International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:13, No:9, 2019

Energy Saving in Handling the Air-Conditioning Latent-Load Using a Liquid Desiccant Air Conditioner: Parametric Experimental Analysis

Mustafa Jaradat

Abstract**—**Reasonable energy saving for dehumidification is feasible with the use of desiccants. Desiccants are able to lower the humidity content in the air irrespective of the dew point temperature. In this paper, a tube bundle liquid desiccant air conditioner was experimentally designed and evaluated using lithium chloride as a desiccant. Several experiments were conducted to evaluate the influence of the inlet parameters on the dehumidifier performance. The results show a reduction in the relative humidity in the range of 17 to 46%, and the change in the humidity ratio was between 1.5 to 4.7 g/kg, depending on the inlet conditions. A water removal rate in the range between 0.54 and 1.67 kg/h was observed. The effects of air relative humidity and the desiccant flow rate on the dehumidifier's performance were investigated. It was found that the moisture removal rate remarkably increased with increasing desiccant flow rate and air inlet humidity ratio. The dehumidifier effectiveness increased sharply with increasing desiccant flow rate. Also, it was found that the dehumidifier effectiveness slightly decreased with air humidity ratio.

Keywords**—**Air conditioning, dehumidification, desiccant, lithium chloride, tube bundle.

I. INTRODUCTION

AIR conditioning marketplace demand leads to extensive loads on electrical grids. Desiccant-based dehumidification with indirect evaporative cooling could reduce the cooling energy use by up to 81%. Also, it could shift most of the energy needs to thermal energy sources, reducing annual electricity use by up to 90% [1].

Dehumidification in conventional vapour compression systems is mainly performed by cooling the air below its dew point temperature. The subcooled air needs then to be reheated to meet the comfortable human temperature. These sub-cooling and reheating systems lead to excessive energy consumption. In contrast, water vapour from the air stream can be removed more efficiently using desiccant systems. Hygroscopic salt solutions of lithium bromide (LiBr), calcium chloride ($CaCl_2$), and lithium chloride (LiCl) are used as liquid desiccants.

Fig. 1 shows the main components of an open cycle liquid desiccant system. The air is dehumidified in the absorber as it comes in contact with the concentrated air stream. The diluted solution leaving the absorber is regenerated in the regenerator where it is heated to raise its vapor pressure. Waste heat or solar energy can be used to heat up the diluted solution.

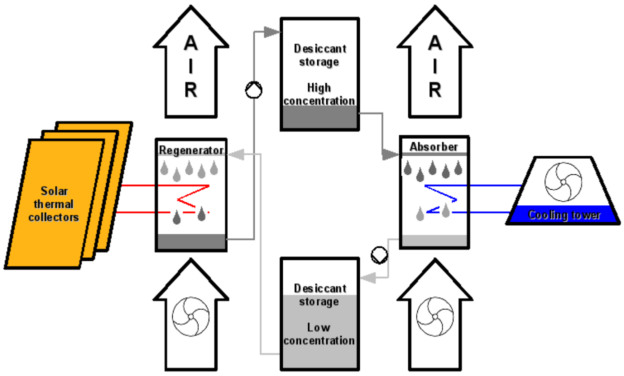

Fig. 1 Schematic diagram of a solar driven liquid desiccant air-conditioning system [2]

Desiccant dehumidification dates back to the 1930's after Kathabar Systems developed the earliest liquid desiccant dehumidifier, mainly for industrial applications, [3]. In the last few decades, desiccant systems were more implemented and studied by many researchers. Extensive investigations were carried out as a result of the increasing desire for air conditioning and the demanding modern codes and standards on ventilation and indoor air quality [4].

The most important experienced potential of desiccant dehumidification was in the supermarket industry. Pesaran [5] stated that more than 500 supermarkets were installed that utilize desiccant dehumidification coupled with electric-driven refrigeration systems in the USA by the year of 1992. This number is 20 times higher than those installed by the year 1987. Also, he introduced three case studies of desiccant-based air conditioning in a supermarket in New England, a three story (150 rooms) hotel in West Palm Beach, Florida and a six-story office building in Houston. In the first case study, the conventional air conditioning system is replaced with a desiccant based air conditioner. The system used a desiccant wheel with silica gel as the desiccant material manufactured by Munters DryCool. He came to the conclusion that using desiccant-based air conditioners could more precisely control the humidity levels within the supplied air stream. This will possibly eliminate the maintenance of freezers according to frost problems. Furthermore, the possibility of independent control of the humidity and temperature allows an evaporator

Mustafa Jaradat is an assistant professor at the German Jordanian University in the Energy Engineering Department, Amman, 11180 Jordan (phone: +962 6 429 4444 Ext: 4221; fax: +962 6 430 0215; e-mail: Mustafa.jaradat@ gju.edu.jo).

to function at higher temperatures. An energy cost savings of $8,500/year was achieved in the presented case study.

Potential studies of desiccant systems as an alternative or hybrid to conventional air conditioning systems have drawn considerable interest over the last few years. Liu et al. [6] presented an evaluation between liquid desiccant dehumidification systems and traditional air conditioning systems. The evaluation was focused on the operation cost, driving energy source, humidity control and indoor air quality. He concluded that a savings of up to 40 % of the operating costs are achievable by applying liquid desiccant-based cooling systems.

Liquid desiccant systems have several benefits compared to solid desiccant systems. The main advantage of liquid desiccant systems is the separation between absorption and regeneration cycles, Öberg and Goswami [4]. Besides, the concentrated solution could be used for storing energy in a thermochemical form, Keßling et al. [7]. The capability to heat up the desiccant solution during the regeneration process leads to greater energy effectiveness than with solid desiccant types according to Lowenstein et al. [8].

There are many different technologies available for the liquid desiccant dehumidifier. Those units could be built in different ways according to method designed to distribute the liquid desiccant and the structure in which both of the desiccant and air interact. Liquid desiccant dehumidifiers with packing material either in structured or random packing as the contact medium between air and solution are so far the most studied types of heat and mass exchangers. Related researches in packing liquid desiccant systems in both structured and random types of packed-bed type are reported by many authors, for example [9]-[14]. However, liquid desiccant flow rates need to be high in the packed beds to be able to provide good surface wetting of the packing materials and to maintain the desiccant solution at a relatively high temperature through the regeneration process as stated by Lowenstein et al. [15].

In this paper, a tube bundle absorber made of polypropylene (PP) was constructed and tested for air conditioning application. Externally cooled LiCl solution was used as desiccant. The design aims to have a robust construction that withstands the corrosive solution. A parametric analysis was performed with the solution flow rate and the humidity ratio as controlled variables.

II. Description of the Investigated Dehumidifier

The dehumidifier was made plastic tubes covered with textile sleeves. The textiles were used to increase the exposure time and thus to enhance heat and mass transfer coefficients. The concentrated LiCl solution is intended to flow from an upper tank into the sealed pipe due to the hydrostatic pressure and from the side holes to the textile. The desiccant solution trickles down the textile and thus comes into contact with the air to be dehumidified in a cross flow configuration. At the bottom of the absorber, the desiccant solution is collected and discharged.

In this paper, the absorber is with tube bundle geometry. The absorber is subdivided into two modules each with 12 tubes in two rows. This creates an absorber with 24 tubes distributed over four rows of tubes. The rows of tubes were in staggered arrangement. The advantage of the modularization is the simpler manufacturing and that each module is connected to separate tank of the desiccant solution. This results in advantages in the investigation of the absorption behavior of the individual rows and better accessibility of the tubes for investigations, repairs and maintenance. The modules are connected in series and can be extended by any number.

The absorber was made of PP pipes because it is resistant to the corrosive lithium chloride and can be processed well. In addition to the PP boards, HT-PP pipes, and connecting pieces were used. In addition to the HT pipes, which are available from a diameter of 40 mm, there are the matching connectors, sleeves, and plugs. The height and the width of the absorber were 1.0 m × 0.52 m. The absorber has 24 pipes each with a diameter of 40 mm and a pitch of 80 mm. The total area of the absorber is equal to 0.52 m^2, and Fig. 2 shows the staggered tubes.

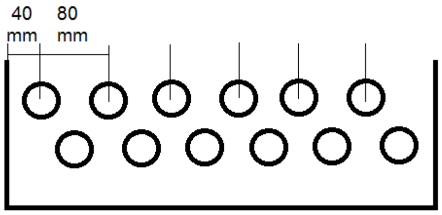

Fig. 2 Arrangement of the first rows of the absorber

The PP tubes were covered with 0.4 mm thick sleeves made of cellulose. Prior to the attachment of the textiles, several experiments were performed to evaluate the wetting behavior of these textiles. Fig. 3 shows the first module of the absorber with two rows.

Fig. 3 PP tubes covered with textile sleeves

The modules were connected with in a frame made of PP with a thickness of 40 mm. the absorber inlet and outlet were connected to the 250 mm diameter air ductwork of the test port by using two diffusers. The diffuser needs to bring the pre-conditioned air for each experiment to 1040 mm in height and 500 mm in width on the absorber's face. The diffuser distributes the air and the reduction brings it back together. In principle, there are two identical parts, which achieve an opposite effect. For this purpose, a frame was designed which is identical to the flow surface of the absorber module. The diffuser or reducer is shown in Fig. 4, and it has the same height as the modules at 1635 mm and is 750 mm long. The aluminum corrugated hoses (or flex hoses) used in the lab can be pulled over the round opening to connect the module to the test environment. In the diffuser and the reduction, the measuring devices necessary for the measurement can be introduced.

Fig. 4 Assembly of the absorber with air diffusers

In order to ensure a good distribution of the air through the air duct of the absorber modules, adjustable diffusers (were installed in the diffuser. Finally, the diffuser was insulated with an Amaflex® insulation to dissipate as much heat as possible over the large external surface, thus measuring the actual increase in temperature due to absorption.

Aqueous LiCl solution is introduced from above and it flows through a distributor above each of PP tubes. Each PP tube has two opposite bores with a diameter of 1 mm.

III. INSTRUMENTATION AND EXPERIMENTAL SETUP

A. Instrumentation

Ambient air is supplied the to an air handling unit accompanied with air heater/cooler and humidifier/ dehumidifier to create the target conditions required for each experiment. Air flow rate is measured with a vortex-meter. The air relative humidity and the air temperature are measured by using a humidity and temperature sensors. Relative humidity and temperature were measured at the absorber entrance and exit. The related air characteristics such as humidity ratio and enthalpy were obtained by using humid air equations from ASHRAE [16].

The desiccant solution circuit consists of plastic tanks for the concentrated and diluted desiccant solutions. Filters were installed at a diaphragm pump inlet to get rid of possible contaminates that could close the 1-mm bores of the liquid desiccant distributor. The volume flow rate of the desiccant solution is measured by a magnetic inductive flowmeter. The temperature of the desiccant solution is measured with Pt100 resistance thermometer sensors applied at the absorber inlet and outlet. The density of the solution is measured by taking samples of the solution at the absorber inlet and outlet. The desiccant concentration is derived by the measured desiccant density and temperature by applying the correlations given by Conde [17]. Fig. 5 shows instrumentation of the absorber air circuit.

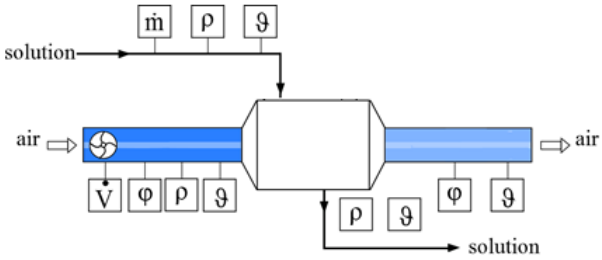

Fig. 5 The experimental setup of the absorber

B. Experimental Setup

The tube bundle absorber was tested by varying the desiccant solution mass flow rate and the air inlet humidity ratio. Two test sequences each with four experiments were performed as shown in Table I.

TABLE I
TEST SEQUENCES CARRIED OUT IN THE DEHUMIDIFIER

	$\dot{m}_a$ kg/h	$\dot{m}_{sol}$ kg/h	ϑ_a °C	ω_a g/kg	ϑ_{sol} °C	ξ_{sol} kg/kg
TS1	356	14..56	24.6	14	27.5	0.44
TS2	357	44.0	25.3	14..20	27.5	0.44

Two test sequences were carried out by varying one of the inlet parameters, denoted by the gray shaded cells in Table I. In the 1st test sequence (TS1), the solution mass flow rate ($\dot{m}_{sol,i.}$) was varied between 14 to 56 kg/h, and the air inlet humidity ratio ($\omega_{a,i}$) was varied from 13.6 to 20.2 g/kg in TS2, while the remaining inlet parameters were maintained quasi constant.

The change of the process air temperature $\Delta\vartheta_a$, the change of the process air humidity ratio $\Delta\omega_a$, and the moisture removal rate $\dot{m}_v$ were evaluated to analyze the experiments.

The water vapour removal rate from the air stream to the concentrated LiCl-H2O solution in the absorption process, $\dot{m}_v$, was calculated regarding the air side. On the air side, it is a function of the humidity ratio spread of the air $\Delta\omega = \omega_{in} - \omega_{out}$, as given in (1):

$$\dot{m}_v = \dot{m}_a(\omega_{in} - \omega_{out}) \tag{1}$$

The dehumidification load is given by (2):

$$\Delta\dot{H}_d = \frac{\dot{m}_a(h_{fg,in}\,\omega_{in} - h_{fg,out}\,\omega_{out})}{3600} \tag{2}$$

IV. RESULTS AND DISCUSSION

Two inlet parameters of the air and the desiccant solution were chosen as controlled variables that influence the dehumidifier performance. Those include desiccant flow rate and air inlet humidity ratio. The effect of each parameter is analyzed separately for clarity as follows.

A. LiCl Solution Flow Rate

In the first experimental set, the effect of the desiccant flow rate was investigated regarding the water removal rate and solution mass fraction spread. In this set, the air mass flow rate and inlet temperature were held constant at about 360 kg/h and 24.6 °C, respectively. The desiccant solution flow rate was varied to four values as shown in Table II.

TABLE II
INLET PARAMETERS FOR THE DESICCANT SOLUTION AS A CONTROLLED VARIABLE

	$\dot{m}_{sol}$ $\frac{kg}{h}\pm2$	ϑ_a °C±0.5	ω_a $\frac{g}{kg}\pm0.6$	ϑ_{sol} °C±0.2	ξ_{sol} $\frac{kg}{kg}\pm0.005$
I	15.0	24.0	14.0	28.0	0.440
II	30.0	24.0	14.0	28.0	0.440
III	40.0	24.0	14.0	28.0	0.440
IV	55.0	24.0	14.0	28.0	0.440

In Figs. 6 - 8, water vapour removal rate, concentration spread, and dehumidification load are plotted as a function of the desiccant solution flow rate.

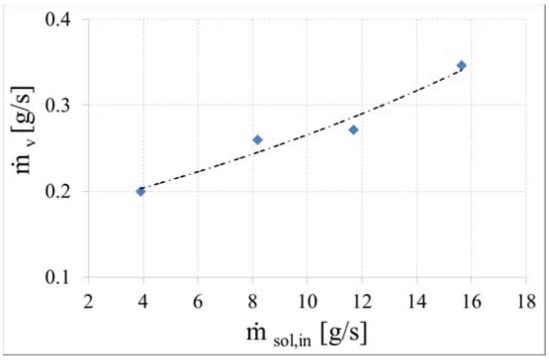

Fig. 6 Water vapour removal rate as a function of solution mass flow rate

The water vapour removal rate increases considerably by increasing the desiccant flow rate, as shown in Fig. 6. This trend is expected, because by increasing the solution flow rate, both of the solution concentration and temperature are less likely to go up and thus keeping the desiccant solution at low vapor pressure. Furthermore, increasing the desiccant flow rate will increase the surface area of desiccant exposed to the air by enhancing the wetting of the attached textiles.

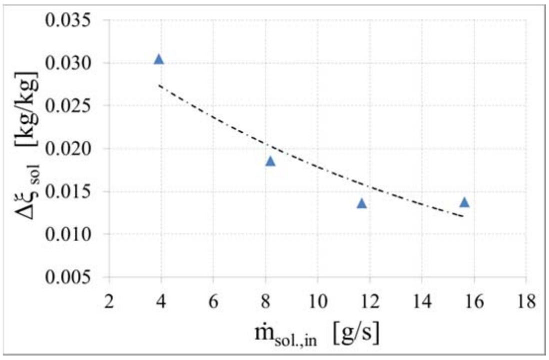

Fig. 7 Concentration spread as a function of solution mass flow rate

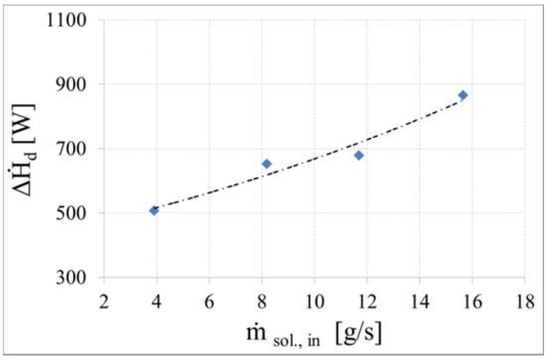

Fig. 8 Dehumidification load as a function of solution mass flow rate

The concentration of the desiccant solution at the absorber outlet is increased by only about 1.3% for high flow rates of the desiccant solution. In comparison, the concentration is increased by about 3% for low flow rates of the solution, as shown in Fig. 7. The concentration spread is inversely proportional to the desiccant flow rate. Liquid desiccant systems are very effective for storing energy for air dehumidification demands. It was verified by previous research that high air to solution mass ratios lead to sufficient energy storage in the liquid desiccant [10]. A crucial evaluation regarding the energy storage in liquid desiccant systems is the volumetric energy storage capacity. The volumetric energy storage capacity is characterized by the stored energy per volume of the stored liquid desiccant. The higher the volumetric energy storage capacity the smaller the storage tank is. High flow liquid desiccant dilutes the concentrated LiCl-H_2O solution less than that for low flow, resulting in lower storage capacity. Moreover, the dehumidification load increases by increasing the solution flow rate, as shown in Fig. 8. The dehumidification load was up to 900 W for a solution flow rate of 55 kg/h. This is due to the increase in the difference in the actual dehumidification ($\Delta\omega$), while the maximum possible difference remains unchanged.

B. Air Inlet Humidity Ratio

Table III shows the inlet parameters with the air inlet humidity ratio as a controlled variable.

TABLE III
INLET PARAMETERS WITH THE AIR INLET HUMIDITY RATIO AS A CONTROLLED VARIABLE

	$\dot{m}_{sol}$ kg/h	ϑ_a °C	ω_a g/kg	ϑ_{sol} °C	ξ_{sol} kg/kg
I	44	25.0	13.9	27.0	0.44
II	44	25.0	16.6	27.0	0.44
III	44	25.0	18.6	27.0	0.44
IV	44	25.0	20.2	27.0	0.44

The influence of air inlet humidity ratio on the dehumidifier performance is shown in Figs. 9-11.

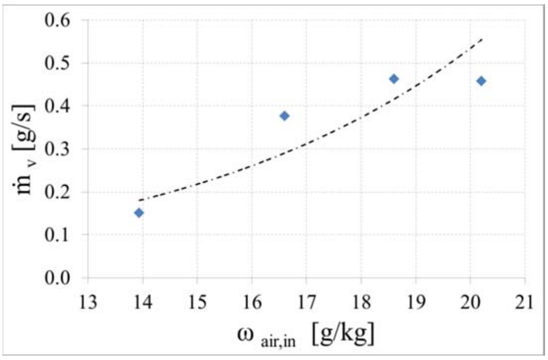

Fig. 9 Water vapour removal rate as a function of humidity ratio

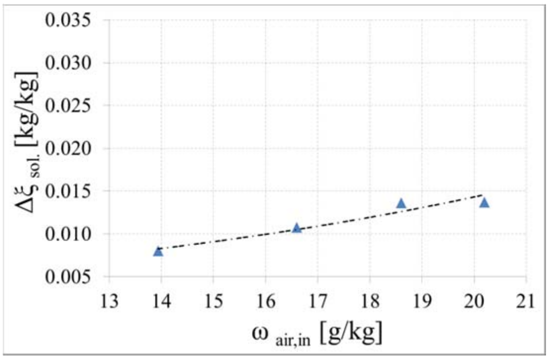

Fig. 10 Concentration spread as a function of humidity ratio

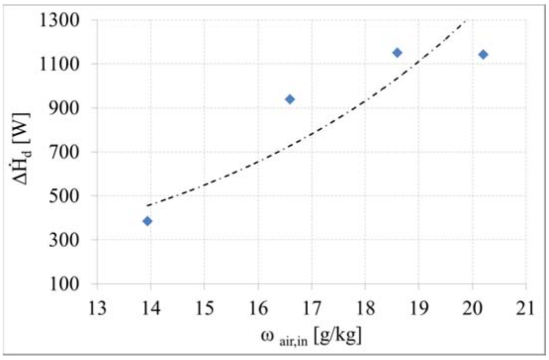

Fig.11 Dehumidification load as a function of humidity ratio

The water vapour removal rate, concentration spread of the desiccant, and the dehumidification load are increased by increasing the air inlet humidity ratio. The effect on the moisture removal rate is caused by the increased water vapor pressure difference between the air and the desiccant with increasing air inlet humidity ratio.

As shown in Fig. 9, the water vapour removal rate was between 0.25 g/s to 0.46 g/s for an air inlet humidity ratio between 13.9 g/kg to 20.2 g/kg, respectively. The mass fraction spread is also increased of up to 0.014 kg/kg by increasing the air inlet humidity ratio, as shown in Fig. 10.

V. CONCLUSION

A tube-bundle absorber was designed, constructed, and instrumented to evaluate its performance. Through a series of parametric tests, optimal configuration and operation were identified in terms of: desiccant flow rate and air inlet humidity ratio. The results indicate that water transfer rate from the air stream to the concentrated solution increases by increasing the desiccant flow rate and the air inlet humidity ratio.

Liquid desiccants are a perfect alternative to conventional vapour compression air conditioning systems. The dehumidification load was up to 1.2 kW which was handled using the liquid desiccant solution without the need to cool the air below its dew point temperature. However, the diluted liquid desiccant needs to be concentrated to continue the absorption cycle. This process takes place in the regenerator. The potential of applying waste heat recovery or solar energy as a heat source for regenerating the desiccant solution will be of great value.

ACKNOWLEDGMENT

Sincere thanks for the funding by the German Ministry for Research and Education, BMBF, in the framework of the research project "Open Sorption Processes" (OpenSorp, AZ 03SF 0444). Also, the support of Dipl. Ing. Lars Schiemann and Gregor Schumm in the construction of the absorber is highly appreciated.

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