the solutions was calculated.

The solute-solvent ratio was 0.28 and considering that the loss of mass is due solely to the loss of H_2O in the solution, the volume of water at the end of the experimentation is calculated, which for both teams in the test represents a loss of 0.37 liters of water.

The data obtained from the regeneration of the salt are presented in the Table 2, where they are expressed as a function of the initial and final relative density of $CaCl_2$-H2O at room temperature (22-25 °C), where the masses of water are presented removed for each case. Of which a superior performance is observed by the "Flat Team" achieving water losses of up to 2.5 liters and in contrast to the "Staggered Team" a loss of 2 liters was obtained.

Equipment Configuration	Test date	Relative density Start	After regeneration	Water mass (kg) Initial	Final	Lost
Staggered	31 May	1.18	1.19	20	19.63	0.37
	3 June	1.18	1.21	20	19.3	0.6
	6 June	1.175	1.275	20	17.96	2.04
	7 June	1.175	1.27	20	18.6	1.4
	15 August	1.18	1.26	20	18.93	1.07
Flat	31 May	1.18	1.19	20	19.6	0.4
	3 June	1.18	1.27	20	18.6	1.4
	6 June	1.175	1.29	20	17.35	2.56
	7 June	1.175	1.28	20	17.6	2.4
	15 August	1.18	1.265	20	18.8	1.2

Table 2 Regeneration data table

Regarding the temperature of the solution, it is observed that the temperature was up to 72 °C, which supports the salt regeneration data.

Although the global energy data received by the equipment gives a coherent relationship between the temperature, the regeneration of the saline solution and the solar radiation in the environment of the equipment, that is, there is a greater regeneration of salt when they are registered, higher temperatures and higher solar radiation, we have to take into account that this energy is not 100% used by the equipment. However, an estimate of energy use can be made from the volume of water evaporated by the regenerators.

For this, it is necessary to know the sensible and latent heats of the solution and from them, obtain the total energy necessary. There was a greater use of energy from the flat equipment. This can be attributed to the geometry of the equipment, where the stepped equipment makes less use of solar energy, due to the fact that the temperature on the plate is not homogeneous in the height and width of its steps.

The energy required by the average Flat and Stepped Equipment was 161.41 and 149.61 kJ respectively. For the process to be viable, the values must be greater than the energy required by the fluid recirculation pumps and thus be able to have a positive saved energy balance. For this, the electrical consumption was measured in each recirculation cycle during the tests with a multimeter according to the methodology suggested by Venables M. [XIII]. According to the results obtained, it was found that 7.2% of the solar energy used for the staggered equipment and 5.4% for the Flat Equipment. This shows a positive balance in energy saved for the regeneration of salts.

Conclusions

The inclined plane type regenerator performed better than the stepped equipment, achieving solution temperatures of up to 72 °C in contrast to the stepped equipment whose maximum temperature was 58 °C.

The design of both equipments turned out to be adequate since it was shown to be able to regenerate $CaCl_2$ solutions.

The design and implementation of a monitoring system for climatic and physical conditions of fluids with low-cost and accessible sensors was achieved.

The regeneration of aqueous $CaCl_2$ solutions was achieved, reaching values in the mass fraction of the salt of 0.25.

The performance of the staggered equipment did not meet expectations, despite having a longer residence time of the solution in the equipment, the temperatures reached by the latter were lower than those of the flat equipment.

The configuration of the staggered equipment avoids having a homogeneous temperature on the plate due to the angle of incidence of solar radiation.

The use of solar energy by the equipment in the regeneration of salts denotes the achievement in the implementation of renewable energy in the evaporation of chemical solutions.

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