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Study of Desiccant Regeneration in a Structured Packed Tower

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Abstract: The performance of a liquid desiccant regenerator, equipped with structured packing made of wood, was investigated for the regeneration of triethylene glycol (TEG). The effects of air and desiccant flow rates, air and desiccant temperature, and desiccant concentration were studied to assess their impact on the regeneration process. The influence of these parameters on the performance of the desiccant regenerator was evaluated in terms of the rate of water evaporation and the effectiveness of the regeneration process. It was found that under the conditions of this study, the desiccant inlet temperature was the most favorable variable, while the inlet desiccant concentration was the least favorable with respect to the regeneration process. The air mass flux increased the rate of water evaporation, but reduced the regenerator effectiveness significantly. The other parameters had a negligible effect. The results of this study were in agreement with the Chung and Luo correlation and published literature.

Keywords: Triethylene glycol (TEG), desiccant, regenerator performance, structured packing, air conditioning, dehumidification

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INTRODUCTION

Liquid desiccant cooling systems have been employed to reduce the latent cooling load in vapor compression air conditioning systems, as well as to control air humidity (1). Since desiccants are able to absorb more than simply water vapor, they can also remove contaminants and odors from an air stream to improve indoor air quality. Furthermore, desiccants have been used to eliminate organic vapors, and in special circumstances, to control microbiological contaminants (2). Previous work (1, 3, 4) showed that a liquid desiccant cooling system can reduce the overall energy consumption and shift the energy use from electricity to renewable energy or cheaper fuels. The first non-industrial application, where desiccant-cooling equipment received acceptance, was in supermarkets (5).

The main components of a liquid desiccant cooling system are the dehumidifier (or absorber), and the regenerator (or stripper) (6, 7). Desiccants absorb (or release) moisture because of the difference in vapor pressure between the surface of the desiccant and the surrounding air. Air dehumidification is said to occur when the vapor pressure at the desiccant surface is lower than that of the air (8). The moisture that diffuses from the air to the desiccant causes a dilution of the desiccant, which must be regenerated (i.e. concentrated) to restore the original condition (9). Regeneration of this spent desiccant, (i.e., the desiccant released moisture and so the absorbent solution was concentrated), is said to occur when the water vapor pressure of the desiccant is higher than that of the surrounding air. This is usually achieved by heating the desiccant to its regeneration temperature and bringing it in contact with an air stream (8).

The equipment commonly utilized to bring the desiccant and air in contact are wetted wall/falling film absorbers, and spray chambers or packed towers (2, 10–17). These absorbers and regenerators have been studied by researchers for desiccant cooling, with more emphasis being on packed towers. The latter have a higher pressure drop and initial cost, but provide a high contact area per unit volume between air and desiccant for moisture transfer to take place. Spray chambers are not that effective but are compact and have low initial cost and pressure drop. Wetted wall columns not only have low-pressure drop and low initial cost, but also provide high contact area per unit volume. They seem to be ideally suited for desiccant cooling systems, since airside pressure drop is important for keeping energy costs low (7).

The economics of a desiccant operation depend on the desiccation cycle. In the air dehumidification process, it generally proceeds without much energy input, other than that for fan and pump requirements. Some cooling may be required in this process but it is insignificant compared with that needed in the regeneration process. However, in the regeneration process, in addition to the fan and pump power requirements, energy is needed for heating and cooling of the desiccant. Since the largest energy requirement is for desiccant regeneration, the process greatly influences the overall system performance. Regeneration requires heat which can be supplied by gas, solar or waste heat (18). Different ways for regenerating liquid desiccants have been proposed (1, 19–21). Equipment commonly employed as regenerators in desiccant systems are: boilers (22, 23), solar trickle collector regenerators (24, 25), spray chambers containing hot water finned coils (10, 13), and packed bed absorption towers (14–17, 26).

Many design parameters and operating conditions affect the performance of the packed bed dehumidifier/regenerator. Examples of these variables are: air and desiccant flow rates, air temperature and humidity, desiccant temperature and concentration, and the area available for heat and mass transfer. The influence of these and other design variables must be known in order to properly simulate the performance of the packed bed dehumidifier/regenerator (27).

A number of experimental studies have been reported in the open literature regarding packed bed tower operating as a desiccant dehumidifier. For example, Fumo and Goswami (1), Chung et al. (28), Chen et al. (29), Patnaik et al. (30), McDonald et al. (31), Potnis and Lenz (32), and Ullah et al. (33) carried out experiments on packed bed dehumidifiers using salt solutions as the desiccant. Öberg and Goswami (26), Chung et al. (34), Park et al. (35), Peng and Howell (36), Chebbah (37), Park et al. (38, 39), Chung and Luo (40), and Chung and Wu (41) reported experimental results using triethylene glycol as the desiccant. Moreover, Chung (42) reported some experimental findings using both lithium chloride and triethylene glycol as the desiccant. A summary of the variables investigated by various researchers, the ranges and effects of these variables on moisture removal rate and dehumidifier effectiveness can be seen in previous work from our group (15–17).

Data on packed bed tower operating as a desiccant regenerator has also been reported (21, 30, 32, 43, 44). Löf et al. (21) examined the regeneration of lithium chloride in a packed bed using heated air as a regeneration heat source. The study assessed the overall heat and mass transfer coefficients as a function of flow rates and inlet temperatures. Patnaik et al. (30) conducted experiments on a packed bed tower for the regeneration of aqueous lithium bromide. Ertas et al. (43) reported on using a mixture of calcium chloride and lithium chloride in an aqueous solution as a desiccant. They investigated desiccant regeneration as a function of desiccant flow rate, inlet desiccant conditions (temperature and concentration), and inlet air humidity. Potnis and Lenz (32) conducted an experimental study which considered the impact of desiccant flow rate on the regeneration of aqueous lithium bromide in a packed bed regenerator, as well as in a packed bed dehumidifier. Martin and Goswami (44) carried out experiments on packed bed regenerator, using triethylene glycol as a desiccant. They provided additional data for desiccant regeneration, showing that higher desiccant flow rates were necessary to ensure adequate wetting of the packing. Higher liquid flow rates were used in their study compared to those conducted earlier by others. Moreover, Fumo and Goswami (1) presented the performance of a packed tower absorber and regenerator for an aqueous lithium chloride desiccant system. The rates of dehumidification and regeneration as well as the effectiveness of the dehumidification and regeneration processes were assessed.

In this paper, the performance of a structured packed tower regenerator was investigated using triethylene glycol (TEG) as the desiccant. The performance of the desiccant regenerator, with a structured packing density of 200 m^2/m^3, was evaluated and expressed in terms of the rate of water evaporation (i.e., the regeneration rate), as well as the effectiveness of the regeneration processes. Regeneration was assessed under the effects of various operating conditions such as air and desiccant flow rates, air temperature and humidity, and desiccant temperature and concentration. Results were compared with literature correlations.

EXPERIMENTAL

For desiccant regeneration, the air conditioned to the required temperature and humidity at the air conditioning (AC) unit was introduced into the contact tower from the bottom (Fig. 1). The tower had a total height of 0.6 m with a

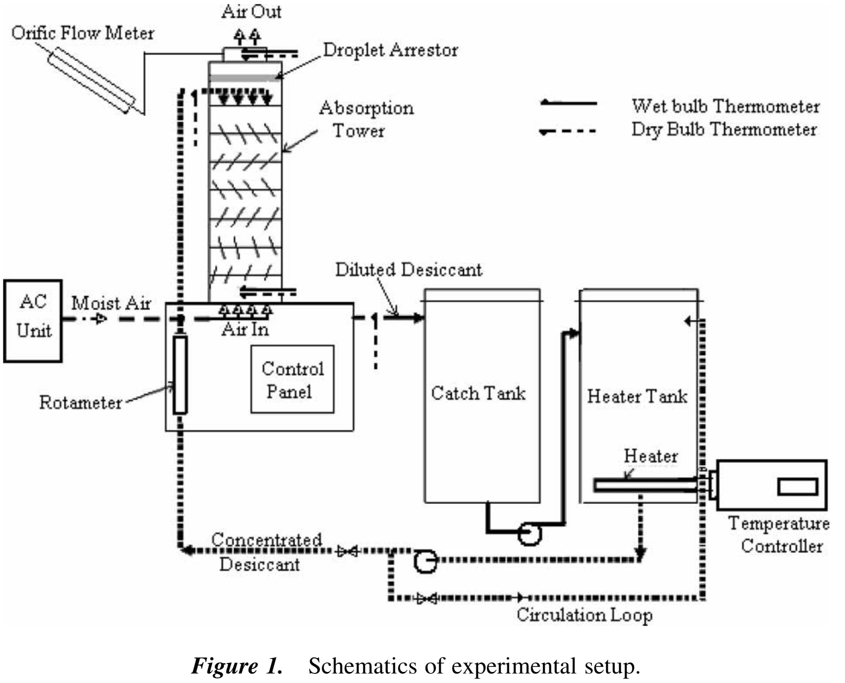

Figure 1. Schematics of experimental setup.

structured type packing consisting of 8 decks with 18 plates per deck resulting in packing density of $200\,m^2/m^3$ and a packing height of 0.48 m. Triethylene glycol (TEG) was employed as the desiccant. The latter, at the required temperature, concentration, and flow rate, was pumped into the top of the tower via the rotameter. The desiccant, flowing countercurrent relative to the dry air, was distributed over the packing. It absorbed moisture as it came into contact with the humid air. The concentrated desiccant flowed by gravity to the catch tank where it was stored. Uniform temperature and concentration of the desiccant were ensured using an electric heater with temperature controller and the circulation loop shown in Fig. 1. The flow rate was monitored using a rotameter that had been calibrated under different desiccant temperatures. The dry bulb and wet bulb air temperatures were monitored using mercury thermometers located at the inlet (bottom) and exit (top) of the absorption tower. Also, two more mercury thermometers were employed to measure the inlet (tower top) and exit (tower bottom) desiccant temperatures. The air flow rate was monitored using an orifice flow meter.

During a run, the inlet and exit temperatures and flow rates of both the desiccant and the air were measured after allowing for sufficient time for steady state to be reached. Samples of the inlet and exit TEG solution were then collected. The TEG concentration was determined using a calibrated refractive index meter. Before each run the entire contact column including the packing, the thermometers, and the droplet arrester were cleansed using fresh water and then dried using warm and dry air supplied from the AC unit.

To prepare the diluted desiccant at the desired temperature and concentration, the concentrated desiccant was pumped from the catch tank to the heater tank. Then a predetermined amount of distilled water was added. The heater as well as the circulation pump was then turned on. The prepared solution was, after that, pumped to the contact tower where the desiccant came into contact with the dry air supplied from the AC unit.

The performance of the regeneration process considered in this study was evaluated by calculating the rate of mass evaporated ($\dot{m}_{evap}$) and the column effectiveness (ε_Y) from the following relations:

$$\dot{m}_{evap} = G.A.(Y_{out} - Y_{in}) \quad (1)$$

$$\varepsilon_Y = \frac{Y_{out} - Y_{in}}{Y_{equ} - Y_{in}} \quad (2)$$

where G is the air mass flux and A the packed column cross-sectional area. Y_{in} and Y_{out} are the air inlet and outlet specific humidities. Y_{equ} is the air equilibrium specific humidity of the air at equilibrium with the desiccant at the inlet concentration and temperature.

For comparison, the column effectiveness under the conditions of this study was also calculated from a correlation by Chung and Luo (40).

$$\varepsilon_Y = \frac{1 - \{0.024(G_{in}/L_{in})^{0.6} \exp[1.057(T_{G_{in}}/T_{L_{in}})]/(az)^{-0.185} X^{0.638}\}}{1 - \{0.192 \exp[0.615(T_{G_{in}}/T_{L_{in}})]/X^{-21.498}\}} \quad (3)$$

where X is defined as a function of the ratio of desiccant solution vapor pressure depression to the pure water vapor pressure $((P_{water}\text{-}P_{soln})/P_{water})$, a is the surface area-to-volume ratio of packing in m^2/m^3, z is the packing height in m, $T_{G_{in}}$ and $T_{L_{in}}$ denote the inlet temperatures of the air and the desiccant, respectively. G_{in} and L_{in} represent the mass flux of air and desiccant, respectively.

RESULTS AND DISCUSSION

The results obtained in this study are presented in Table 1 and Figs. 2–6. The mass of water evaporated increased as the air mass flux (G) increased (Fig. 2a) This was attributed to the fact that the increasing G made better contact between the gas and the liquid phases. On the other hand, as G increased the air outlet specific humidity (Y_{out}) decreased resulting in a lowering of the column effectiveness (see Equation (2) and Fig. 2b). At $G = 0.5\,kg/m^2$-s, Y_{out} was the highest. This was due to two factors; the small air flow rate and the high desiccant inlet temperature (50 °C). The effectiveness calculated from the Chung and Luo correlation (40) was less affected by G (Equation (3)). This could be attributed to the fact that the correlation was developed from data generated using highly dense and random packing whereas structured and less dense packing was used in this study. In addition, the Chung and Lou correlation (40) was developed from experimental data using relatively higher air and desiccant mass fluxes, G and L.

Figure 3 shows the effect of air inlet temperature ($T_{a,\ IN}$) on the water evaporation rate and the column effectiveness. Over the temperature range covered in this study, it was noticed that while Y_{in} and Y_{eq} were fixed, the outlet specific humidity Y_{out} increased as $T_{a,\ IN}$ went up, resulting in a slight improvement in the effectiveness. The effectiveness predicted by the Chung and Luo correlation (40) indicated no change in this range. Furthermore, in the temperature range investigated, the results for the mass evaporated (Fig. 3a) indicated that the effect of $T_{a,\ IN}$ on the column regeneration performance was not significant.

The consequence of desiccant inlet concentration on the water evaporation rate and column effectiveness is presented in Fig. 4. The Chung and Luo correlation (40) showed that ε_Y was not affected by increasing the desiccant concentration (Fig. 4b). However the results of this study showed a decrease in ε_Y as the desiccant concentration increased. This was reasonable as less water was dissolved in the concentrated desiccant (affecting Y_{out},

Table 1. Experimental data for TEG-air-water system in structured packed tower regenerator

Air flux (kg/m2 s)	Liquid flux (kg/m2 s)	Air inlet temperature (°C)	Air inlet humidity (kg H_2O/kg dry air)	Air outlet humidity (kg H_2O/kg dry air)	Liquid inlet temperature (°C)	TEG concentration (wt. %)	Equilibrium humidity (kg H_2O/kg dry air)	Water evaporation rate (g/s)	Effectiveness
0.5	1.33	35	0.0135	0.0306	50	90.0	0.03176	0.193	0.937
1.0	1.33	35	0.0135	0.0292	50	90.0	0.03176	0.354	0.862
1.5	1.33	35	0.0148	0.0269	50	90.0	0.03176	0.408	0.711
2.6	1.33	35	0.0162	0.0267	50	90.0	0.03176	0.611	0.671
3.0	1.33	35	0.0174	0.0260	50	90.0	0.03176	0.574	0.592
1.0	1.33	35	0.0156	0.0283	50	89.0	0.02907	0.287	0.951
1.0	1.33	35	0.0152	0.0277	50	89.5	0.02996	0.280	0.850
1.0	1.33	35	0.0151	0.0270	50	90.0	0.03176	0.266	0.709
1.0	1.33	35	0.0148	0.0265	50	90.5	0.03267	0.264	0.647
1.0	1.33	35	0.0138	0.0254	50	91.0	0.03312	0.261	0.560
1.0	0.51	35	0.0127	0.0281	50	90.0	0.03176	0.345	0.806
1.0	0.92	35	0.0127	0.0290	50	90.0	0.03176	0.367	0.857
1.0	1.33	35	0.0129	0.0297	50	90.0	0.03176	0.379	0.893
1.0	1.74	35	0.0129	0.0299	50	90.0	0.03176	0.383	0.903
1.0	2.16	35	0.0130	0.0306	50	90.0	0.03176	0.395	0.937
1.0	2.66	35	0.0134	0.0310	50	90.0	0.03176	0.397	0.960
1.0	3.16	35	0.0135	0.0315	50		0.03176	0.405	0.985
1.0	1.33	35	0.0137	0.0235	45	90.0	0.02462	0.222	0.902
1.0	1.33	35	0.0138	0.0249	47	90.0	0.02639	0.249	0.881
1.0	1.33	35	0.0140	0.0295	50	90.0	0.03176	0.351	0.875

(*continued*)

Table 1. Continued

Air flux (kg/m2 s)	Liquid flux (kg/m2 s)	Air inlet temperature (°C)	Air inlet humidity (kg H_2O/kg dry air)	Air outlet humidity (kg H_2O/kg dry air)	Liquid inlet temperature (°C)	TEG concentration (wt. %)	Equilibrium humidity (kg H_2O/kg dry air)	Water evaporation rate (g/s)	Effectiveness
1.0	1.33	35	0.0143	0.0316	53	90.0	0.03448	0.390	0.858
1.0	1.33	35	0.0144	0.0334	55	90.0	0.03722	0.427	0.833
1.0	1.33	35	0.0146	0.0381	57	90.0	0.04465	0.530	0.783
1.0	1.33	31	0.0112	0.0276	50	90.0	0.03176	0.368	0.796
1.0	1.33	32	0.0115	0.0278	50	90.0	0.03176	0.368	0.806
1.0	1.33	35	0.0129	0.0293	50	90.0	0.03176	0.368	0.867
1.0	1.33	37	0.0136	0.0303	50	90.0	0.03176	0.376	0.919
1.0	1.33	40	0.0150	0.0317	50	90.0	0.03176	0.376	0.995

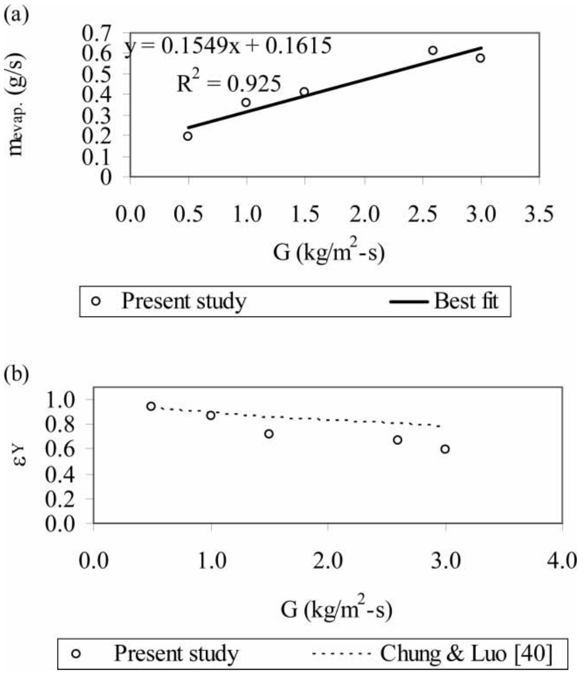

Figure 2. The effect of air flux on evaporation rate and regeneration effectiveness.

which was reduced). Therefore less would be evaporated at the same conditions, mainly at low air flow rate ($G = 1\,kg/m^2{\cdot}sec$). Since G and Y_{in} were kept constant in this case, the water evaporation rate decreased as Y_{out} decreased. Increasing the desiccant concentration by 2% decreased the evaporation rate by about 10% (Fig. 4a).

As shown in Fig. 5a, the water evaporation rate increased as the desiccant flow rate (L) was raised. This was reasonable as the contact was enhanced, more water vapor would be released and thus increasing Y_{out}. This would also lead to an improvement in the column effectiveness (Fig. 5b), since Y_{in} and Y_{eq} remain constant under such conditions. However, the augmentation in the rate of water evaporation under these circumstances was limited; the increase was 17% for a six–fold enhancement in the flow rate. The effectiveness approached unity, which meant Y_{out} became very close to Y_{eq}. This decreased the driving force. The agreement was good between our experimental data and the Chung and Luo correlation as shown in Fig. 5b.

Fig. 6 shows the effect of desiccant inlet temperature ($T_{L,\ IN}$) which influenced both Y_{out} and Y_{eq}. As the desiccant inlet temperature was raised, Y_{eq} increased, as it was a function of temperature and inlet concentration, the latter being constant in this case. In addition Y_{out} became greater with $T_{L,\ IN}$. Initially the increase in Y_{out} and Y_{eq} was proportional. At high

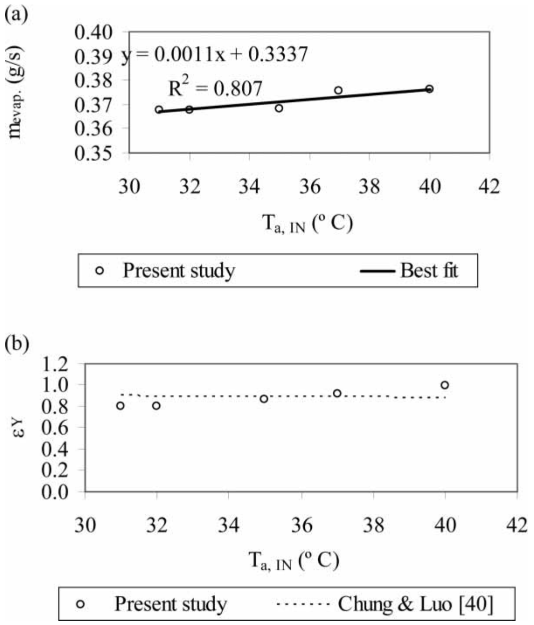

Figure 3. The effect of air inlet temperature on evaporation rate and regeneration effectiveness.

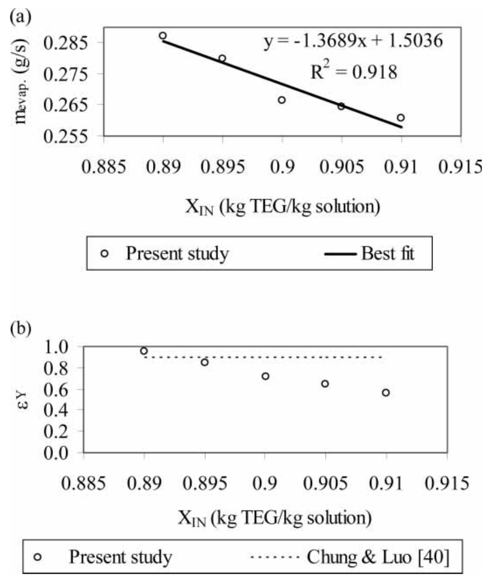

Figure 4. The effect of TEG inlet concentration on condensation rate and dehumidification effectiveness.

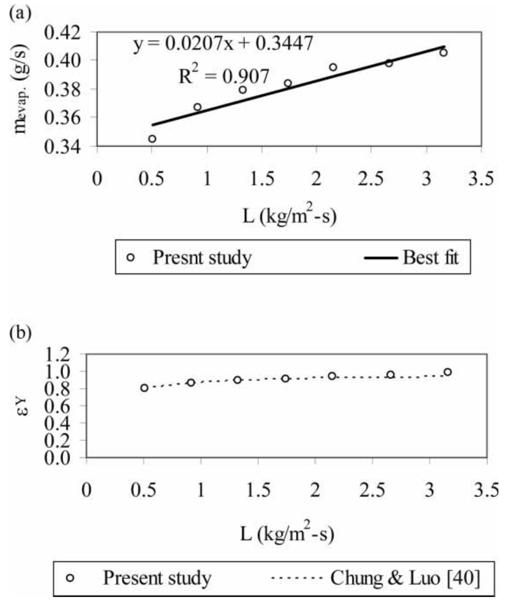

Figure 5. The effect of TEG flux on condensation rate and dehumidification effectiveness.

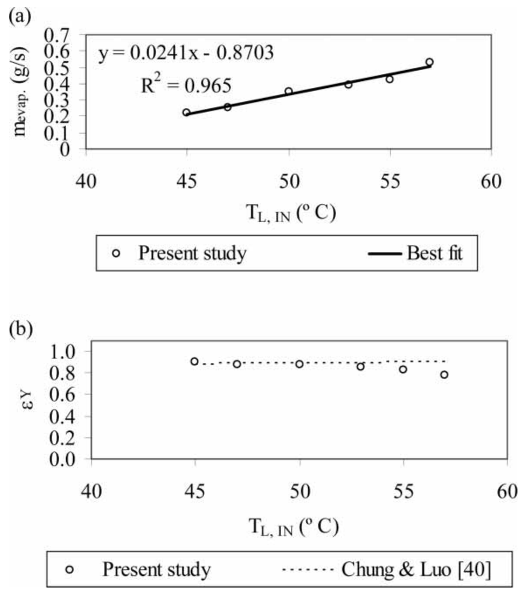

Figure 6. The effect of TEG inlet temperature on condensation rate and dehumidification effectiveness.

temperature the improvement in Y_{eq} was greater, making ε_Y less with increasing desiccant inlet temperature. The decrease in ε_Y became more pronounced at high $T_{L,\ IN}$.

Based on the results obtained in this study it was found that the desiccant inlet temperature ($T_{L,\ IN}$) was the most influential variable in the regeneration process. Increasing $T_{L,\ IN}$ by 12°C, improved the water evaporation rate (m_{evap}) by more than 100%, whereas a 9°C increase in $T_{a,\ IN}$ enhanced m_{evap} by only 2%. In regeneration it was found to be more convenient to heat the desiccant than to heat the incoming air. This should not be surprising since it is easier to heat a liquid than a gas due to the physical properties of gases and liquids (Table 1).

Table 2 summarizes the effect of the parameters considered in this study on the regeneration process with regard to column effectiveness and the mass evaporated. G and $T_{L,in}$ had the most effect on the mass evaporated. However increasing G reduced the column effectiveness significantly. On the other hand, increasing $T_{L,in}$ had a negligible effect on the column effectiveness. The desiccant concentration, even with the small range considered in this study, had a strong effect on the ε_Y, but a negligible effect on the mass evaporated. This showed that $T_{L,in}$ was the most influential parameter in regeneration. The results obtained in this study were in agreement with previous studies on the effect of system parameters on the column effectiveness and water evaporation rate (Table 3). Although Martin and Goswami (44) indicated no effect due to desiccant mass flux (L), the results of our study showed a slight increase. This might be due to the higher range of L considered in their study relative our work. There was disagreement between the results of Patanaik et al. (30) and those obtained in the current study on the effect of $T_{a,\ IN}$. The range of $T_{a,\ IN}$ in their work was much higher than that considered in our study. As mentioned above, heating the desiccant was more effective and feasible than heating the incoming air (increasing $T_{a,\ IN}$). Therefore, going for high inlet air temperature might not be effective. Increasing the air mass flux made the difference between the air inlet and outlet specific humidity (Y_{in} and Y_{out}) very small, resulting in a reduction in the column effectiveness.

Table 2. Summary of the effect of parameters on the regeneration process

Parameter (range)	ε_Y	$\Delta\varepsilon_Y$	Mass evaporated (g/s)	Change in mass evaporated
G (0.5–3.0)	0.94–0.59	−0.35	0.19–0.57	0.36
Conc. (0.89–0.91)	0.95–0.56	−0.39	0.29–0.26	−0.03
L (0.51–3.20)	0.99–0.81	0.18	0.35–0.41	0.06
$T_{L,in}$ (45–57)	0.90–0.83	−0.07	0.22–0.53	0.31
$T_{a,in}$ (31–40)	1.00–0.78	0.22	0.37–0.38	0.01

Table 3. Effect of design variables investigated in this study as well as those reported in the Literature

Reference	Desiccant	Performance parameter	Independent variable				
Present study	TEG		$L kg/m^{2-}s$	$X_{in} kg/kg$	$T_{L, IN}$(°C)	$G kg/m^2 - s$	$T_{a, IN}$(°C)
			0.5–3.16	.89–.91	45–57	0.5–3.0	31–40
		M_{evap}	↑	↓	↑	↑	↑ ↓
		ε_y	↑	↓	↑ ↓	↓	↑ ↓
Fumo and Goswami (1)	LiCl		$L kg/ m^{2-}s$	$X_{in} kg/kg$	$T_{L,IN}$(°C)	$G kg/m^2 - s$	$T_{a, IN}$(°C)
			5.2–7.57.54	.33–.349	54.2–60	0.8–1.44	29.4–40
		M_{evap}	↑	↓	↑	↑	↑ ↓
Martin and Goswami (44)	TEG		$L kg/ m^{2-}s$	$X_{in} kg/kg$	$T_{L,IN}$(°C)	$G kg/m^2 - s$	$T_{a,IN}$(°C)
			4.2–6.5	93–.95	60–70	0.4–2.0	30–50
		M_{evap}	↑ ↓	↓	↑	↑	↑ ↓
		ε_y	↑ ↓	↑ ↓	↑ ↓	↓	↑ ↓
Patanaiket al. (30)	LiBr		$L kg/m^{2-}s$	$X_{in} kg/kg$	$T_{L,IN}$ (C)	Y_{in} (g/kg)	$T_{a,IN}$ (C)
			1.1–1.5	0.57–6	40–56	5–9	55–75
		M_{evap}	↑	↓	↑	↓	↑
Potnis and Lenz (32)	LiBr				L (kg/ $m^{2-}s$)		
					1–3		
		M_{evap}			↑		

↑ Performance parameter increases with increasing variable

↓ Performance parameter decreases with increasing variable

↑ ↓ Variable has no significant on the performance parameter

CONCLUSIONS

The results showed that as the air mass flux increased, the rate of water evaporation improved but the column effectiveness decreased. On the other hand, raising the inlet temperature of the desiccant increased the rate of water evaporation. This had a negligible effect on the column effectiveness. The inlet desiccant concentration had a strong negative effect on the column effectiveness. The results of this study were in close agreement with the Chung and Luo correlation for predicting the column effectiveness. Furthermore, the overall effects of the parameters observed in our investigation were in agreement with those published by others.

NOMENCLATURE

A	cross sectional area of dehumidifier column (m^2)
G	air mass flux ($kg/m^2 \cdot s$)
L	liquid desiccant mass flux ($kg/m^2 \cdot s$)
m	water condensation rate (g/s)
X	desiccant concentration (kg TEG/kg solution)
Y	air humidity ratio (kg water/kg dry)
z	tower height (m)
ε	effectiveness (dimensionless)

Subscripts

equ	equilibrium
in	inlet
out	outlet
y	air humidity ratio

Abbreviations

TEG	triethylene glycol

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