Experimental Study of a Solar Collector/Regenerator for Liquid Desiccant Systems

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Abstract

One of the key components of a solar liquid desiccant system is the regenerator, in which the diluted solution from the absorber is reconcentrated for its reuse in the air dehumidification task. Among the different types of regeneration units stands out the solar collector/regenerator (C/R), in which the liquid sorbent is exposed simultaneously to the solar radiation and the air stream, thus enhancing the regeneration process. In order to assess its thermal performance, an experimental study of a single-glazed forced convective C/R has been carried out using calcium chloride solution. The results of the conducted tests show that the water desorption rate increases strongly with the rise of the solar radiation and the inlet solution temperature as well as with the diminution of the gap height and the tilt angle. For the analysed measuring range, the water desorption rate firstly increases and then reaches a stable value by augmenting the air volumetric flow rate. Finally, the regeneration performance diminishes by increasing the solution volumetric flow rate.

Keywords: Liquid desiccant, solar collector/regenerator, experimental performance.

1. Introduction

The imperative need to mitigate the global environmental problems of greenhouse effect and ozone layer depletion, as well as the electrical energy consumption associated with the widespread use of vapour compression machines in air conditioning applications has recently contributed to renew the interest in direct solar thermally-driven liquid sorption systems, in which the diluted desiccant solution is reconcentrated by means of its simultaneous exposure to the solar radiation and the scavenging air stream into a single device named collector/regenerator (C/R). This equipment offers a great potential not only for simplifying and reducing the costs of liquid sorption systems via the elimination of the regeneration chamber, but also for improving the thermal regeneration efficiency through the further heating of the liquid sorbent.

When integrated to liquid desiccant systems, the solar collector/regenerator plays a key role since for every kilogram of water vapour absorbed by the concentrated solution in the dehumidifier, the same amount should be desorbed from the diluted one in the C/R (Collier, 1979), giving a direct measure of the system performance (Hawlader et al., 1992; Yang and Wang, 1995).

The solar collector/regenerators can be classified as open-type, closed-type and convective-type. Several theoretical works (Yang and Wang, 2001; Kaushik et al., 1992) and experimental studies (Gezahegn et al., 2013; Kabeel, 2005; Hawlader et al., 1997) carried out under different operating conditions have demonstrated that the convective C/R performs generally better than the other types in both humid and temperate climates, since its glazing limits the thermal losses to the ambient and also keeps the desiccant solution free from contamination due to dirt and rains. Furthermore, depending on the use of blowers, the convective collector/regenerators can operate in natural and forced ventilation modes.

Experimental studies on the performance of both counterflow forced and natural convective solar C/Rs operated under the hot humid climate of Kaohsiung, Taiwan, were realised by Yang and Wang (1994) by using aqueous LiCl solution as liquid desiccant Their findings indicated that, the water desorption rate of the forced convective C/R rose more significantly with increasing ambient temperature than for the natural convective one. Additionally, the forced convective C/R performed much better than the natural convective one for low inlet solution mass fractions from 40.90 to 42.50%. When the inlet mass fraction became higher than 42.50%, forced

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convection was unnecessary. It was also observed that the evaporation rate decreased with the glazing height for the forced convective C/R, while the natural convective C/R had an optimum glazing height.

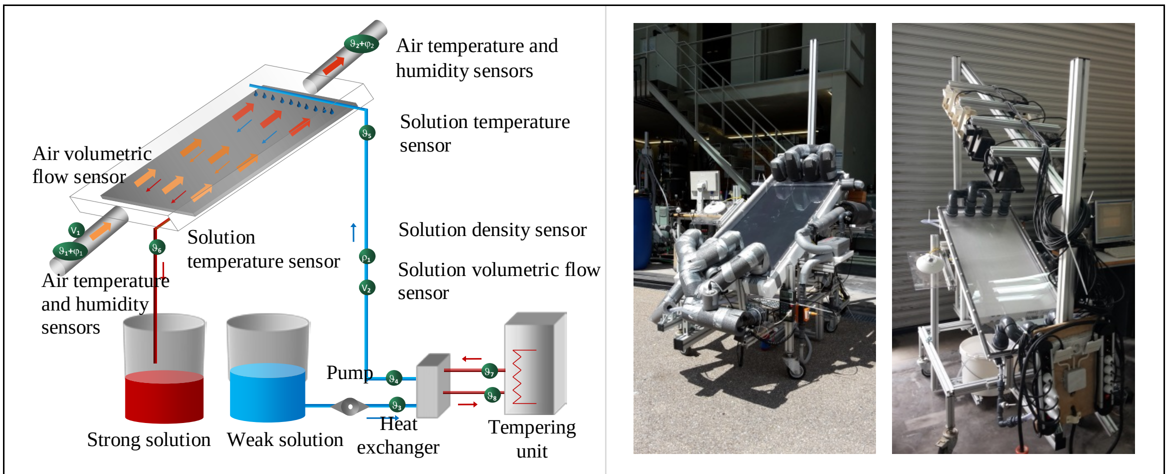
Kabeel (2005) tested a cross flow forced convective collector/regenerator and a natural convective solar regenerator with aqueous $CaCl_2$ solution as liquid sorbent. It was observed that the desorption rate and the regeneration efficiency of both C/Rs rose strongly with enhancing the air mass flow rate. However, for higher air mass flow rates, said performance indices diminished again due to the fall of the solution temperature. Furthermore, the evaporation rate and the regeneration efficiency fell with rising the inlet solution mass fraction, operating the forced cross flow regenerator better than the natural one for medium solution mass fractions. Nevertheless, the performance difference between both C/Rs was small at higher mass fractions.

Despite the studies carried out by the aforementioned authors, the relevant experimental data of convective collector/regenerators are still very scarce. This work provides some light on this issue by experimentally investigating the effect of operating parameters such as the solar radiation, the inlet solution temperature and the volumetric flow rates of air and solution as well as geometric parameters such as the gap height and the tilt angle on the performance of a single-glazed forced convective C/R.

2. System description

In order to investigate the influence of both climatic and operating conditions on the performance of a forced convective collector/regenerator, a test bench comprising a collector/regenerator, fans, solution tanks, pumps, flow regulator/indicator, PID controller, and data acquisition devices was designed and constructed in the sorption laboratory at the University of Applied Sciences Stuttgart (see Fig. 1).

The collector/regenerator is made of polycarbonate and has a total area of 0.65 m² (0.5 m width × 1.3 m length), a gap height of 0.04 m or 0.1 m and a sprinkling area of 0.5 m² (0.5 m width × 1.0 m length). Its inclination angle can be variably set. The stainless steel absorber plate is painted with a special black nanocoating lacquer and is covered with a black cotton cloth for ensuring uniform wetting and absorption of the solar radiation. The C/R can be operated in both counterflow and parallel flow modes. The forced air is supplied by an axial fan with continuous flow control in the range of 2.5 to 25 m^3/h. A solution pump delivers the desiccant solution to the liquid distributor header at flow rates between 2.5 and 15 l/h. The temperature of the liquid sorbent is controlled before entering the C/R by the combination of an ARCTIC cold bath/circulation thermostat HAAKE AC 150-A10 and a plastic heat exchanger B3-12A-30-2.0. The volumetric flow rates, temperatures, relative humidities and the densities of the fluids involved in the regeneration process are measured both at the inlet and outlet of the collector/regenerator by means of the sensors summarised in Tab. 1. Data are taken at 5 seconds interval after the initial wetting and stabilising.



(a) System sketch | (b) Test bench

Fig. 1: System sketch and test bench of the collector/regenerator.

Tab. 1: Model parameters for the analysed air- and water-based solar collectors.

Manufacturer	Sensor	Measured parameter	Measuring range	Rated accuracy
Kobold	Flowmeter MIK-5NA	Volumetric flow rate solution/water	0,6 l/h-30 l/h	± 2 %
KEY Instruments	Flowmeter MR-3000		0,24 l/h -3,0 l/h 1,2 l/h -18,0 l/h	±4 %
Honeywell	Flowmeter AWM 720P	Volumetric flow air	0-12 m^3/h	± 2 %
Rotronic	Sensor module HC2-S3	Air temperature	-10-90 °C	± 0,1 K
		Relative humidity	0-100 %	± 0,8 % R. H.
Fühlersysteme	Cable temperature sensor KT/E	Temperature solution/water	-50-250 °C	-
Anton Paar	Density transmitter L-Dens 313	Solution density	0,5-2 g/cm^3	± 0,001 g/cm^3
KippZonen	Pyranometer CMP 11	Global radiation	< 4000 W/m^2	-

3. System performance measures

The performance of the collector/regenerator is evaluated on the basis of the water desorption capacity and the water desorption rate. The water desorption capacity ($\Delta\chi_{des}$) in [kg/kg] is defined as the amount of moisture added to an air stream during the regeneration process:

$$\Delta\chi_{des}=\chi_{a,out}-\chi_{a,in} \qquad \text{(eq. 1)}$$

On the other hand, the water desorption rate ($\Delta\dot{m}_{des}$) indicates the change of the amount of water vapour transferred to the air stream $\dot{m}_a$, and therefore evaporated from the hygroscopic solution per unit time:

$$\Delta\dot{m}_{des}=\dot{m}_a\cdot(\chi_{a,out}-\chi_{a,in}) \qquad \text{(eq. 2)}$$

Where $\chi_{a,in}$ and $\chi_{a,out}$ are the absolute humidities of the air at the inlet and outlet of a sorption unit, respectively.

The fluids involved in the regeneration process are characterised through the changes of their temperature ($\Delta T_{a/s}$) and mass fraction ($\Delta\xi_s$):

$$\Delta T_{a/s}=T_{a/s,out}-T_{a/s,in} \qquad \text{(eq. 3)}$$

$$\Delta\xi_s=\xi_{s,out}-\xi_{s,in} \qquad \text{(eq. 4)}$$

The mass and energy balance between air and desiccant solution are analysed through the dimensionless quantities κ_{mass} and κ_{energy}, which are given by (Jaradat et al., 2011):

$$\kappa_{mass}=\frac{\dot{m}_a\cdot\Delta\chi_{des}}{\dot{m}_s\cdot\Delta\zeta_s} \qquad \text{(eq. 5)}$$

$$\kappa_{energy}=\frac{\dot{Q}_a+\dot{Q}_s}{\dot{Q}_{solar}} \qquad \text{(eq. 6)}$$

Where ζ_s is the water content in the desiccant solution given as function of the solution mass fraction ξ_s by eq. 6.

$$\zeta_s=\frac{1-\xi_s}{\xi_s} \qquad \text{(eq. 7)}$$

4. Experimental results and discussion

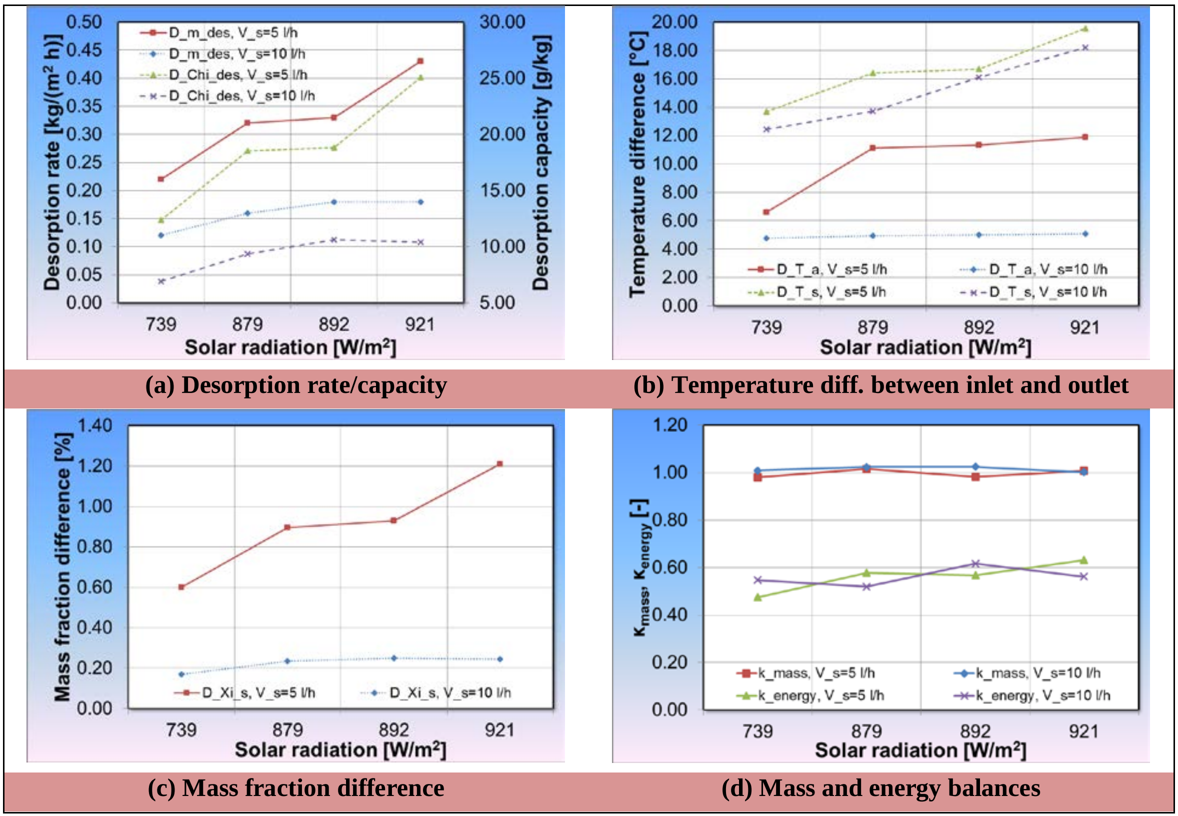
To analyse the performance potential of the collector/regenerator several measurement series were carried out under different boundary conditions for the aqueous calcium chloride ($CaCl_2$) solution at natural sunlight. The volumetric flows of the regenerating air and the hygroscopic solution were varied between 2.5 m^3/h and 25.0 m^3/h and 2.5 l/h to 15.0 l/h, respectively.

4.1 Effect of the solar radiation on the C/R performance

Fig. 2 shows that the desorption rate, the desorption capacity, the temperature differences of air stream and $CaCl_2$ solution between inlet and outlet as well as the mass fraction difference of liquid sorbent between inlet and outlet increased strongly as the solar radiation rose at the boundary conditions summarised in Tab. 2, since the absorbed solar radiation is the energy source for water evaporation from the diluted solution. Furthermore, it can be observed from Fig. 2(d) that the values of κ_{mass} for test sequences at solution volumetric flow rates of 5.24 l/h and 9.77 l/h were very close to the unity, while the values of κ_{energy} exhibited an average relative deviation of 43.8%, which reflected the heat losses mechanisms such as the radiative heat transfer between the absorber plate and the collector glazing as well as the convective and radiative thermal losses to the environment.

Tab. 2: Boundary conditions for the experiments with fluctuating solar radiation (gap height = 4 cm, tilt angle = 30°).

Test seq.	Air volumetric flow [m^3/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
1	7.50	27.15	9.41	5.11	26.19	38.24
2	7.56	29.08	8.72	10.07	24.45	37.89



(a) Desorption rate/capacity **(b) Temperature diff. between inlet and outlet**

(c) Mass fraction difference **(d) Mass and energy balances**

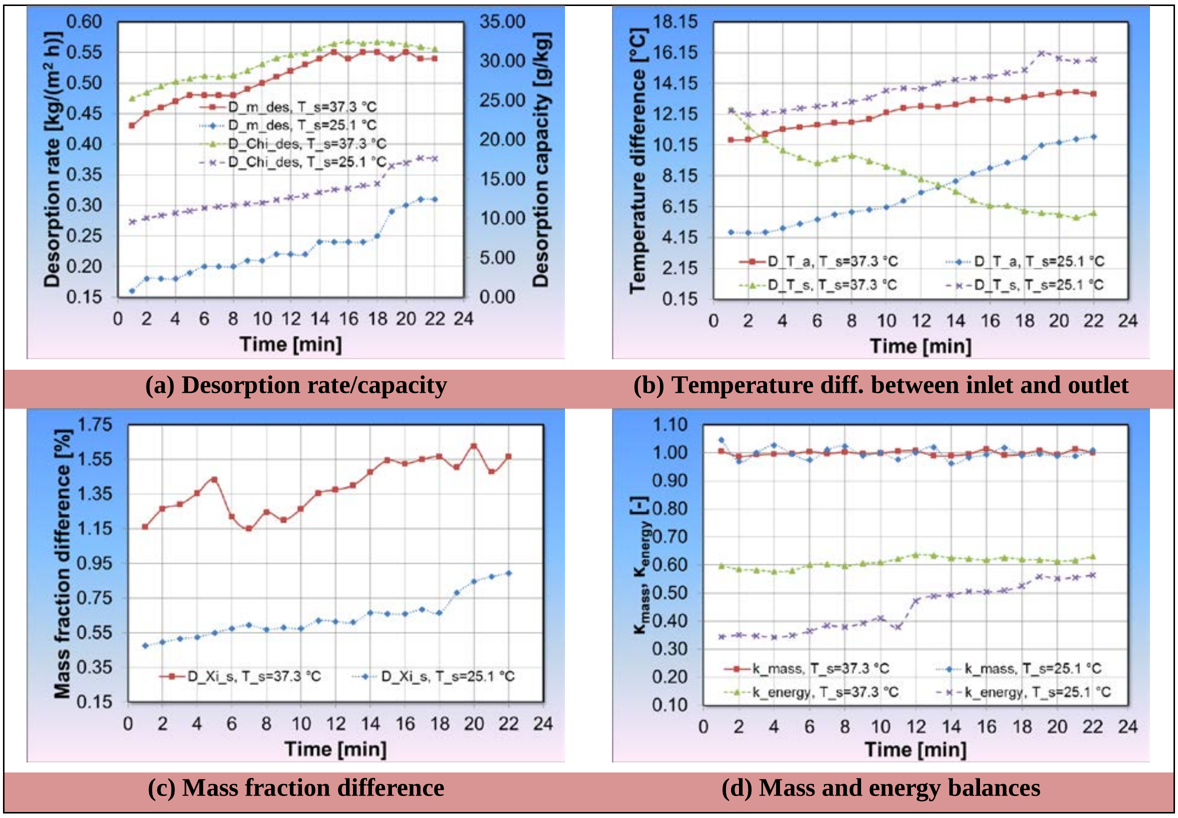
Fig. 2: Experimental results for the collector/regenerator with different solar radiation levels.

4.2 Effect of the inlet solution temperature on the C/R performance

From Fig. 3(a), it is clearly shown that both the desorption rate and the desorption capacity averagely increased by 56% as the inlet desiccant temperature rose from 25.1 °C to 37.3 °C at the boundary conditions summarised in Tab. 3. This was a consequence of the higher solution vapour pressure and the associated greater driving force for the mass transfer between the liquid sorbent and the regenerating air. According to Fig. 3(b), the temperature difference of the regenerating air averagely augmented from 7.2 °C at an inlet solution temperature of 25.1 °C to 12.3 °C at an inlet solution temperature of 37.3 °C. Moreover, the temperature difference of the liquid sorbent fell from a high value of 12.5 °C to a low one of 5.8 °C at an inlet solution temperature of 37.3 °C due to the heat transfer from the desiccant film to the adjacent air stream. Conversely, the temperature difference of the hygroscopic liquid followed an upward trend at an inlet solution temperature of 25.1 °C because of the progressive solar heating of the liquid film. On the other hand, the mass fraction difference of desiccant solution between inlet and outlet averagely rose by 54% as the inlet solution temperature enhanced from 25.1 °C to 37.3 °C (see Fig. 3(c)). Finally, the values of κ_{mass} for test sequences 3 and 4 were very close to the unity, whereas the values of κ_{energy} for same tests exhibited average relative deviations of 39.1% and 55,6%, respectively (see Fig. 3(d)), which could be result not only of the heat losses from the collector/regenerator but also of sensors' accuracy and measurement errors.

Tab. 3: Boundary conditions for the experiments with fluctuating solution temperatures (gap height = 4 cm, tilt angle = 30°).

Test seq.	Solar radiation [W/m²]	Air volumetric flow [m³/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
3	909	7.43	30.53	9.80	5.21	37.33	36.78
4	848	7.46	25.67	9.41	5.05	25.07	38.56



(a) Desorption rate/capacity **(b) Temperature diff. between inlet and outlet**

(c) Mass fraction difference **(d) Mass and energy balances**

Fig. 3: Experimental results for the collector/regenerator at different solution temperatures.

4.3 Effects of the fluid volumetric flow rates on the C/R performance

For the operating conditions analysed in experimental runs (see Tab. 4), the desorption rate obtained with the solar collector/regenerator firstly augmented with increasing the air volumetric flow rate, until it stabilised at a certain value as shown in Fig. 4(a). This net effect resulted from the combination of two facts:

- Increase of the mass transfer coefficient between the desiccant solution film and the regenerating air by enhancing the air volumetric flow rate.

- Further decrease of the solution temperature and consequently, of the solution vapour pressure and the driving force of mass transfer within the C/R by rising the air volumetric flow rate.

At a solution volumetric flow rate of 7.5 l/h, doubling the air volumetric flow rate from 5.0 m^3/h to 10 m^3/h increased the desorption rate by about 11% from 0.26 kg/(m^2 h) to 0.29 kg/(m^2 h). Said enhancement slightly rose by increasing the solution volumetric flow rate.

Conversely, as shown in Fig. 4(b), the desorption capacity decreased with augmenting the air volumetric flow rate due to the reduction in the temperature increase of the air stream in the collector/regenerator, which led to a lower vapour pressure difference between the desiccant solution and the air. At a solution volumetric flow rate of 7.5 l/h, doubling the air volumetric flow rate from 5.0 m^3/h to 10 m^3/h decreased the desorption capacity by about 43% from 21.65 g/kg to 12.26 g/kg.

Tab. 4: Boundary conditions for the experiments with fluctuating fluid volumetric flow rates (gap height = 4 cm, tilt angle = 30°).

Test seq.	Solar radiation [W/m^2]	Air volumetric flow [m^3/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
5	873-918	4.96- 25.08	28.57-30.03	9.52-10.40	2.47	24.93-25.87	37.70-38.18
6	870- 920	4.96-24.97	25.79-28.66	8.76- 9.80	4.98	24.61-25.80	37.49-38.16
7	886-928	2.52-25.03	26.03-32.40	9.43-9.93	7.44	24.53-25.47	37.42-38.25
8	875-922	2.61-24.95	25.45-31.37	8.64-9.44	10.03	24.59-25.22	37.42-38.12
9	872-904	2.41-24.99	24.70-28.88	8.93-9.85	15.01	24.78-25.23	37.30-38.00

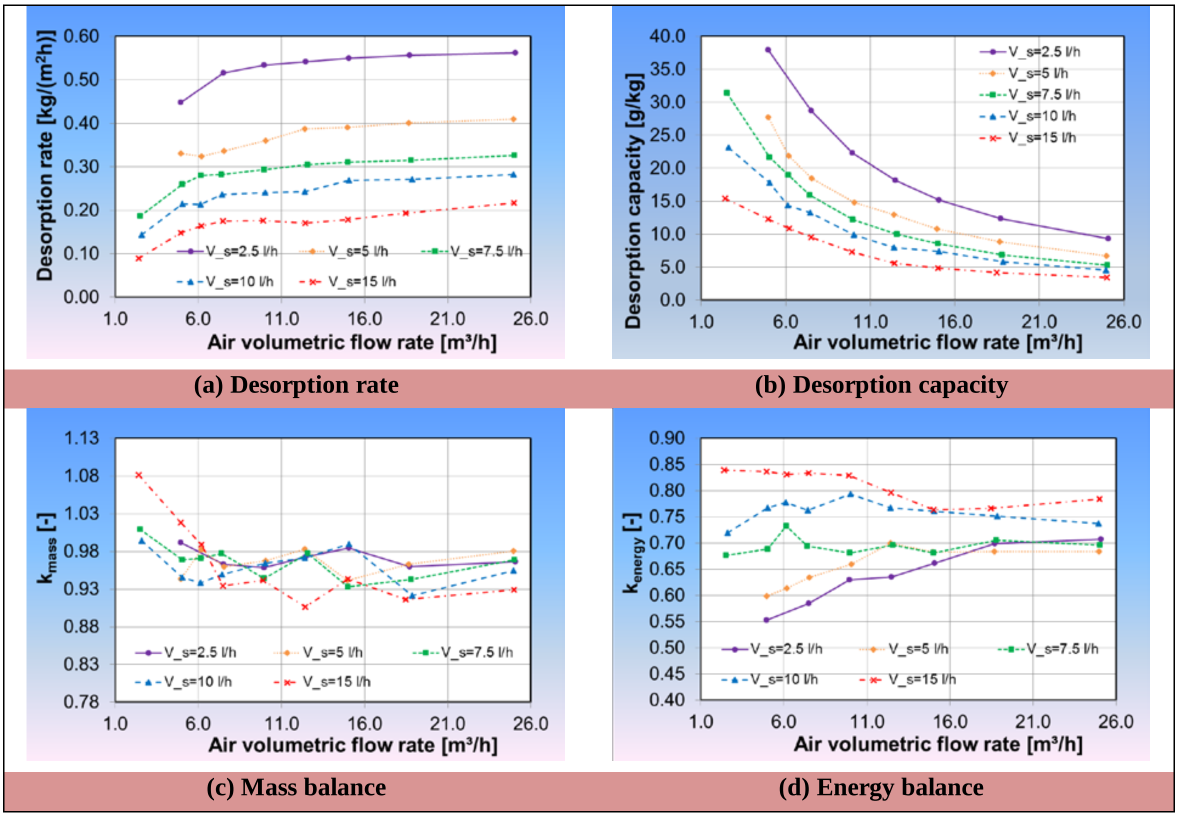


Fig. 4: Experimental results for the collector/regenerator at different fluid volumetric flow rates.

On the other hand, the desorption rate and the desorption capacity decreased with augmenting the solution volumetric flow rate as shown in Fig. 4(a) and Fig. 4(b). The higher the solution volumetric flow rate, the shorter the residence time of the liquid sorbent within the collector/regenerator. Consequently, the hygroscopic solution was heated little, thus reducing the vapour pressure difference between the solution film and the air. At an air volumetric flow rate of 15.0 m^3/h, doubling the solution volumetric flow rate from 5.0 l/h to 10.0 l/h reduced both the desorption rate and the desorption capacity by about 31% from 0.39 kg/(m^2 h) to 0.27 kg/(m^2 h) and from 10.79 g/kg to 7.39 g/kg, respectively. These reductions slightly increased by enhancing the air volumetric flow rate. Finally, according to Fig. 4(c) and Fig. 4(d), the values of κ_{mass} were very close to the unity, whereas the values of κ_{energy} were deviated from the unity, especially at lower solution volumetric flow rates. These deviations reflected both the heat losses mechanisms from the collector/regenerator and problems related to sensors' accuracy and measurement errors.

4.4 Effects of the gap height on the C/R performance

At a constant air volumetric flow rate, the reduction of the gap height led to an average increase in the flow velocity of the regenerating air within the collector channel. The higher the air volumetric flow rate, the greater the enhancements in the air flow velocity and in the Reynolds number. As a result, the heat and mass transfer coefficients between the desiccant solution and the regenerating air also augmented. According to the operating conditions summarised in Tab. 4 and Tab. 5 for a solution volumetric flow rate of 7.5 l/h, the desorption rate and the desorption capacity averagely increased by about 5% by reducing the gap height from 10 cm to 4 cm (see Fig. 5). Greater increases in the regeneration performance were achieved at low air volumetric flow rates.

Tab. 5: Boundary conditions for the experiments with fluctuating fluid volumetric flow rates (gap height = 10 cm, tilt angle = 30°).

Test seq.	Solar radiation [W/m^2]	Air volumetric flow [m^3/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
10	863-909	5.09-25.20	30.06-35.03	9.09-11.08	2.41	24.58-26.48	37.54-38.13
11	885-923	4.87-25.03	31.64-33.98	9.38-11.39	4.96	24.65-25.78	37.39-38.07
12	883-934	2.48-25.10	29.57-33.66	9.57-11.79	7.52	24.84-25.59	37.36-37.90
13	891-918	2.55-24.90	28.36-32.80	10.16-12.16	10.00	24.82-25.43	37.47-37.90
14	877-913	2.63-25.06	25.98-31.46	9.85-12.25	15.01	24.97-25.26	37.54-37.82

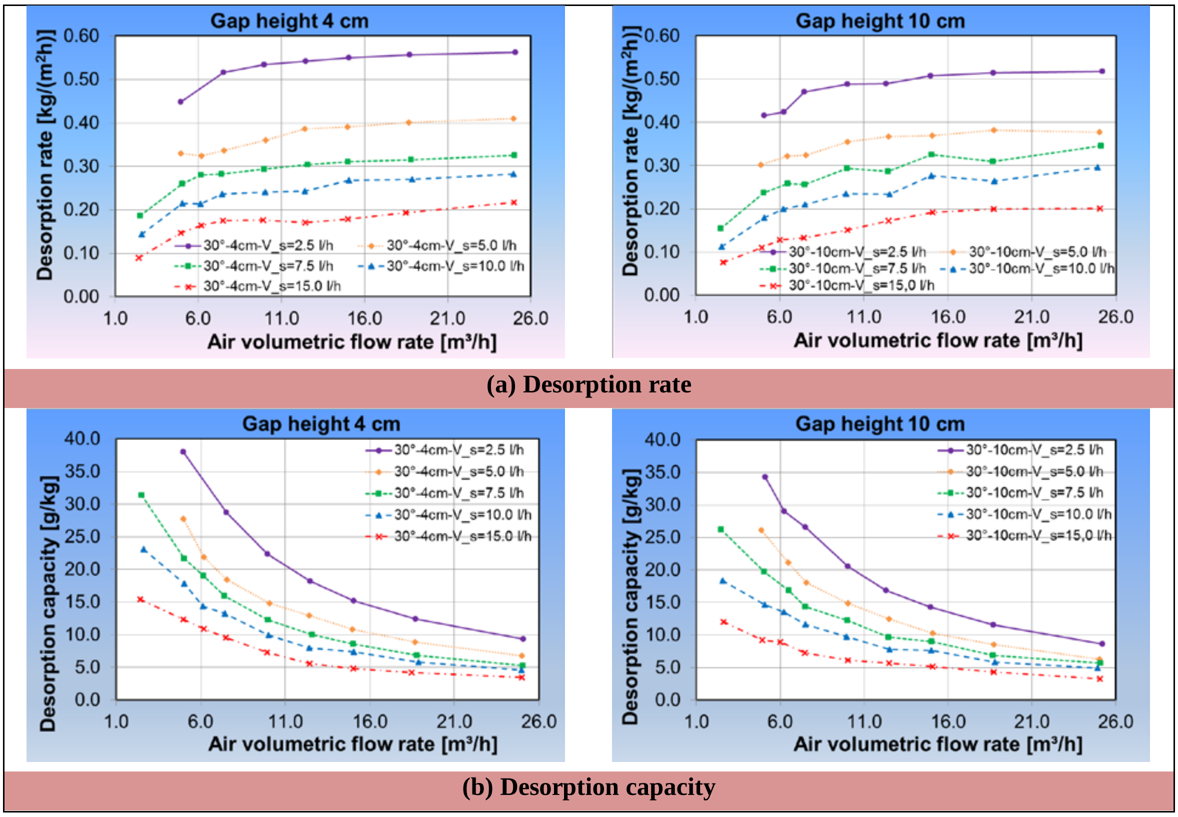


Fig. 5: Experimental results for the collector/regenerator at different fluid volumetric flow rates and gap heights.

4.5 Effects of the tilt angle on the C/R performance

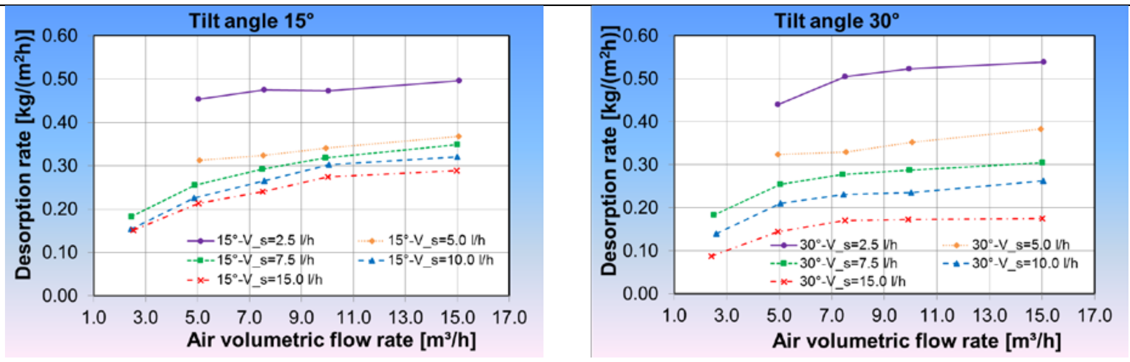
From Fig. 6, the regeneration performance could be increased by reducing the inclination angle of the collector/regenerator from 30° to 15° due to the longer residence time of the desiccant solution on the absorber surface. Consequently, the liquid sorbent was quickly heated. According to the operating conditions summarised in Tab. 5 and Tab. 6 for a solution volumetric flow rate of 7.5 l/h, both the desorption rate and the desorption capacity averagely augmented by about 6% by decreasing the tilt angle from 30° to 15°.

Tab. 6: Boundary conditions for the experiments with fluctuating fluid volumetric flow rates (gap height = 4 cm, tilt angle = 15°).

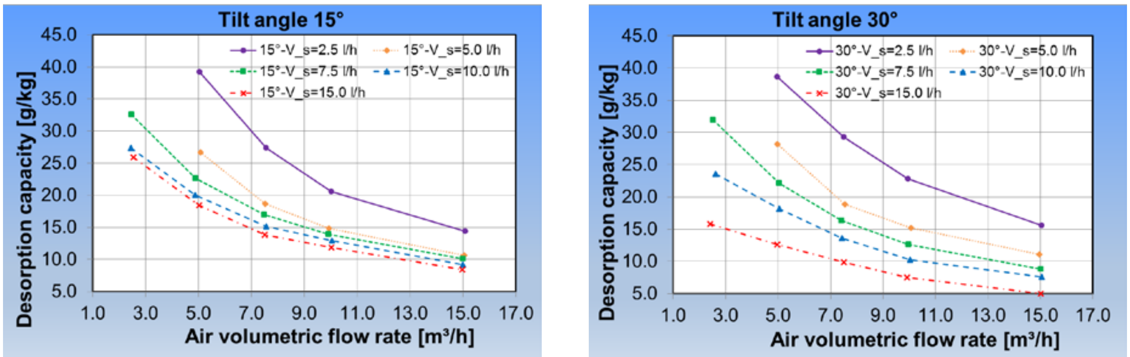
Test seq.	Solar radiation [W/m²]	Air volumetric flow [m³/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
15	876-897	5.04-15.08	29.53-30.56	8.81-9.04	2.49	24.90-25.38	37.56-38.04
16	885-900	5.08-15.05	26.84-28.75	9.04-9.45	5.03	24.75-25.27	37.54-38.04
17	872-894	2.46-14.99	28.03-30.49	8.44-8.73	7.56	24.83-25.26	37.52-37.89
18	868-936	2.44-15.00	26.51-28.73	8.32-8.66	10.03	24.93-25.01	37.38-38.07
19	866-911	2.54-14.97	28.00-29.80	8.44-8.73	15.00	24.87-25.21	37.41-37.88

Tab. 7: Boundary conditions for the experiments with fluctuating fluid volumetric flow rates (gap height = 4 cm, tilt angle = 30°).

Test seq.	Solar radiation [W/m²]	Air volumetric flow [m³/h]	Air temperature [°C]	Air absolute humidity [g/kg]	Solution volumetric flow rate [l/h]	Solution temperature [°C]	Solution mass fraction [%]
20	873- 918	4.96-15.06	28.57-29.71	9.52- 9.89	2.48	24.93-25.87	37.77-38.18
21	883-911	4.96-14.96	25.79-27.96	8.76-9.17	4.95	24.82-25.80	37.49-38.11
22	905-928	2.52-15.01	29.60-32.40	9.66-9.93	7.41	24.53-25.47	37.42-38.25
23	875-922	2.61-15.05	29.22-31.37	8.64-8.95	9.94	24.59-25.22	37.44-38.12
24	872-904	2.41-24.99	24.70-28.88	8.93-9.85	15.01	24.78-25.23	37.30-38.00



(a) Desorption rate



(b) Desorption capacity

Fig. 6: Experimental results for the collector/regenerator at different fluid volumetric flow rates and tilt angles.

5. Conclusions

A single-glazed forced convective collector/regenerator was experimentally tested at the climatic conditions of Stuttgart. The experimental tests results indicated that the volumetric flow rates of the air and the desiccant solution as well as the gap height and the tilt angle of the collector played an important role in the assessment of the regeneration performance. Further studies will be carried out in order to optimise the construction of the C/R for specific requirements of air conditioning applications.

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