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Experimental Evaluation of a Novel Tube Bundle Solar Driven Liquid Desiccant Regenerator

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Abstract

A novel design of an internally heated tube-bundle heat and mass exchanger is presented and experimentally examined in this paper. The main focus for the design of the regenerator was to avoid carryover of the lithium chloride solution (LiCl-H_2O) to the regenerator air-stream. Furthermore, an important aim was to realize an improved heat and mass transfer coefficients, as well as higher chemical, physical, and thermal stability of the construction and to reach an even wettability and maximum uniform distribution of the liquid desiccant in the regenerator.

The presented regenerator is the core of a demonstration plant of a liquid desiccant system that will be used for drying hay bales. The system will be installed in an agricultural domain in North Hessen, Germany. The liquid desiccant regenerator is made of copper pipes, protected from the corrosive medium, the LiCl-solution, with a thin powder coating layer. The copper tubes are covered with textile sleeves. The total exposed surface area of the regenerator is about 4 m^2. The air stream and the LiCl solution flow are arranged in a cross flow configuration.

The regenerator is tested in the laboratory at Kassel University. Four test sequences each with three experiments were performed by varying one of the inlet parameters in each test sequence. The moisture removal rate is studied as a function of desiccant mass flow rate, desiccant inlet temperature, heating-water inlet temperature and air inlet temperature. It is found that the moisture removal rate increases with increasing desiccant flow rate, desiccant inlet temperature and heating-water inlet temperature. Also, increasing the air inlet temperature has only a small effect on the increment of the moisture removal rate; this raises the question about the viability of preheating the regeneration air before coming in contact with diluted desiccant solution especially if the regenerator is internally heated.

The diluted desiccant solution could be re-concentrated by using heating water with a temperature of 50 °C. Furthermore, an increase in the concentration of the LiCl-solution by 4% is observed when the inlet heating-water temperature is 70 °C.

Keywords: Liquid desiccant, tube-bundle, regenerator, heat and mass exchanger, drying.

1. Introduction

The main components of an open-loop liquid desiccant system are the absorber and the regenerator. In the absorber, moisture which is absorbed from the ambient air stream dilutes the desiccant solution. The diluted solution is re-concentrated in the regenerator, where it is heated to increase its water vapor pressure. An ambient air stream contacts the heated solution in the regenerator. There, water is desorbed from the desiccant solution into the air and the solution is re-concentrated. Figure 1 shows a schematic diagram of a solar driven liquid desiccant system for HVAC or drying applications.

In order to drive the process, i.e. the regeneration of the salt solution, low-temperature heat can be used. for example solar energy or waste heat, etc.

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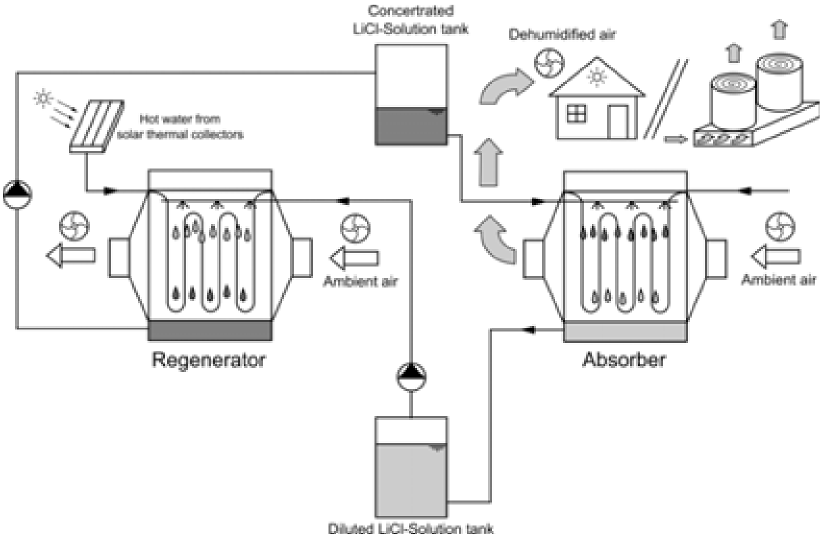

Fig. 1: Schematic diagram of a solar driven liquid desiccant system for HVAC or drying applications.

Both solid and liquid desiccant can produce dry air with dew point temperature lower than water freezing-point, ASHRAE (2008). Because no overcooling of the process air is required, desiccant dehumidification is particularly suitable for applications where the latent load dominates, Waugaman et al. (1993).

Although the solid desiccant is more widely applied for air-conditioning applications of commercial buildings, accounting for two thirds of desiccant systems sold TIAX (2004), the liquid desiccant dehumidifier demonstrates many design and performance advantages in comparison to the solid desiccant wheel, Oberg and Goswami (1998). The regeneration temperature required for liquid desiccant is lower than that of solid desiccant. Desiccant solution can be either heated directly outside the regenerator or internally-heated by hot water in the regenerator. It is more difficult to heat the regeneration process of a solid desiccant inside the unit. The energy efficiency of the liquid desiccant system is thus higher than that of solid ones, Harriman (1994). Also, the pressure drop through a liquid desiccant contactor is smaller than that through a solid desiccant wheel and can be further reduced by the plate type contactor, Lowenstein et al. (2006).

Liquid desiccant regenerators or absorbers 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. Reviews on the packed-bed type are reported by Oberg and Goswami (1998) and Lowenstein (2008). Furthermore, Factor and Grossman (1980) and Lazzarin et al. (1996) cite several authors who provide an overview of various packing materials.

Internally heated/cooled plate type heat and mass exchangers have drawn the focus since 1990s. Kipping and Bischoff (1993) examined a plate type absorber. The absorber is made of twin wall desiccant-resistance plastic. Good surface wetting of the plates with the salt solution is achieved by means of corona discharge treatment of polymers. An evaporative cooled air stream is used to dissipate the heat of sorption.

Lävemann et al. (1993) and Lävemann and Peltzer (2005) investigated a plate-type absorber cooled by water in which the process air and the salt solution were in cross-flow configuration. The liquid desiccant is distributed via membrane tubes above the heat transfer plates. The absorber plates were covered with fleece; capillary forces cause further spreading of the solution along the exchange surface. References to further experimental work of absorbers with plastic sheets and coated aluminum plates are discussed by Lowenstein (2008).

Tubular desiccant heat and mass exchangers may be divided into coiled tubing and tube bundle. The distribution of the salt solution is carried out through nozzles or openings in a distribution system. The surface of the tubes is used as a contact surface between air and salt solution. While in the tubes, a cooling or heating medium removes the heat of absorption or heats the salt solution in the absorber or regenerator, respectively. These types of absorbers and regenerators were presented by various authors. For example, Kipping and Bischoff carried out basic experiments on an absorber with offset pipes. The liquid desiccant trickles down from the first pipes layer is distributed to the underlying pipes by a particular pipe arrangement design. Further improvement of the liquid desiccant distribution and extension of the residence time of the solution was achieved by covering the tube with a layer of non-woven polyester. The cooling of the desiccant solution was carried out by adiabatically humidified exhaust air from the conditioned space. The cooling air stream flows through the pipes in a cross flow configuration, Röben (1998). Also, Röben presented experimental investigations on tube-bundle absorber installed in two arrangements. In the first absorber, the tubes were installed vertically within a cylindrical tube. In the second absorber, the tubes were installed horizontally in a square vessel. However, difficulties for the contact between air and the desiccant solution were observed in the former arrangement due to greater clearance between the pipes and vessel walls by its cylindrical shape, Röben (1998).

Khan (1998) and Khan and Sulsona (1998) studied numerically the performance of an internally cooled dehumidifier cooled by water or refrigerant (NH_3) cooled tube bundles. It was suggested to keep desiccant flow rate as low as possible if it is possible to maintain the coils completely wet with the desiccant solution

In this work a novel internally heated bundle-type regenerator in combination with an aqueous solution of LiCl, is examined and evaluated in terms of its regeneration performance. The copper tube-bundle is protected from corrosion with a thin layer of powder coating. Furthermore, the tubes are coated with thin cellulose fibers with high capillary force, Jaradat et al. (2008).

2. Description of the Investigated Regenerator

The desiccant regeneration system consists of a heat and mass exchanger made of copper pipes, protected from corrosive medium with a thin powder coating layer. Textile sleeves are applied to the copper tubes. The total exposed surface area of the regenerator is about 4 m^2. The diluted LiCl solution is throttled over the tubes and it trickles down by gravity, flowing along an air stream in a cross flow configuration. Hot water flows through the copper tubes in counter flow configuration.

The regenerator consists of 22 tubes. Each tube bundle is made of copper; 5 m long, 12 mm outer diameter and 1 mm wall thickness. The bending of the tube bundle is done with hand bending machine with a bending radius of 24 mm. The copper tubes are coated with a thin powder coating with a layer thickness of 0.24 mm to protect them from the corrosive medium of the LiCl solution. The powder coating used is a composition of polyester, polyurethane, polyester-epoxy and acrylics. The coated tubes are then covered with 0.4 mm thickness of cellulose fibers (Tencel ®). Figure 2 shows the copper tubes after bending.

Fig. 2: Bended copper tubes; before powder coating (left), after powder coating (middle) and with Tencel ® sleeves (right)

The casing of the regenerator is constructed with polycarbonate plates (area cross section 10 x 15 mm) since polycarbonate is stable and corrosion resistant. Polycarbonate plates are adhered by dichloromethane. The tube bundles are held in the polycarbonate housing with pressure clamps. The tube-bundles are soldered together with an offset of 20 mm. The connections of the tube bundle are located outside the regenerator housing. Every second tube is connected in series. Figure 3 shows the installation of the tube-bundles.

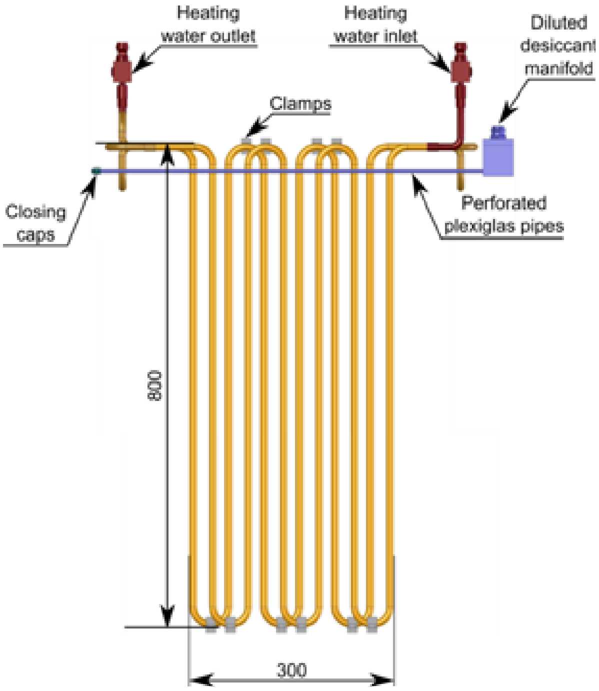

Fig. 3: Installation of the tube-bundles

The liquid desiccant distributor consists of 21 parallel poly-methyl methacrylate (PMMA) pipes to horizontally distribute the liquid desiccant over the textile attached to the copper tubes. 21 parallel pipes extend outwardly from openings in the lower edge of one of the sides of the liquid desiccant manifold and are closed from the free end. Each PMMA pipe is perforated from both sides, the double-sided hole allows the simultaneous wetting of two tube rows. The diameter of the fine bores is 0.5 mm and the liquid desiccant is distributed horizontally at the center of each copper pipe. Figure 4 shows a 3D assembly of the liquid desiccant regenerator.

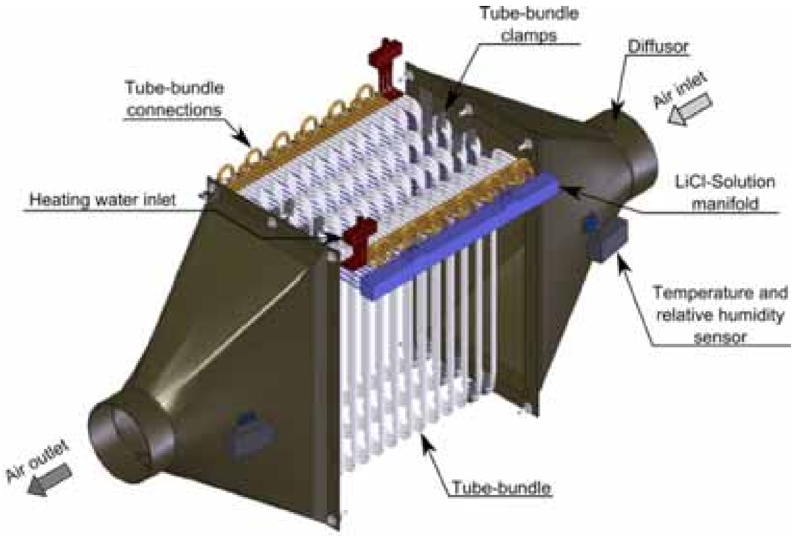

Fig. 4: 3D assembly of the regenerator along with the illustration of heating water and desiccant manifolds

The regenerator is insulated with 19 mm thick synthetic rubber with a thermal conductivity of k = 0.033 W/(m K). The front side of the dehumidifier was insulated with removable extruded polystyrene foam sheet (k = 0.08 W/(m K)). The front insulation is removable, allowing for the inspection of the desiccant flow conditions inside the box. An air diffuser was installed at the regenerator inlet to enhance the uniformity of the air flow through the test section, although no attempts were made to directly assess the uniformity.

3. Experimental Setup

The mass flow and temperature for all of fluid streams as well as the water mass fraction in the desiccant and air flow streams were monitored in the test rig. Figure 5 shows an overall view of the regenerator with air, water and desiccant handling units.

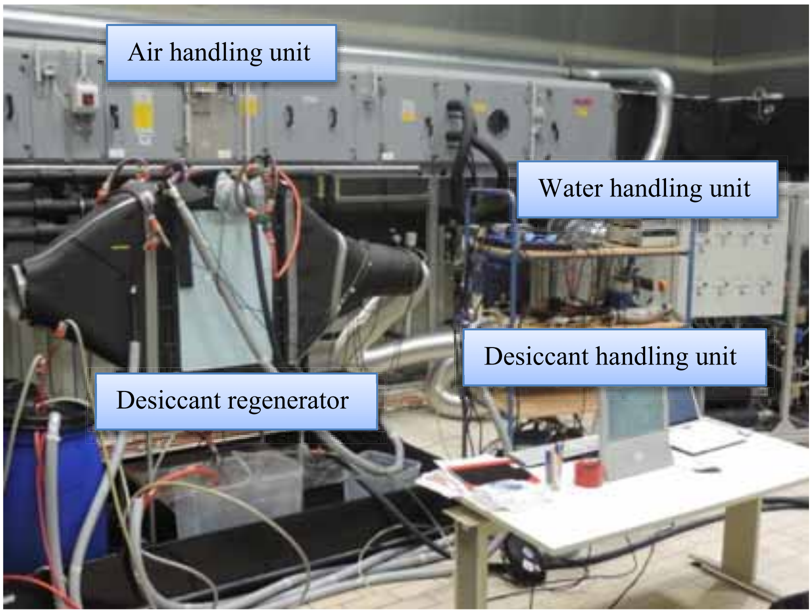

Fig. 5: Liquid desiccant regenerator in the pilot plant stage in the laboratory, Institute of Thermal Engineering - Kassel University

3.1. Air channel ductwork

Depending on the desired conditions, air can be cooled, heated, dehumidified and/or humidified through an air handling unit. Figure 6 shows a schematic diagram of the air handling unit used to bring the ambient air to the desired setup conditions. The air handling unit used in this study consists of an air cooler with a cooling capacity of 16.8 kW, two air heaters with a total heating capacity of 38 kW, air humidifier, steam generator, with a capacity of 30 kg/h, two fans, air filters and dampers.

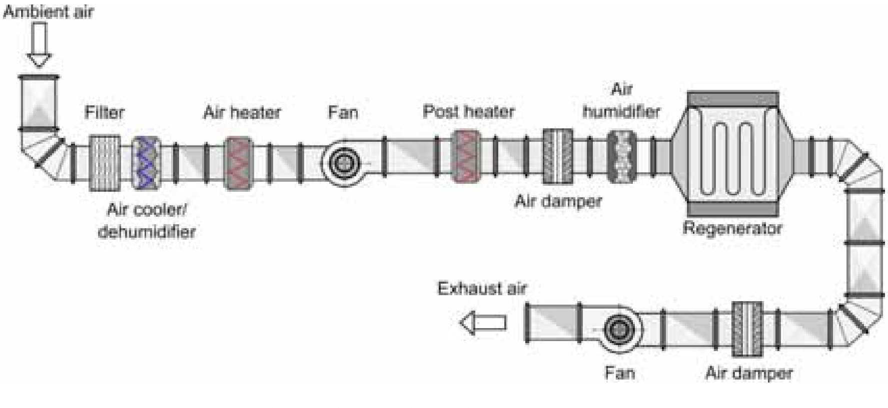

Fig. 6: Air handling unit and regenerator

3.2. Desiccant and water hydraulic system

The liquid desiccant circuit is shown in Figure 7. The desiccant circuit consists of two desiccant storage tanks made out of plastic. The desiccant solution is drawn from the primary tank with the help of a membrane pump. A filter with a pore size of (300 µm) is installed in the inlet suction-line in order to prevent plugging of the small holes in the liquid desiccant distribution system from possible contaminates.

A 30 m long powder coated copper coil is integrated in the primary tank. The heating-water stream passes through the coil in order to preheat the desiccant solution to the desired temperature. The desiccant volume flow rate, density and temperature are continuously monitored while passing through two coriolis flow meters which are installed at the regenerator inlet and outlet.

The heating water flow rate and temperature is controlled by using a water handling unit. The controlled parameters, flow rate and the temperature of heating-water, are continually monitored using a magneto-inductive flow meter and Pt100 sensors, respectively.

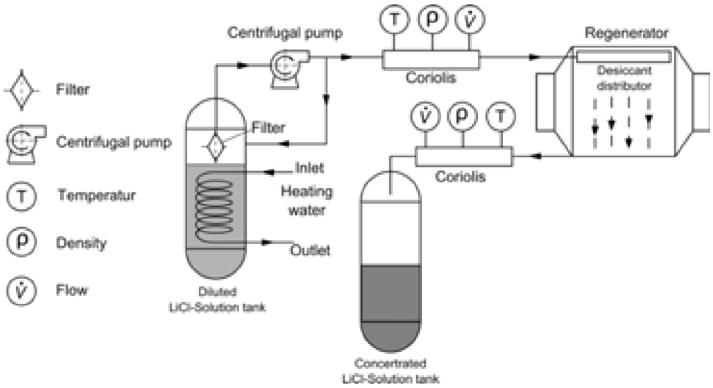

Fig. 7: Schematic diagram of the LiCl-solution hydraulic circuit

4. Methodology

The regenerator was tested under non-adiabatic conditions by using hot air and water streams. 12 experiments were performed in four experimental sequences. The following inlet parameters were maintained constant for all experiments; the air volume flow rate at about 350 m^3/h, the mass fraction of the LiCl solution at about 0.36 kg/kg, the inlet air humidity ratio at about 10 g/kg and the heating water mass flow rate at about 420 kg/h. Four test sequences were accomplished by varying one of the inlet parameters while keeping the other parameters constant. In the test sequences I to IV, one of the following parameters; the desiccant solution flow rate, the desiccant solution temperature, the heating-water temperature and regeneration air temperature were varied respectively. The duration of the individual experiments was 90 minutes, starting when the inlet conditions at the regenerator entrance reached quasi steady state conditions. The aim of the experiments is to study the effect of mentioned controllable parameters, listed in Table 1, on the moisture removal rate from the diluted desiccant solution and on the desiccant outlet mass fraction.

Tab. 1: Controllable parameters during regenerator experiments

Test sequence	$\dot{V}_{LiCl,in}$ l/h	$T_{LiCl,in}$ $°C$	$T_{water,in}$ $°C$	$T_{air,in}$ $°C$	$MR(\frac{\dot{m}_a}{\dot{m}_{LiCl}})$
I	20	40	70	40	15.7
	40	40	70	40	8.6
	60	40	70	40	5.8
II	40	25	70	40	8.6
	40	40	70	40	8.6
	40	50	70	40	8.6
III	40	40	50	40	8.6
	40	40	70	40	8.6
	40	40	80	40	8.7
IV	40	40	70	28	8.6
	40	40	70	40	8.6
	40	40	70	50	8.6

Figure 8 shows a schematic diagram of the inlet and outlet parameters monitored. The air temperature and relative humidity were monitored using temperature and relative humidity sensors (testo 6610) with an accuracy of ± 1 % of relative humidity and ± 0.3 °C for temperature readings. The desiccant flow rate, density and temperature, were monitored using a coriolis flow meter (Promass 80I08 from Endress + Hauser) with an accuracy of 0.15% of the measured value. Heating-water temperature and flow rate were monitored using a magnetic inductive flow meter (OPTIFLUX 1050 from Krohne) with an accuracy of 0.5% of the measured value. The air flow rate was measured with an ultrasonic flow meter (Prosonic flow B 200 from Endress + Hauser) with an accuracy of 1.5% of the logged signal.

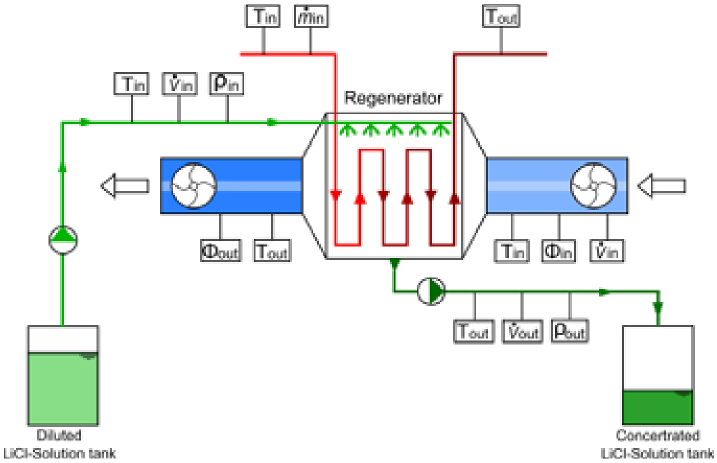

Fig. 8: Schematic diagram of the instrumentation system; controlled variables of air, desiccant and heating water

The signals from the instruments were continuously logged by the data acquisition system LabVIEW with a time step of 10 seconds.

The mass transfer performance of the regenerator is evaluated in terms of the moisture removal rate. The moisture removal rate, $\dot{m}_{vap}$, is calculated by Equation 1.

$$\dot{m}_{vap} = \dot{m}_a . (\omega_{a,out} - \omega_{a,in}) \qquad \text{(eq. 1)}$$

5. Results and Discussion

The moisture removal rate from the diluted desiccant solution to the regeneration air stream $\dot{m}_{H_2O}$,and desiccant outlet mass fraction $\xi_{des,o}$ were studied as a function of the desiccant flow rate, the desiccant inlet temperature, the heating-water flow rate and inlet temperature as shown in section 4.

The maximum value reached for $\dot{m}_{vap}$ is 5.8 kg/h, corresponding to $\xi_{des,o} = 39.0$ % for high internal heating temperature of 80 °C (test sequence III.3), whereas the maximum value for $\xi_{des,o}$ of 39.3 % for small flow rates of the liquid desiccant (test sequence I,1).

The effect of desiccant flow rate $\dot{m}_{des}$ on the moisture removal rate $\dot{m}_{vap}$ is shown in Figure 9. The air to desiccant mass ratios were 15.7, 8.6 and 5.8, respectively. The moisture removal rate $\dot{m}_{vap}$ increases remarkably with increasing desiccant flow rate, as long as the air flow rate provided is sufficient and the outlet air is not saturated. Figure 10 shows the corresponding values for the reduction of the desiccant mass fractions ($\Delta\xi_{des}$), i.e. the mass fraction width for the regeneration of the desiccant solution. The higher the mass flow rate of the desiccant $\dot{m}_{des}$ for the given reference conditions, the lower the #$\Delta\xi_{des}$, due to the smaller exposure time of the desiccant exchanger area. This shows that a high humidity removal width $\Delta\xi_{des}$ can only be reached with low moisture removal rates $\dot{m}_{vap}$ for the given reference conditions in test sequence I.

Figure 11 shows in addition the desiccant outlet temperature $T_{des,o}$ over the desiccant mass flow rate $\dot{m}_{des}$. With increasing $\dot{m}_{des}$, corresponding to lower $\Delta\xi_{des}$, a smaller ratio of water is removed and less desorption heat is needed per kg of desiccant solution. This leads to higher outlet temperatures $T_{des,o}$ for high desiccant mass flow rates $\dot{m}_{des}$ in the given configuration. Moreover, an increase of the desiccant flow rate may improve the wetting area of the tube-bundles and thus increasing the mass transfer area.

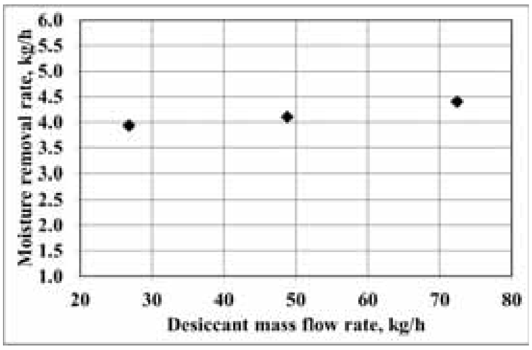

Fig. 9: Moisture removal rate as a function of desiccant mass flow rate

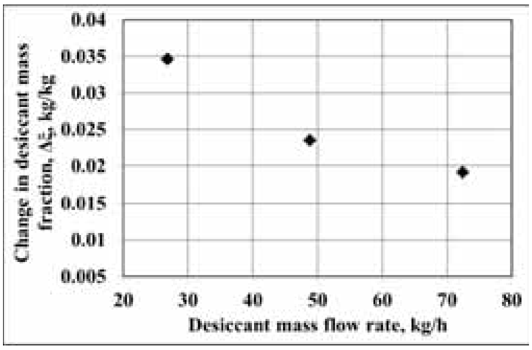

Fig. 10: The change in the desiccant mass fraction as a function of desiccant mass flow rate

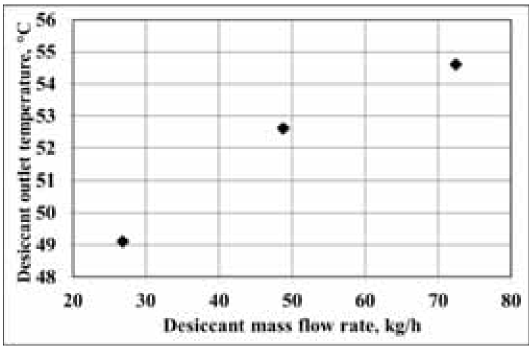

Fig. 11: Desiccant outlet temperature as a function of desiccant mass flow rate

In the second test sequence the desiccant inlet temperatures were set to 25 °C, 40 °C, and 50 °C. The moisture removal rate increases with increasing desiccant inlet temperature, as shown in Figure 12, due to the higher desiccant vapor pressure and hence an increase in mass transfer potential within the regenerator. The same effect is shown in the third test sequence, when the heating water inlet temperature was increased, Figure 13. Figure 14 shows that a high internal heating temperature also leads to a strongly improved values for $\Delta\xi_{des}$.

In the fourth test sequence the air inlet temperature was varied between 25 °C and 50 °C. As shown in Figure 15, the moisture removal rate is only affected slightly by the air inlet temperature. This effect is fairly weak since the preheated desiccant solution has higher thermal capacity compared to the air stream, as well as the desiccant film is continuously heated by heating-water with a temperature of 70°C.

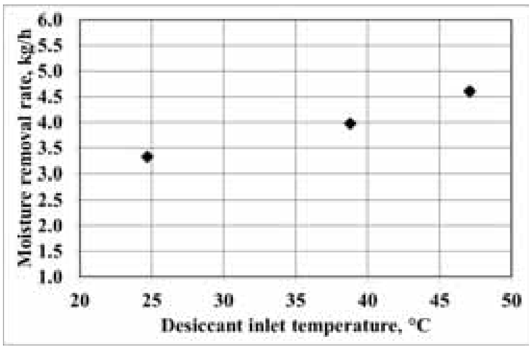

Fig. 12: Moisture removal rate as a function of desiccant inlet temperature

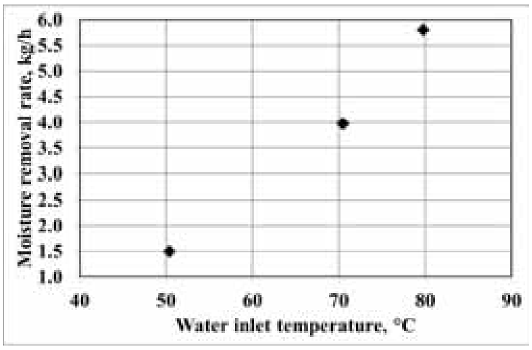

Fig. 13: Moisture removal rate as a function of heating water inlet temperature

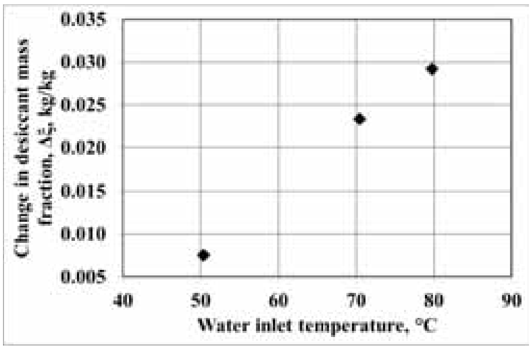

Fig. 14: The change in the desiccant mass fraction as a function of heating water inlet temperature

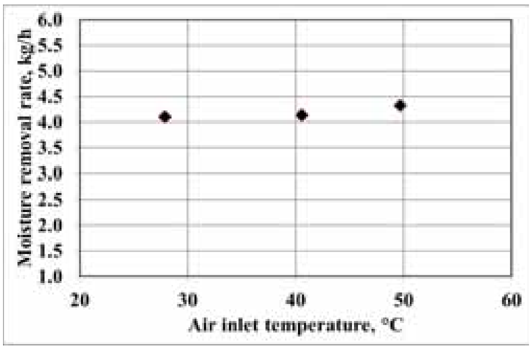

Fig. 15: Moisture removal rate as a function of air inlet temperature

6. Conclusions and Outlook

A tube-bundles type heat and mass exchanger was constructed and tested in a pilot plant stage as a liquid desiccant regenerator. It is made of copper pipes, protected from the corrosive medium with a thin powder coating layer. The copper tubes are covered with textile sleeves. The examined liquid desiccant regenerator is designed and constructed with the aim to ensure higher heat and mass transfer coefficients; higher chemical, physical, and thermal stability of the construction and to reach an even wettability and maximum uniform distribution of the liquid desiccant on the heat and mass transfer surface in the regenerator.

The moisture removal rate increases with increasing desiccant flow rate, desiccant inlet temperature and heating water inlet temperature. The strongest effect has the heating water temperature for the given reference conditions. The maximum value reached was $\dot{m}_{vap}$=5.8 kg/h. The highest outlet desiccant mass fraction for the given reference conditions was reached with a very low desiccant flow rate. Increasing the air inlet temperature has a small effect on the increment of the moisture removal rate for the given conditions. This raises the question about the viability of preheating the regeneration air before coming in contact with diluted desiccant solution especially if the regenerator is internally heated.

Further improvements in the regenerator design will be done in the near future by adjusting the installation of the tube-bundles. The tubes will be connected in such a way that minimizes the distance between the adjacent tubes. Furthermore, the liquid desiccant distribution system will be enhanced to ensure better and even wettability of the textiles attached to the bundles surface. The experimental results obtained will be compared with a finite difference model which is currently in progress in the Institute of Thermal Engineering at Kassel University.

The present regenerator is the core of a demonstration plant of a liquid desiccant system for drying hay bales. The system will be installed in an agricultural domain. 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. The sorption field plant will be used for drying hay bales; the moisture of the hay needs to be reduced to about 10% in order to allow the storage without the risk of rotting.

Acknowledgment

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