SOLAR-DRIVEN LIQUID-DESICCANT DEHUMIDIFIER/REGENERATOR FOR DRYING AGRICULTURAL PRODUCTS

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Abstract

Drying of agricultural products is essential for preserving product quality and achieving a long storage life and it is directed to wide range of products such as herbal plants, seeds, fruits, vegetables, forage, hay etc. Drying of agricultural products consumes significant amounts of energy usually by burning diesel or gas. An alternative drying technique is being developed to reduce energy, cost and improve product quality by replacing fossil fuel energy with a liquid desiccant absorber and solar-driven regenerator. It operates by drying with only a small increase in air temperature and a substantial reduction in the drying air relative humidity.

A plate type heat and mass exchanger has been built and tested in a pilot plant stage as an air dehumidifier and desiccant regenerator. The results were analyzed and compared with a numerical model for validation. The results of the supply air adiabatic dehumidification show a consistent reduction in the relative humidity and an increase in the air temperature, which are the main factors that affect how readily moisture moves from the drying product. The parametric analysis results in reduction of the air relative humidity in the range of 18-46% points and an increase in the air temperature in the range of 3.7-8.0 K are observed, depending on the inlet parameters. The concentration of the diluted desiccant solution (from 38% to 43%) was done possible by using hot water of 55 ºC, which is an optimal temperature for solar thermal collectors.

Keywords: desiccant, hay, humidification, regeneration

1. Introduction

Crop drying is the most energy consuming process in all processes on the farm [1]. The purpose of drying is to remove moisture from the agricultural produce so that it can be processed and/or safely stored for increased periods of time. Hot air drying increases the temperature of the air (and product) and lowers the air relative humidity (RH) and thus allows the air to carry moisture from the product. Forced air ensures continuous supply of air to replace saturated air. Although this is adequate in relatively dry and less humid weather, it is not possible to reduce the actual moisture level (absolute humidity) in the air in humid climates.

Most driers operate by heating ambient air using diesel or gas burners. Ambient air (without heating) driers use less energy compared with hot air driers; but they are known to cause damage to seeds (and grain) due to prolonged exposure to humid air. Solar drying has many advantages over the previous methods; but relies heavily on weather conditions, Figure 1 (left) shows the current hay drier that is completely driven by fusel fuel and it will be improved with desiccant drier in the demonstration plant stage.

Desiccant dehumidification was initially investigated for use in air-conditioning in order to reduce energy consumption and improve efficiency of vapour-compression systems. The advancements made in desiccant technology led to its expansion into other fields such as crop protection and drying [2].

Air dehumidification in liquid desiccant systems remove the moisture directly from the air by absorbing the moisture by a strong solution of liquid desiccant e.g. lithium chloride (LiCl), calcium chloride ($CaCl_2$). The main components of an open-loop liquid desiccant air-conditioning system are the absorber (dehumidifier) and the desorber (regenerator) shown in Figure 1 (right).

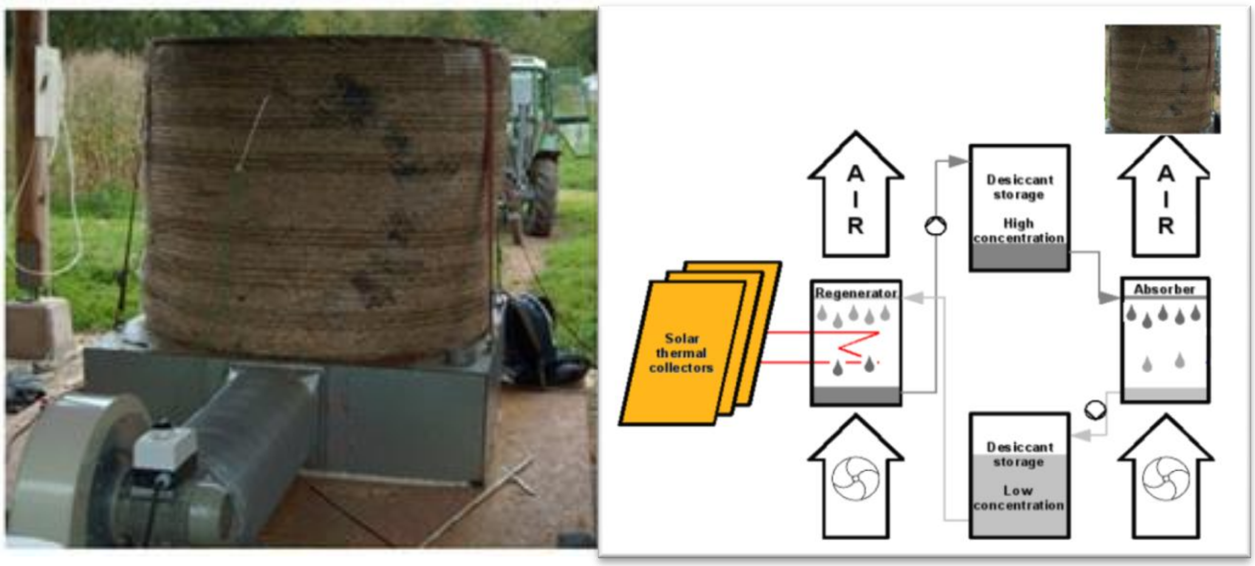

Fig. 1. Hay drier, future demonstration plant (left), Schematic diagram of a solar driven liquid desiccant drier (right)

In the absorber, moisture absorbed from the process air stream dilutes the desiccant solution by loading the desiccant with water vapour. The solution weakened by absorption of moisture is reconcentrated in the regenerator, where it is heated to elevate its water vapour pressure, the heat drives out the moisture and the strengthened solution is returned to the dehumidifier. A scavenging air stream, usually ambient air, contacts the heated solution in the regenerator. There, water evaporates from the desiccant solution into the air and the solution is reconcentrated.

2. Description of the Investigated Dehumidifier/Regenerator

In the heat and mass exchanger prototype, the desiccant solution and the air stream are brought into contact in a cross flow configuration. The dehumidifier consists of a stack twin wall polycarbonate plates. The plates are covered with textile fibers in order to increase the exposure time of the desiccant on the plates and thereby enhance the desired mass transfer and heat exchange. The overall exposed surface area of the investigated absorber is about 3.9 m^2. The distribution system of the sorbent uses parallel plexiglass tubes to horizontally distribute the LiCl solution over the fleece. The tubes penetrate the dehumidifier stack of plates horizontally and spread the desiccant solution over the coated plates through a number of equally spaced holes. The size and number of the holes are selected according to distribution tests carried out [3] to provide the desired liquid flow. Figure 2 shows the prototype in the pilot plant stage.

Fig. 2. An overview of the whole liquid desiccant test-rig in the laboratory pilot plant stage

3. Instrumentation and Experimental Setup

The prototype plant was operated in the laboratory in various conditions that represent the real conditions of the demonstration plant. In order to obtain the desired information from the test rig, a number of instruments were used. The basic variables to measure were mass flow and temperature for all of the flow streams and water mass fraction in the desiccant and air flow streams.

The desired air flow rate was established with the help of a centrifugal fan. The air volume flow rate is measured while passing through a vortex flow meter. Afterward, air was directed to a series of instruments each one with a specific task. First, there was an electric air heater to heat the air to the needed set value. The air could be heated up to 55 °C according to the needed air conditions at the prototype entrance.

Depending on the desired conditions air could be cooled and/or dehumidified by using an air handling unit. The air handling unit can provide cooling and/or dehumidification of the air according to the needed conditions at the heat and mass exchanger inlet. The needed air temperature and/or relative humidity for each experiment trial is controlled by modulating the chilled water flow rate through the air handling unit coils.

In addition the air channel network is equipped with a steam generator device in order to humidify the air according to the required set-value. Relative humidity and temperature were continually monitored by using humidity and temperature transmitters (HygroFlex). Two HygroFlex sensors were applied in the middle of the round-to-rectangle ducts (at the inlet and outlet) and they positioned deeply in the center of the air flow streams.

Lithium chloride was chosen because of its favorable properties; very stable and has low vapour pressure [4]. The desiccant solution was withdrawn from the upper surface of the primary tank with the help of a positive displacement pump. The density and the temperature of the LiCl solution discharged from the primary tank to the heat and mass exchanger was continually monitored while passing through a density meter. The flow rate of the strong LiCl solution is continually monitored by using a magneto-inductive flow meter. The LiCl solution left the magneto inductive flow meter entered the desiccant distributor and then throttled over the textile attached over the twin-wall plates. The desiccant is trickles down by gravity and left the prototype. The density and the temperature of the desiccant that left the prototype were continually monitored by passing through the density transmitter.

4. Measurements

4.1. Air dehumidification

The prototype was tested in an adiabatic dehumidifier mode. Totally, 12 experimental runs were conducted with the following parameter ranges: Air inlet temperature of 24.5–30.1 ºC, air humidity ratio of 13.9–20.2 g/kg and desiccant mass flow rate of 13.8–44.7 kg/h. The following factors have been tried to keep them fixed; the air mass flow rate was kept constant of 375 kg/h ± 4 kg/h, desiccant inlet temperature of 27 ºC ± 1.1 ºC and desiccant concentration of 43.3%–44.0%.

Table 1. Summary of the experimental set and the operation conditions for air dehumidification, the shadowed cells show the parameters varied during the test sequence

	$\bar{\dot{m}}_{des.}$ kg/h	$\bar{T}_{air,in}$ ºC	$\bar{\omega}_{air,in}$ g/kg
Test seq.1	var:14.1-56.3	24.6 ± 0.1	14.36 ± 0.27
Test seq.2	14.2 ± 0.63	var:24.5-30.1	14.69 ± 0.21
Test seq.3	44 ±0.54	25.3 ± 0.2	var:13.64-20.20

Table 1 summarizes the three experimental sets; each set consists of four test runs. In the first experimental set the desiccant flow rate is varied while keeping the air inlet temperature (26 °C), the air absolute humidity (20.2g/kg). In the second experimental set the air temperature is varied while keeping the air absolute humidity (19.2 8g/kg) and desiccant flow rate (69.6g/m^2.s) constant. In the third experimental set the air absolute humidity is varied while keeping the air inlet temperature (25.4 °C) and desiccant flow rate (69.5g/m^2.s) constant.

4.2 Desiccant regeneration

Eventually, the prototype was tested in a non-adiabatic regenerator mode by using hot air and water streams. Six experimental runs were conducted with the following parameter ranges: fixed air flow rate of 302 kg/h, fixed air inlet temperature of 38.3 °C, fixed inlet heating-water temperature of 50.3 °C. Two experimental sequences were conducted as shown in Table 2.

Table 2. Summary of the experimental set and the operation conditions for desiccant regeneration, the shadowed cells show the parameters varied during the test sequence

	$\bar{\dot{m}}_{heating-water}$ kg/h	$\bar{\omega}_{air,in}$ g/kg	$\bar{\dot{m}}_{des.}$ kg/h	$\bar{T}_{air,in}$ ºC
Test seq.1	98	var: 5.5-10.2	12	38.3
Test seq.2	177	5.5	var: 12-35	38.3

The first non-adiabatic regeneration experimental sequence was done by varying the air inlet absolute humidity while fixing the heating water, air and desiccant mass flow rates. The water/air ratio is 1to3. The second sequential test was done by varying the desiccant mass flow rate while fixing the air and water mass flow rates. The water/air ratio was increased 2to3. The concentration of the diluted LiCl solution at the inlet is 36%.

5. Results and Discussion

The results of the supply air adiabatic dehumidification show a consistent reduction in the relative humidity, a consistent reduction in the humidity ratio, and an increase in the air temperature. In the experimental runs 8 shown in Figure 3, the change in the relative humidity reaches about 42 points and an increase in the air temperature of about 5.2K.

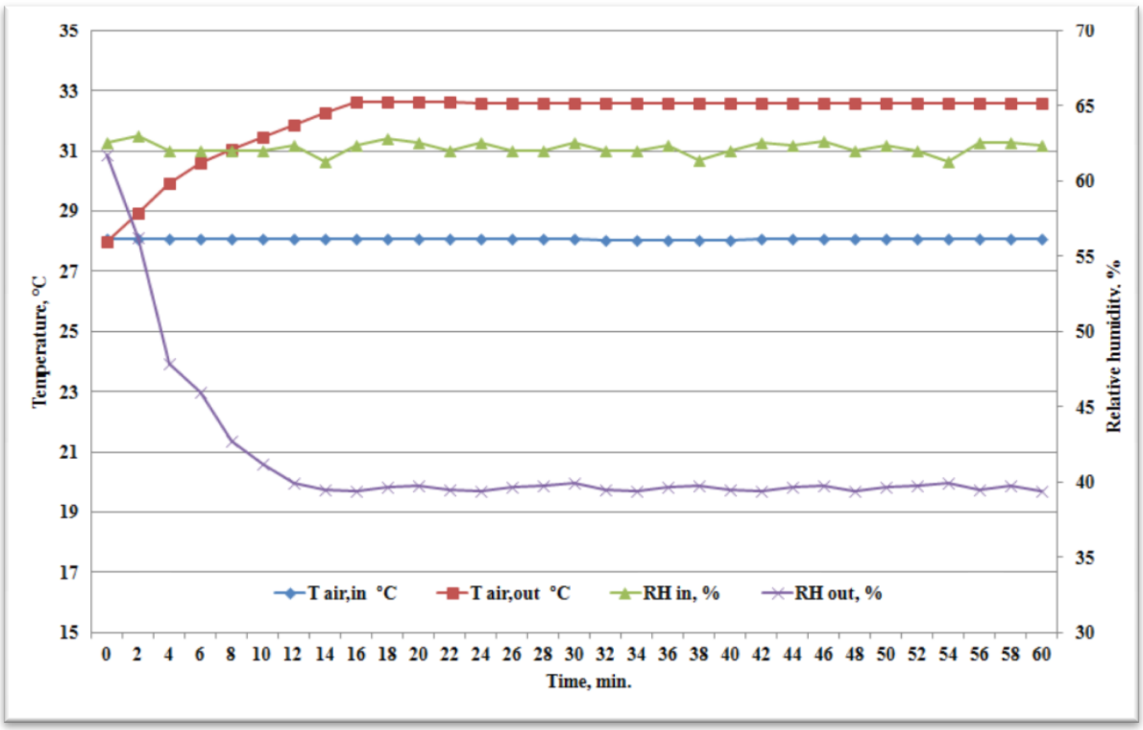

Fig. 3. The interaction between the inlet parameters in exp. run #3(dehumidification); $\dot{m}_a$=373 kg/h, $\dot{m}_{des.}$=13.8 kg/h.

In order to bring the diluted desiccant solution back to the optimal concentration for dehumidification (43% in this study), hot water was used together with hot air to supply the thermal energy required to increase the vapour pressure at the desiccant surface. Figure 4 shows the interaction between heating water and air conditions at the inlet and outlet.

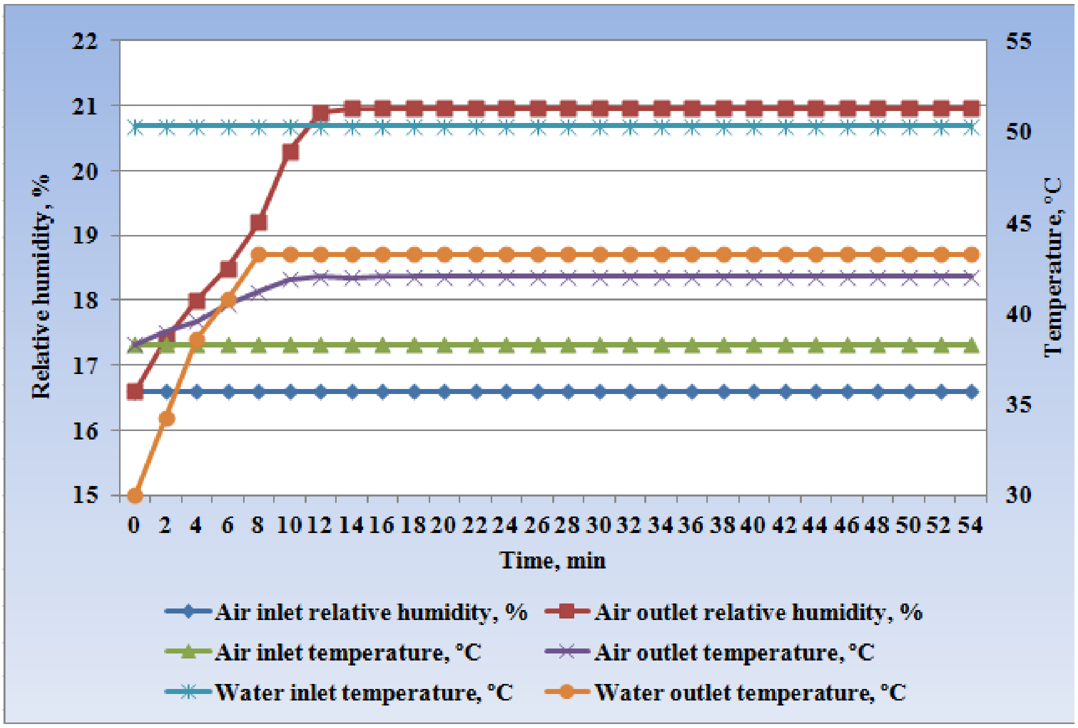

Fig. 4. The interaction between the inlet parameters in one of the regeneration experimental runs; $\dot{m}_a$=374 kg/h, $\dot{m}_{des.}$=14.4 kg/h, $\dot{m}_{heatingwaterr}$=360 kg/h.

5.1. Effects of inlet parameters on the performance

The mass transfer performance of the dehumidifier was evaluated in terms of the moisture removal rate. The moisture removal rate, $\dot{m}_v$, is calculated by Eq. 1 [5].

$$\dot{m}_v = \dot{m}_a \cdot (\omega_{a,in} - \omega_{a,out}) \qquad \text{Eq.1}$$

As shown in Figure 5.a, the moisture removal rate increased remarkably with increasing desiccant flow rate. Since, increasing the desiccant flow rate will decrease the variation of the desiccant concentration through the dehumidifier, and also will decrease the variation of the desiccant temperature. As the result, increasing the desiccant flow rate decreased the variation of the surface vapor pressure of the desiccant through the dehumidifier and, hence, increased the average water vapor pressure difference between the desiccant and air in the dehumidifier. Increasing the desiccant flow rate also increased the mass transfer coefficient between the desiccant and the air in the dehumidifier. The moisture removal rate increases with increasing the air inlet humidity ratio, as shown in Fig.5.b. The effect on the moisture removal rate was caused by the increased average water vapor pressure difference between the air and the desiccant with increasing air inlet humidity ratio.

Regenerator

The moisture removal rate from the diluted desiccant stream to the scavenging air stream for non-adiabatic desiccant regeneration and the most representative results are shown in 5.d, e and f. it has been noticed from the adiabatic regeneration tests, hot air only was ,,,not enough to bring the diluted desiccant solution back to it is original concentration. Hot water was used together with hot air in order to increase the change in the desiccant mass fraction. The air and heating water inlet temperatures were kept constant at 38.3 and 50.8, respectively. In the first experimental sequence, the air inlet absolute humidity was varied between 5.5-10.2 g/kg while fixing the desiccant mass flow rate at 12 kg/h and heating-water mass flow rate at 98 kg/h that represents water to air mass ratio of 1:3.

The experimental results were compared with a numerical finite difference model. As shown in Figure 5, the blue points represent the experimental results and the red points represent the finite difference results. The comparison between the experimental and numerical results show a little divergence beyond the estimated uncertainty for the experimental data.

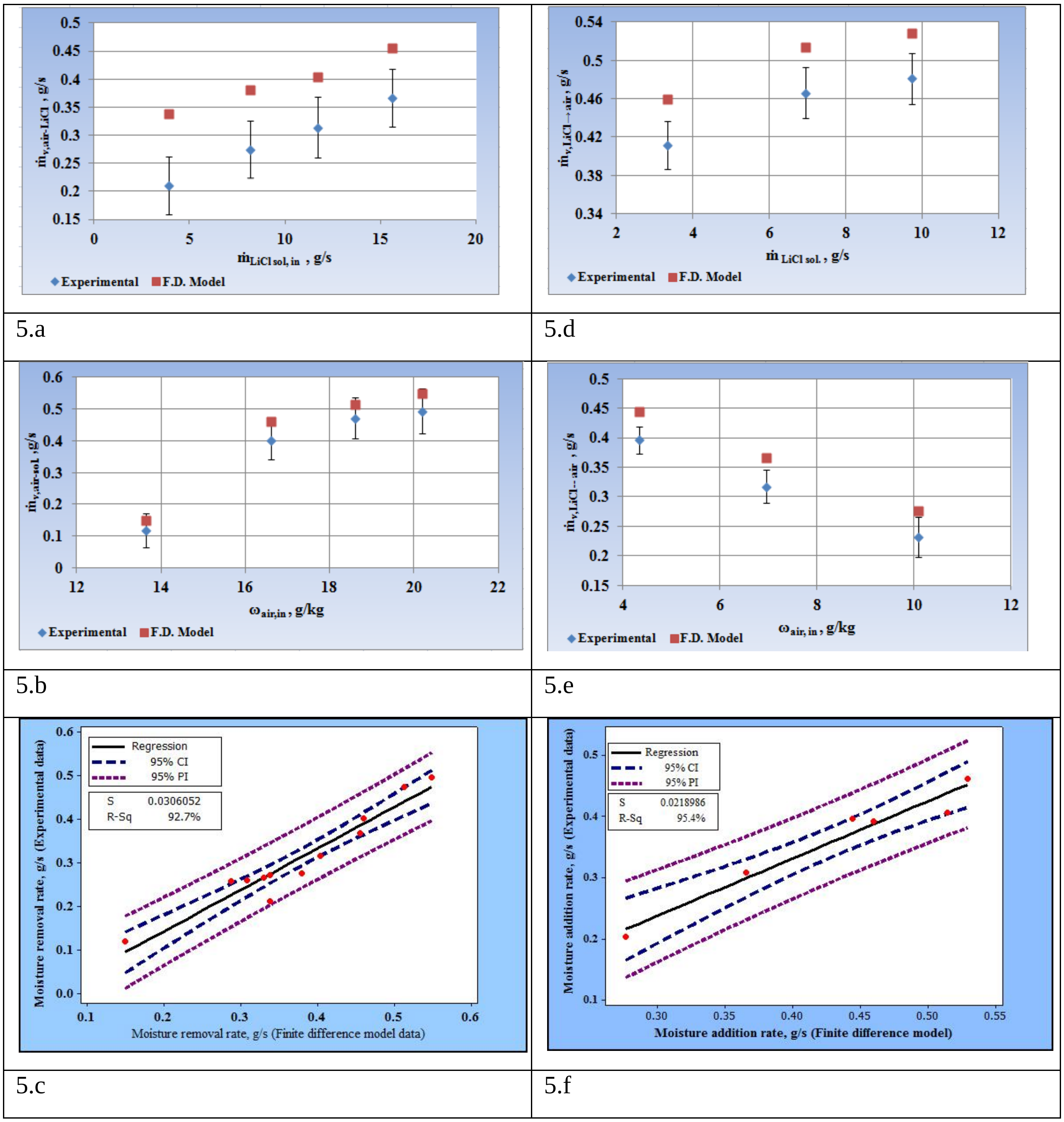

Fig. 5. Moisture removal rate in the dehumidifier (left) and in the regenerator (right) as a function of the desiccant flow rate and the air absolute humidity

5. Conclusion

Comprehensive testing was done in the laboratory for different climate conditions (air temperature and relative humidity). Different air to LiCl mass ratios were investigated the experimental results of supply air dehumidification provide effective air dehumidification. The reduction in the supply air humidity ratio could reach 4.8 g/kg, and a storage capacity (SC) that could reach about 440 KJ/m^3.

A plate type heat and mass exchanger has been built and tested in a pilot plant stage as an air dehumidifier and desiccant regenerator. The results were analyzed and compared with a numerical model for validation. The results of the supply air adiabatic dehumidification show a consistent reduction in the relative humidity and an increase in the air temperature, which are the main factors that affect how readily moisture moves from the drying product. The parametric analysis results in reduction of the air relative humidity in the range of 18-46% points and an increase in the air temperature in the range of 3.7-8.0 K are observed, depending on the inlet parameters. The concentration of the diluted desiccant solution (from 38% to 43%) was done possible by using hot water of 55 ºC, which is an optimal temperature for solar thermal collectors.

Drying can be maintained during the night by using desiccant solution that has been regenerated during the day. One of the benefits of using liquid desiccant is that it can be adapted to using solar energy for the regeneration of the weak solution.

Acknowledgements

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