Experimental Analysis of Heat and Mass Transfer Coefficients of a Liquid Desiccant System

Mustafa Jaradat, Joseph Addy, Klaus Vajen, Ulrike Jordan

Institute of Thermal Energy Engineering, Kassel University, 34125 Kassel, Germany

Phone: +49-561 804 3890, Fax: +49-561 804 3993

solar@uni-kassel.de, www.solar.uni-kassel.de

ABSTRACT

Heat and mass transfer system was developed and experimentally analyzed to calculate heat and mass transfer coefficients for a liquid desiccant – air contact system in a cross flow configuration for dehumidification of air and regeneration of liquid desiccants. The examined dehumidifier and regenerator are the core of a demonstration plant of a liquid desiccant system for drying hay bales. The system was set up in an agricultural domain. The dehumidifier and the regenerator are designed to overcome the present obstacles such as the carryover of the sorbent into the air stream and the flow mal-distribution of the sorbent over the exposed surfaces.

The basic concept of this system is to directly reduce the moisture and warm up the air, which will be used for drying, only few kelvins above the ambient temperature. The dehumidifier consists of plate type heat and mass exchanger with a total exposed surface of about 75 m^2 made up of polycarbonate plates. The desiccant regeneration system consists of a tube type heat and mass exchanger of copper pipes, protected from corrosion with a thin powder coating layer. Textile sleeves are applied over the copper tubes. The total exposed surface area of the regenerator is about 9 m^2. Hot water supplied by solar collector field flows through the copper tubes to heat the desiccant solution in order to concentrate it again.

First measurements of the demonstration plant showed promising results of the dehumidification of hay bales. The drying time for a hay bale could be reduced significantly. The air stream temperature was increased by about 10 K while relative humidity was reduced by about 40%-points during the tests. The results were analyzed and compared with results from a finite difference model. Two models, a finite difference and an effectiveness model, were developed for cross flow plate type heat exchanger. Both models can be operated with and without internal cooling or heating of the sorption process.

1. INTRODUCTION

Drying of agricultural products is the greatest energy consuming process on the farm (Gunasekaran, 1986). The target of drying is to remove moisture from the agricultural product so that it can be processed and safely stored for increased periods of time, for hay drying the moisture of the hay needs to be reduced to 10 % in order to allow the storage without the risk of rot. Hot air drying increases the temperature of the air (and product) and lowers the air relative humidity 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, such systems are oppressed with fundamental problems; it is not possible to reduce the actual moisture level (absolute humidity) in the air in humid climates.

To achieve the requirements for such processes, a liquid desiccant dehumidification system was developed. The basic concept of this system is to directly reduce the moisture and warm up the air, which will be used for drying, only few kelvins above the ambient. In the absorber, moisture absorbed from the process air stream dilutes the desiccant solution by loading the desiccant with water vapor. The solution weakened by absorption of moisture is re-concentrated in the regenerator, where it is heated to elevate its water vapor pressure, the heat drives out the moisture and the strengthened solution is returned to the dehumidifier. A scavenging air stream contacts the heated solution in the regenerator. There, water evaporates from the desiccant solution into the air and the solution is re-concentrated.

2. EXPERIMENTAL SETUP

Experiments were conducted to measure the moisture transfer as well as the temperature difference during the absorption and regeneration processes. The experiment details for both of the pilot plant and the demonstration plant are discussed next.

2.1 Experimental Facility, Pilot Plant

The Absorber and regenerator are the core devices of the experiment, in which cross-flowed air and liquid desiccant exchanges heat and moisture. The overall exposed surface area of the investigated absorber is about 3.9 m2. The heat and mass exchanger 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 distribution system of the sorbent uses Plexiglas tubes to horizontally distribute the LiCl solution over the attached textile. 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 to provide the desired liquid flow (Jaradat *et al*., 2008).

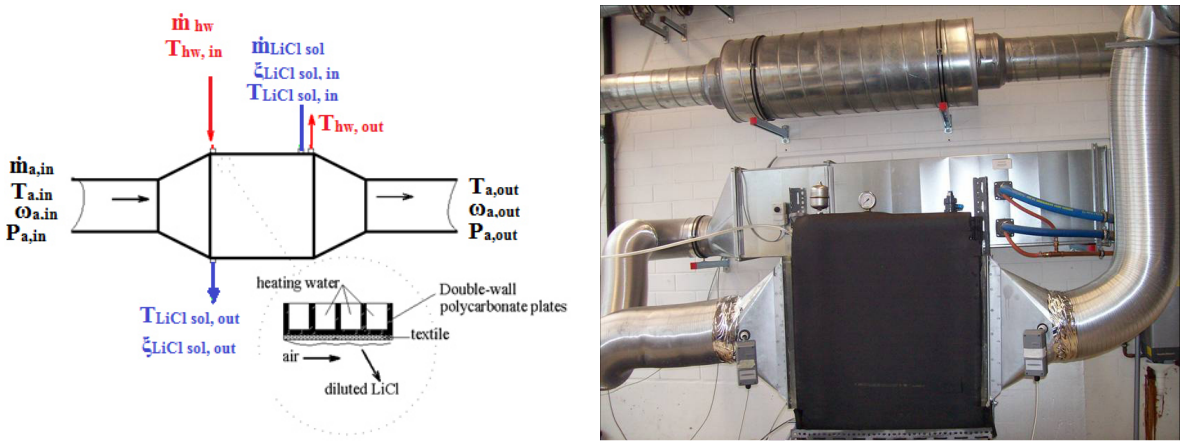


Figure 1: Schematic diagram of the experimental setup, pilot plant stage

The prototype plant was operated in the laboratory, shown in Figure 1, 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 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 is directed to a series of instruments (electric air heater, air cooler/dehumidifier, steam generator) in order to condition the air according to the required set-value. Relative humidity and temperature were continually monitored by using humidity and temperature transmitters (HygroFlex) at the inlet and outlet

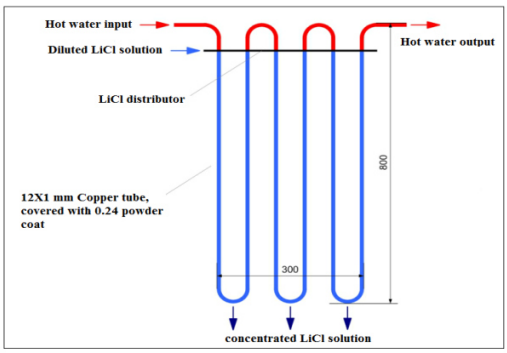
Lithium chloride is used because of its favorable properties; very stable and has low vapor pressure (Conde, 2004). The density and the temperature of the LiCl solution discharged from the desiccant tanks to the heat and mass exchanger is continually monitored while passing through a density meter. The flow rate of the 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 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 and will be converted into mass fraction (ξ).

2.2 Experimental Facility, Demonstration Plant

The demonstration plant consists of two air streams, the absorber and the regenerator air streams. Outdoor air is first filtered for both streams and supplied to the absorber or regenerator. The desiccant absorber consists of a plate type heat and mass exchanger with a total exposed surface of about 75 m^2. The air stream to be dehumidified and the concentrated LiCl solution are set up in a cross flow configuration. The air temperature increases due to the

liberation of sorption heat. The dried and heated air is blown through a hose to a wide air channel with a circular opening for one hay bale.

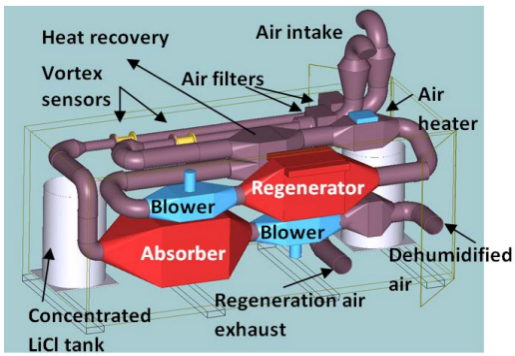
The desiccant regeneration system consists of a heat and mass exchanger made out of copper pipes, protected from corrosive medium with a thin powder coating layer, textile sleeves are applied over the copper tubes. The total exposed surface area of the regenerator is about 9 m^2. The diluted LiCl solution is throttled over the tubes and it trickles down by gravity, flowing along an ambient air stream in a cross flow configuration. Hot water supplied by 155 m^2 solar thermal collectors flows through the copper tubes to heat the desiccant solution in order to concentrate it again.



Bundle tubes with desiccant distributor

LiCl regenerator, 9 m^2

Liquid desiccant dehumidifier, 75 m2



Schematic diagram of the exp. setup

Hay drying system loaded with bales, above: solar roof, right: two water reservoir ($V_{tot.}$ = 43 m³)

Construction of the solar collector field (155m^2)

Figure 2: Demonstration plant in Frankenhausen, KLIMZUG Nordhessen

3. METHODOLOGY

3.1 Air Dehumidification

The prototype was tested in an adiabatic dehumidifier mode. Twelve experimental runs were conducted in three experimental sequences, Table 1.

Table 1: Summary of the experimental set and the operation conditions for air dehumidification measurements in the pilot plant stage, the shadowed cells show the parameters varied during the tests.

	$\bar{\dot{m}}_{des.}$ 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

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 mass fraction (ξ) of 0.43 kg/kg.

3.2 Desiccant Regeneration

The prototype was tested in a non-adiabatic regenerator mode by using hot air and water streams. Six experimental runs were conducted in two experimental sequences. The air mass flow rate was kept constant of 302 kg/h ± 4 kg/h, desiccant inlet temperature of 27 ºC ± 1.1 ºC, inlet heating-water temperature of 50.3 °C and desiccant mass fraction of 0.36 kg/kg, while varying the air humidity ratio and the desiccant mass flow rate.

4. RESULTS

4.1 Analysis of Data/ Pilot Plant

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. Figure 3 shows an example of one of the experiments; the change in the relative humidity reaches about 42 points and an increase in the air temperature of about 5.2K.

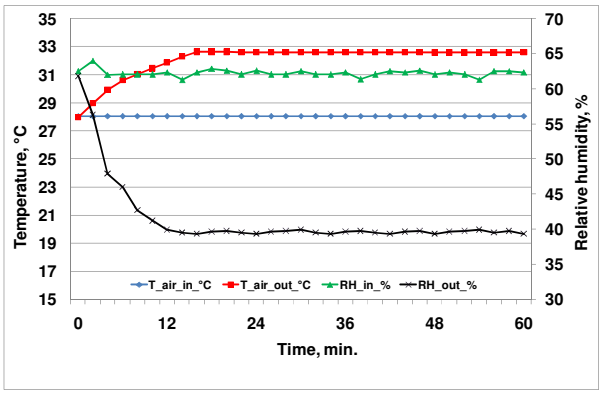


Figure 3: The interaction between the inlet parameters in a dehumidification experiment in the pilot plant stage

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 Equation (1) presented by Lävemann and Peltzer (2005).

$$\dot{m}_v = \dot{m}_a \,.\, (\omega_i - \omega_o) \qquad (1)$$

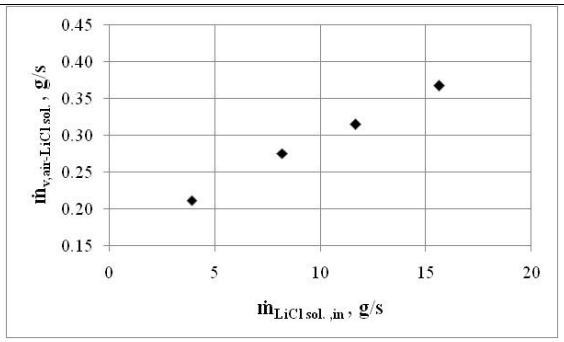
As shown in Figure 4, the moisture removal rate in both directions increased remarkably with increasing desiccant flow rate for both of absorption and regeneration systems. The moisture removal rate increases with increasing the air inlet humidity ratio in the absorber and vice versa for regeneration.

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.

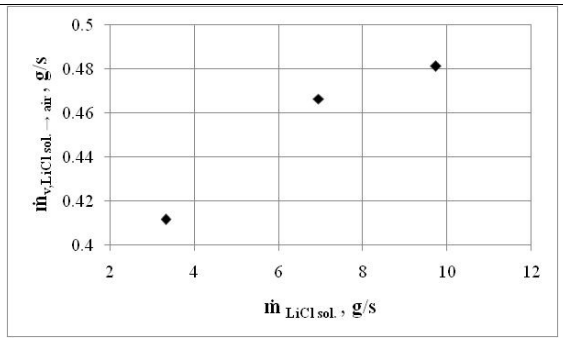
The experimental results were compared with a numerical finite difference model. The finite difference model qualitatively simulates the properties of the circulated fluids of temperatures and concentrations gradients in the absorber and regenerator. It gives quantitatively the best possible prediction of the parameters at the outlet. The model has the following simplifications:

- The mass transfer (diffusion) and heat transfer (heat conduction) assumed constant gradients exist between the nodes.
- The desiccant solution and the air are assumed laminar flow, turbulent flow is not considered. These assumptions lead to underestimation of the mass and heat transfer, since both will be higher in turbulent flow than in laminar.
- The heat transfer and diffusion are considered only perpendicular to the surface instead of parallel, this leads to a slight overestimation of heat and mass transfer.
- The heat conduction and diffusion coefficients for the input conditions are determined and kept constant. In reality, both variables leave with increasing temperature also with higher water content. Thus an underestimation occurred in the absorption mode, and an overestimation occurred in the regeneration mode.
- Uniform distribution of air and salt solution is assumed. In reality, this assumption is difficult to achieve. In the tested absorber and regenerator, the distribution of the salt solution over the air-desiccant exposed surface is tested experimentally. The distribution of the desiccant solution was about 70% uniformly distributed along the air-desiccant solution exposed surface, (Jaradat *et al*., 2008).

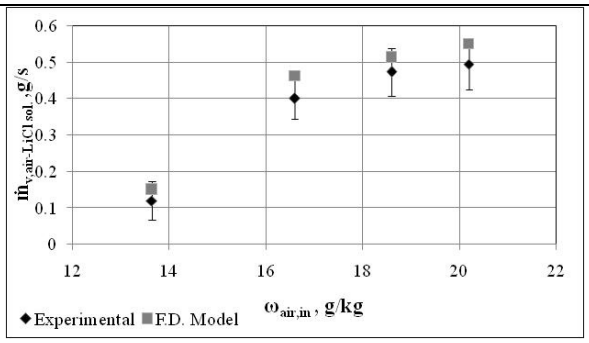
Figure 4 shows the moisture removal rate as a function of the desiccant flow rate and the air inlet humidity ratio for both of the absorber and regenerator. The comparison between the experimental and numerical results shows a little divergence beyond the estimated uncertainty for the experimental data.



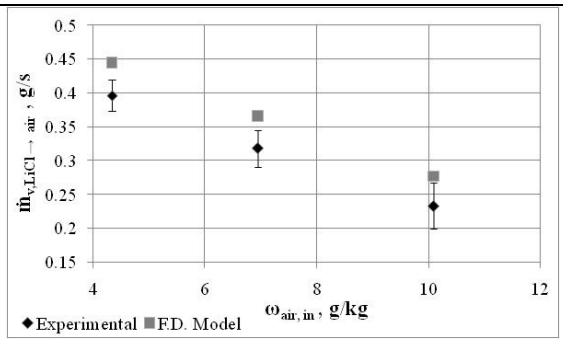
Moisture removal rate from air as a function of desiccant mass flow rate (absorber)



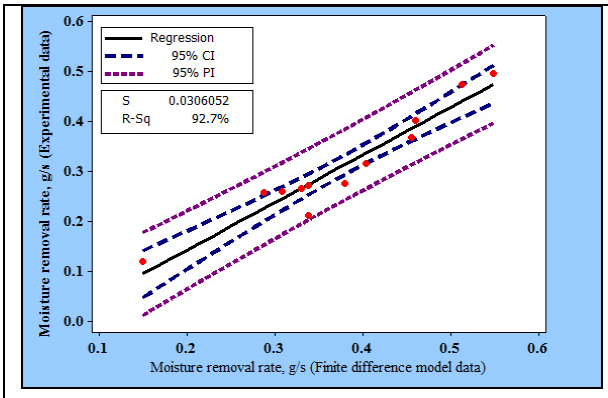
Moisture removal rate from desiccant as a function of desiccant mass flow rate (regenerator)



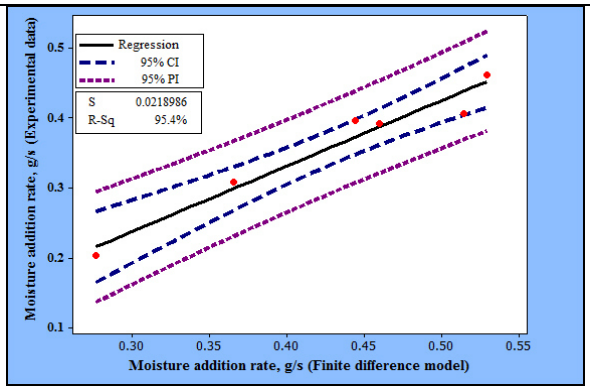
Moisture removal rate from air as a function of air humidity ratio (absorber)



Moisture removal rate from air as a function of air humidity ratio (regenerator)



Comparison between the experimental findings and the numerical model findings for the moisture removal rate (absorber)



Comparison between the experimental findings and the numerical model findings for the moisture removal rate (regenerator)

Figure 4: Moisture removal rate in the dehumidifier (left) and in the regenerator (right) as a function of desiccant mass flow rate and air inlet humidity ratio.

4.2 Analysis of Data/ Demonstration Plant

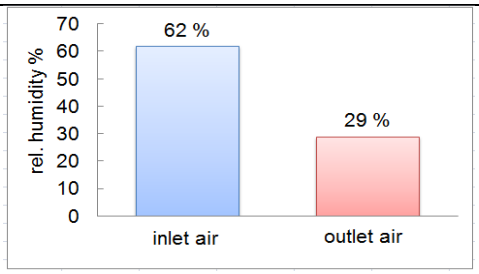
4.2.1. Air Dehumidification

Six dehumidification n experiments were take place. The ambient air temperature and relative humidity varies in the range of 17-24 °C and 60-75 %, respectively. The hay bales initial humidity varies in the range of 30-35%, the hay humidity needs to be reduced to at least 10%. The hay bales weigh between 350 to 500 kg.

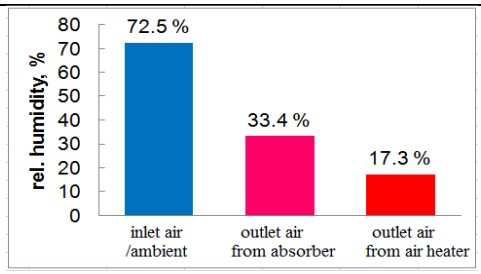
The hay bales were dried using the air came directly from the absorber, Figure 5, or the air is extra heated through an auxiliary solar air heater, Figure 5. The air volume flow rate and the LiCl mass fraction were kept constant of 1360 m3/h and 0.43 kg/kg, respectively. The LiCl mass flow rate was varied in a way to achieve salt solution to air mass ratio (MR) of: 1to10, 1:20 and 1:30.

As shown in Figure 5 (left column), a reduction of the air relative humidity of 33 % points, an increase in the temperature of 10.4 K and a change in the air humidity ratio of 1.2 g/kg has been achieved in the first hay drying test. Also, Figure 7 (right column) shows hay drying for the second test, a rise in the air temperature of 8.3 K due to the heat of condensation and extra 11 K through the auxiliary air heater.

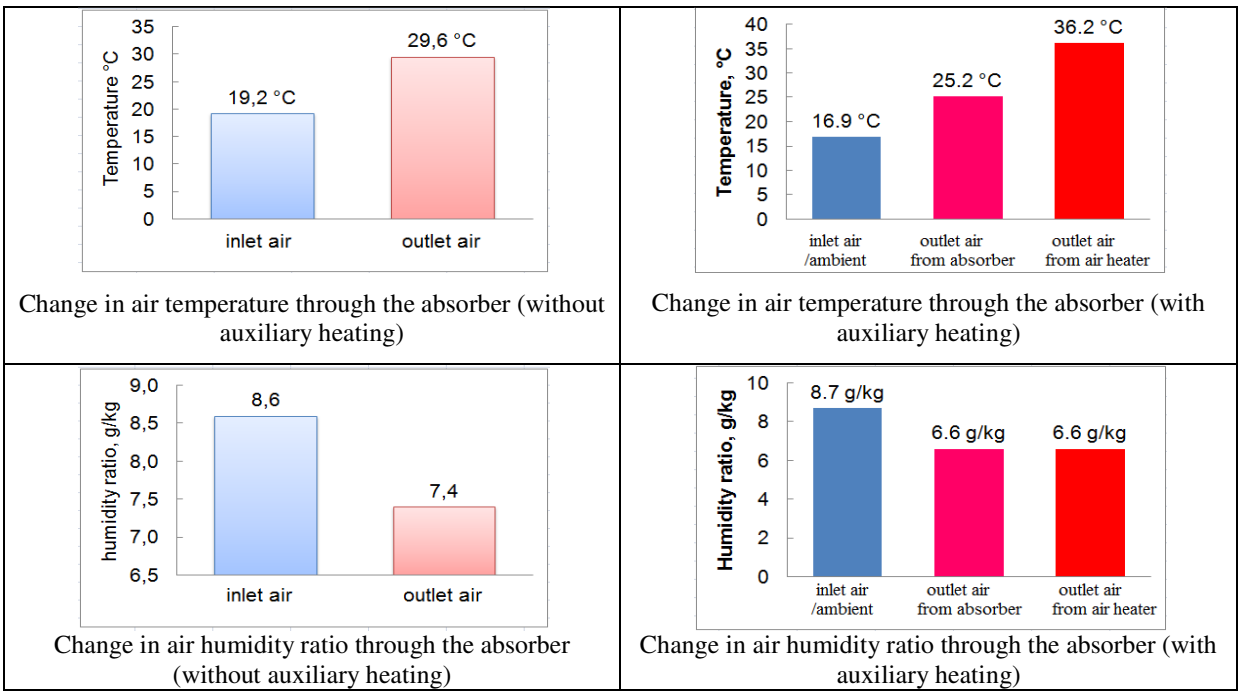
A cut in the hay bales drying time to four hours instead of twenty hours using dehumidified and heated air only through absorption, has been achieved. The drying time depends on many factors, such as the initial hay moisture content, mass, diameter and compactness of pressing.



Change in air relative humidity through the absorber (without auxiliary heating)



Change in air relative humidity through the absorber (with auxiliary heating)



Change in air temperature through the absorber (without auxiliary heating)

Change in air temperature through the absorber (with auxiliary heating)

Change in air humidity ratio through the absorber (without auxiliary heating)

Change in air humidity ratio through the absorber (with auxiliary heating)

Figure 5: Air status; relative humidity, temperature and humidity ratio, leaving the desiccant dehumidifier without auxiliary heating (left) and with auxiliary heating (right) for two hay bales drying experiments

4.2.2 Heat and Mass Transfer Analysis of the Tube Type Regenerator

Heat and mass transfer takes place simultaneously in the vertical bundled tubes. The following assumptions have been formulated in calculating the heat and mass transfer; the pressure gradient and the heat transfer by conduction in the vapor phase are neglected. The heat and mass transfer are determined at steady states.

Considering the energy balanced for the regenerator, the heat transferred from the solar hot water to the desiccant film and flow air is given as

$$\dot{Q} = U.A.\Delta T_{lm} = \dot{m}_h . c_{p,h}\left(T_{h,i} - T_{h,o}\right) \tag{2}$$

U is the overall heat transfer coefficient; A is the total surface area ($A = \pi N d_0 L$) and ΔT_{lm} is the log mean temperature after Grossmann (1986)
The heat transfer coefficient for the hot water through the tubes is determined with the modified correlation for the transition region, which is between laminar and turbulent flow proposed by Gnielinski (1995).

$$Nu = \frac{\varepsilon/8(Re-1000)Pr}{1+12.7\sqrt{\varepsilon/8}\left(Pr^{2/3}-1\right)}\left(1+\left(\frac{d_i}{l}\right)^{2/3}\right) \tag{3}$$

e is the pressure loss coefficient used by Filonenko (1954). The heat transfer coefficient between the desiccant film and air is calculated as

$$h_f = \frac{d_i}{d_a}\left(U - \left(\frac{1}{h_w} + \frac{d_a \ln\left(\frac{d_a}{d_i}\right)}{2k_w}\right)\right)^{-1} \tag{4}$$

The mass transfer coefficients between the desiccant film and the water vapor in the air is defined as the analogy to the heat transfer coefficient is defined as

$$\beta_G = \frac{h_f}{L_e c_{p,G} \rho_G} \tag{5}$$

Le is the Lewis number, $c_{p,G}$ and ρ_G is the specific heat capacity and the density of the gas respectively.

5. CONCLUSIONS

Plate and tube-bundles types heat and mass exchanger were built and tested in a pilot plant stage and, not long, in a demonstration plant stage as an air dehumidifier and desiccant regenerator.
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.
The results were analyzed and compared with a finite difference 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 mass fraction of the diluted desiccant solution is increased (from 0.38 kg/kg to 0.43 kg/kg) by using hot water with a temperature started from 50 ºC, which is an optimal temperature for solar thermal collectors.
Initial measurements in the demonstration plant showed promising results. Drying time of four hours for hay bales was achieved by using the dehumidified air coming from the absorber.
The comparison between the results obtained from the experimental measurements and those obtained from the numerical model showed a deviation in the range of 12%. The result were underestimated in the absorber and overestimated in the regenerator.

NOMENCLATURE

A	total surface area	[m^2]
cp	specific heat capacity	[J/kgK]
d	diameter	[m]
l	length	[m]
Le	Lewis number	[-]
N	total tubes	[-]
Pr	Prandtl number	[-]
Q	Heat transfer	[J]
Re	Reynolds number	[-]
T	temperature	[°C]
U	Overall heat transfer coefficient	[W/m^2K]

Subscripts

a	air	[-]
c	cold	[-]
f	fluid	[-]
g	gas	[-]
h	hot	[-]
i	inlet	[-]
o	outlet	[-]
w	water	[-]

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