Heat and Mass Transfer in Packed Bed Liquid Desiccant Regenerators—An Experimental Investigation

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Liquid desiccant cooling can provide control of temperature and humidity, while at the same time lowering the electrical energy requirement for air conditioning. Since the largest energy requirement associated with desiccant cooling is low temperature heat for desiccant regeneration, the regeneration process greatly influences the overall system performance. Therefore, the effects of variables such as air and desiccant flow rates, air temperature and humidity, desiccant temperature and concentration, and the area available for heat and mass transfer on the regeneration process are of great interest. Due to the complexity of the regeneration process, which involves simultaneous heat and mass transfer, theoretical modeling must be verified by experimental studies. However, a limited number of experimental studies are reported in the literature. This paper presents results from a detailed experimental investigation of the heat and mass transfer between a liquid desiccant (triethylene glycol) and air in a packed bed regenerator using high liquid flow rates. To regenerate the desiccant, it is heated to temperatures readily obtainable from flat-plate solar collectors. A high performance packing that combines good heat and mass transfer characteristics with low pressure drop is used. The rate of water evaporation, as well as the effectiveness of the regeneration process is assessed based on the variables listed above. Good agreement is shown to exist between the experimental findings and predictions from finite difference modeling. In addition, the findings in the present study are compared to findings previously reported in the literature. Also, the results presented here characterize the important variables that impact the system design.

Introduction

Liquid desiccant cooling can provide control of temperature and humidity, while at the same time lowering the electrical energy requirement for air conditioning. The largest energy requirement associated with the use of desiccant cooling is low temperature heat for desiccant regeneration, and this heat can be provided by solar flat-plate collector system or by waste heat. However, the auxiliary energy requirement for desiccant regeneration can be large (Öberg and Goswami, 1998b), so that the effectiveness of the desiccant regeneration process greatly influences the overall performance of the desiccant system. Equipment commonly employed as regenerators in desiccant systems are: boilers (e.g., Marsala et al., 1989; Albers et al., 1991); solar trickle collector regenerators (e.g., Thornbloom and Nimmo, 1995; Gandhidasan, 1994); spray chambers containing a hot water finned coil (e.g., Robison, 1977; Scalabrin and Scaltriti, 1990); and packed bed absorption towers (e.g., Kinsara et al., 1996; Öberg and Goswami, 1998b; Sick et al., 1988). A more detailed review of liquid desiccant system configurations is given by Öberg and Goswami (1998a).

Peng and Howell (1984) have modeled the performance of desiccant regenerators. An open surface trickle solar collector regenerator, a glazed trickle solar collector regenerator, and a regeneration chamber containing a finned tube heating coil were analyzed and compared. The authors concluded that an open solar collector regenerator was not practical for hot and humid climates. As opposed to a glazed trickle collector regenerator, the authors concluded that a regeneration chamber design would be compact, allow for steady operation, and it could be used with low-grade heat from sources other than solar. For these reasons a regeneration chamber was chosen for the present investigation. However, instead of using a finned tube heating coil as the extended heat and mass transfer surface, it was decided to use a packed bed tower since the packing provides very large surface area per unit volume, thus allowing for a compact design.

To advance solar-based liquid desiccant cooling technology, the impact of variables such as air and desiccant flow rates, air temperature and humidity, desiccant temperature and concentration, and the area available for heat and mass transfer on the performance of a packed bed regenerator is of great interest. Gandhidasan (1990) developed a simplified theoretical model for regeneration of a desiccant in a packed bed using solar heated air. Also, the performance of a packed bed regenerator was theoretically evaluated in terms of a humidity effectiveness and an enthalpy effectiveness by Khan (1994). However, desorption of water in a packed bed tower involves simultaneous heat and mass transfer with complex fluid flow patterns, so theoretical models must be verified by experimental studies. Regeneration of lithium chloride in a packed bed was examined experimentally by Löf et al. (1984). With the air providing the heat for the regeneration process, this study examined the overall heat and mass transfer coefficients as a function of flow rates and inlet temperatures. Patnaik et al. (1990) conducted experiments on a packed bed tower for the regeneration of aqueous lithium bromide. They studied the influence of the type of liquid distribution system on the performance of the regenerator, and presented correlations based on experimental results for the rate of water evaporation as a function of inlet air temperature, humidity, inlet desiccant concentration

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and flow rate. A mixture of calcium chloride and lithium chloride in an aqueous solution was considered by Ertas et al. (1994) who investigated desiccant regeneration as a function of desiccant flow rate, inlet desiccant conditions, and inlet air humidity. Potnis and Lenz (1996) conducted an experimental study considering the influence of desiccant flow rate on the regeneration of aqueous lithium bromide in a packed bed regenerator (as well as air dehumidification in a packed bed). Based on the experimental findings, they developed dimensionless liquid-side mass transfer coefficients for both random and structured tower packings.

The objective of the present investigation is to provide additional experimental data for desiccant regeneration to aid in the design of solar-based desiccant systems. Therefore, a thorough experimental analysis was carried out exploring the influence of air and desiccant flow rates, air and desiccant inlet temperatures, inlet air humidity ratio, inlet desiccant concentration, and the area available for heat and mass transfer. Compared to the experimental studies listed above, higher liquid flow rates were used in the present investigation. A preliminary set of experiments showed these higher flow rates to be necessary to ensure adequate wetting of the packing. Compared to the study by Patnaik et al. (1990), the inlet air humidity ratio was significantly higher in the present investigation as it was varied in a range corresponding to outdoor conditions typically encountered in a humid climate. In a desiccant system, dry indoor air may not always be available for the regeneration process. Due to its lower corrosivity and lower surface tension as compared to salt solutions, 95 percent by weight triethylene glycol (TEG) was chosen as the desiccant. The performance of the regeneration process was evaluated in terms of the water evaporation rate and the humidity effectiveness (concept introduced in a later section). The effectiveness of desiccant regeneration in a packed bed has not been experimentally examined before. The experimental findings from the present study were also compared to those obtained from theoretical modeling, as well as other experimental findings reported in the literature.

Humidity Effectiveness—A Performance Parameter for a Packed Bed Regenerator

Analogous to the heat transfer effectiveness commonly used in heat exchanger analysis (ϵ_{HE}, Eq. (1)), the concept of effectiveness can be applied to the heat and mass transfer in a packed bed dehumidifier and regenerator.

$$\epsilon_{\mathrm{HE}} = \frac{Q_{\mathrm{actual}}}{Q_{\mathrm{max}}} \tag{1}$$

The humidity effectiveness of a packed bed dehumidifier/regenerator, ϵ_Y, is defined as the actual change in air humidity ratio across the packed bed, divided by the maximum possible change (Ullah et al., 1988).

$$\epsilon_Y = \frac{Y_{\mathrm{IN}} - Y_{\mathrm{OUT}}}{Y_{\mathrm{IN}} - Y_{\mathrm{equ}}} \tag{2}$$

Here, Y_{IN} and Y_{OUT} are the humidity ratios at the air inlet and outlet, respectively, and Y_{equ} is the humidity ratio in equilibrium with the desiccant at the local solution temperature and concentration. For counter flow arrangement, Y_{equ} would be the humidity ratio of the air in equilibrium with the desiccant at the desiccant inlet.

Knowledge of the humidity effectiveness as a function of design variables gives a valuable design tool since for known inlet desiccant conditions, air humidity, and effectiveness, the outlet air humidity ratio can be found. Then, the outlet desiccant concentration (which is of most interest for the desiccant regeneration process) will follow from a water mass balance across the packed bed. Therefore, the influence of design variables on the humidity effectiveness has been investigated.

A correlation for ϵ_Y as a function of air and liquid flow rates, column and packing dimensions, and equilibrium properties of the desiccant derived by Chung (1994) is given by Eq. (3):

$$\epsilon_Y = \frac{1 - \left\{ \dfrac{0.205 \left(\dfrac{G_{\mathrm{IN}}}{L_{\mathrm{IN}}} \right)^{0.174} \exp\left[0.985 \left(\dfrac{T_{a,\mathrm{IN}}}{T_{L,\mathrm{IN}}} \right) \right]}{(aZ)^{0.134} \pi^{1.650}} \right\}}{1 - \left\{ \dfrac{0.152 \exp\left[-0.686 \left(\dfrac{T_{a,\mathrm{IN}}}{T_{L,\mathrm{IN}}} \right) \right]}{\pi^{3.388}} \right\}} \tag{3}$$

Here, the parameter, π, representing the equilibrium properties of the desiccant is defined as the ratio of the vapor pressure depression to the vapor pressure of pure water.

$$\pi = \frac{p_w(T_{L,\mathrm{IN}}) - p_L(T_{L,\mathrm{IN}}, X_{\mathrm{IN}})}{p_w(T_{L,\mathrm{IN}})} \tag{4}$$

Although this correlation was obtained from experimental data on desiccant air dehumidification in packed beds (absorption mode), its applicability for desiccant regeneration in a packed bed (desorption) is examined in the present study.

Experimental Procedure

The rate of water evaporation from the desiccant as well as the humidity effectiveness of the regeneration process were studied

Nomenclature

a_t = specific surface area of packing (m^2/m^3)
c_p = specific heat (kJ/kg-°C)
F_G = gas phase mass transfer coefficient (kmol/m^2-s)
F_L = liquid phase mass transfer coefficient (kmol/m^2-s)
G = superficial air (gas) flow rate (kg/m^2-s)
h_G = gas side heat transfer coefficient (kJ/m^2-s)
L = superficial desiccant flow rate (kg/m^2-s)
M = molar mass (kg/kmol)
m = flow rate (kg/s) or (g/s)
N_v = molar vapor mass transfer flux (kmol/m^2-s)
p = vapor pressure (Pa)
Q = rate of heat transfer (W)
q = heat transfer flux (kW/m^2)
T = temperature (°C)
TEG = triethylene glycol
X = desiccant concentration (kg TEG/kg solution)
x = desiccant mole fraction (kmol desiccant/kmol solution)
Y = air humidity ratio (kg water/kg dry air or g water/kg dry air)
y = water mole fraction (kmol water/kmol air)
Z = tower height (m)
ϵ = effectiveness
λ = latent heat of condensation/vaporization (kJ/kg)
π = dimensionless vapor pressure difference (Eq. (9))

Subscripts

a = air
equ = equilibrium
evap = water evaporation
G = gas phase
HE = heat exchanger
IN = inlet
i = interface
L = desiccant or liquid phase
OUT = outlet
v = vapor
w = water
Y = humidity
0 = reference state

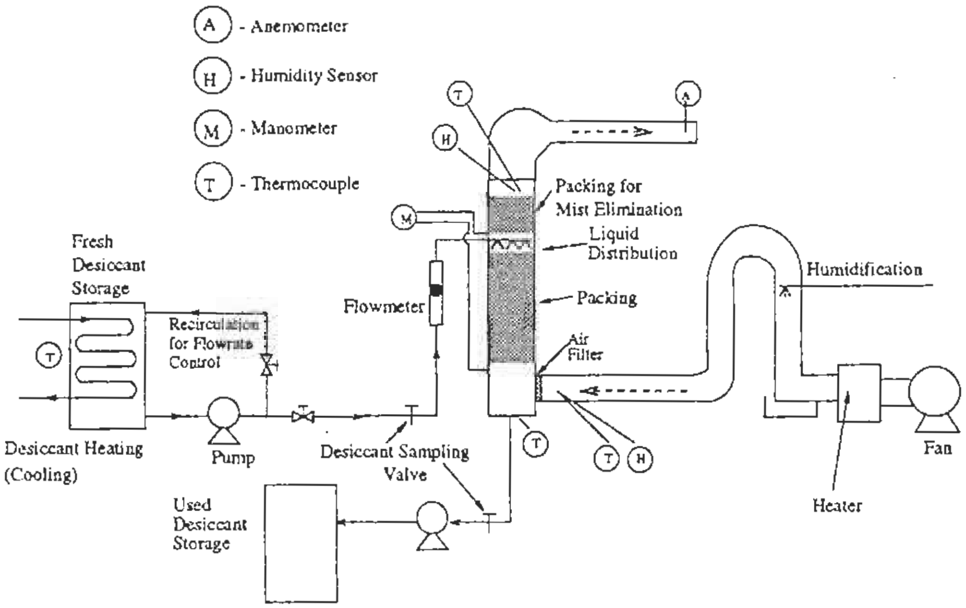


Fig. 1 Experimental facility

experimentally as a function of the following variables: air and desiccant flow rates; air temperature and humidity ratio; desiccant temperature and concentration; and the height of the packed bed.

A schematic of the experimental facility is shown in Fig. 1. The packed bed regenerator was constructed from a 25.4 cm (10 in) diameter acrylic tube to allow for flow visualization. The tower was made in sections so that the bed height could be varied without changing the distance from the liquid distribution to the top of the bed. The inner diameter of the tower was 0.24 m. The packing used was 2.54 cm (1 in) polypropylene Rauschert Hiflow® rings with a specific surface area of 210 m^2/m^3. Fresh, unused triethylene glycol was stored in a tank, and its temperature was adjusted by circulating hot water through a submerged copper coil. Before each experiment, the desiccant was allowed to recirculate to remove temperature and concentration gradients. Air was blown past an air heater and through a humidifying chamber to adjust its temperature and humidity before it entered the packed tower. At the air inlet, an air filter was installed to prevent airborne particles and water droplets from entering the regenerator. When the desired air and desiccant conditions were obtained, the desiccant was allowed to flow through the tower. The desiccant was distributed over the packing by three spray heads evenly spaced in an equilateral triangular configuration. A section of packing (20 cm) was placed above the spray heads, before the air outlet to minimize the loss of desiccant through the air outlet. Once steady state was obtained, measurements were taken for 15 to 20 minutes using a PC-based data acquisition system. These measurements included inlet and outlet temperatures of the desiccant and the air using copper-constantan thermocouples, as well as inlet and outlet air relative humidities using electrical relative humidity transducers. In addition, samples of the desiccant entering and leaving the regenerator were taken during the experiment and analyzed for water content using Karl Fischer titration. The used desiccant was pumped over to a separate storage tank so that the inlet desiccant concentration did not change during the experiment. The liquid flow rate was set approximately using a flow indicator. However, it was measured accurately by a catch-bucket method. The air velocity was measured using a vane anemometer at the air outlet. Finally, an air-over-oil manometer determined the air pressure drop over the packed bed (not including the mist eliminating section).

Experiments were conducted for each variable at three levels (low, intermediate, and high value) while keeping the other variables constant at their intermediate value. Three experiments were conducted at each level to reveal the repeatability of the experimental measurements.

Finite Difference Model for the Packed Bed Regenerator

For theoretical modeling of the desiccant regeneration process in a packed bed, a finite difference model based on a model for adiabatic gas absorption presented by Treybal (1969) was used. Figure 2 shows an overview of the packed bed, as well as a small segment, *dZ*, of the packed bed. In summary, the assumptions made in this model are: adiabatic absorption; concentration and temperature gradients in the flow direction (*Z*-direction, referring to Fig. 2) only; only water is transferred between the air and the desiccant; the interfacial surface area is the same for both heat and mass transfer, and it is equal to the specific surface area of the packing; the heat of mixing is negligible as compared to the latent heat of condensation of water; and the resistance to heat transfer in the liquid phase is negligible.

In the finite difference model, the packed bed height *Z* is divided into small segments, *dZ* (Fig. 2(*b*)), and the mass and energy balances are solved for each segment, from the bottom to the top of the tower, resulting in the governing equations given below. These governing equations include the changes in air humidity, air temperature, desiccant temperature, desiccant concentration, and desiccant flow rate across the segment *dZ*. A detailed derivation of these equations is given elsewhere (Treybal, 1969; Öberg, 1998).

The mass flux of water vapor across the interface (Fig. 2(*b*)), taken positive from the gas to the liquid, is

$$\begin{aligned} N_v M_w a_I dZ &= F_G M_w a_I dZ \ln\left(\frac{1-y_i}{1-y}\right) \\ &= F_L M_w a_I dZ \ln\left(\frac{x}{x_i}\right) = -G dY \qquad (5) \end{aligned}$$

Equation (5) gives the change in air humidity across the segment as

$$\frac{dY}{dZ} = -\frac{M_w F_G a_I}{G} \ln\left(\frac{1-y_i}{1-y}\right) \qquad (6)$$

where the interfacial gas phase concentration is given by:

$$y_i = 1 - (1-y)\left(\frac{x}{x_i}\right)^{(F_L/F_G)} \qquad (7)$$

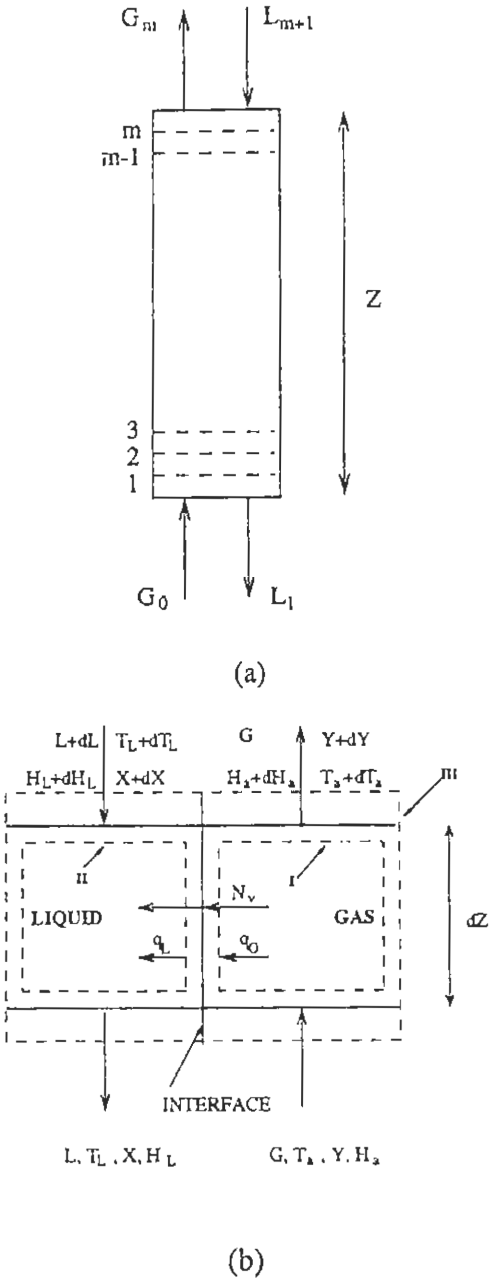


Fig. 2 Packed bed regeneration tower (*a*) tower overview; (*b*) differential segment

Equation (7) is the result of equating the molar vapor mass transfer flux, N_v, as calculated with respect to the gas phase to the molar flux calculated with respect to the liquid phase (Eq. (5)). The vapor-liquid equilibrium data for the triethylene glycol-water system (Dow Chemical Company, 1992) were used along with Eq. (3) to solve iteratively for the interface concentrations in the gas and liquid phases. The equilibrium concentrations are a function of the liquid desiccant temperature and concentration. Empirical correlations for the mass transfer coefficients obtained for packed bed desiccant regenerators are available in the literature. Potnis and Lenz (1996) presented dimensionless liquid-side mass transfer correlations based on experimental results on packed bed liquid desiccant contactors using a lithium bromide solution as the desiccant. However, since the present investigation used TEG as the desiccant, it was decided to use the empirical correlations by Onda et al. (1968) for the gas and liquid phase heat and mass transfer coefficients (h_G, F_G, and F_L). These correlations have predicted data within ±20 percent for a range of operating and system conditions, using organic solvents as well as water (Onda et al., 1968).

The air temperature gradient across the segment is found from an energy balance across the gas phase (control volume I, Fig. 2(*b*)).

$$\frac{dT_a}{dZ} = \frac{-h_G a'(T_a - T_L)}{G(c_{p,a} + Y c_{p,v})} \tag{8}$$

Here $h_G a'$ is the heat transfer coefficient corrected for simultaneous heat and mass transfer.

$$h_G a' = \frac{-G c_{p,v}\dfrac{dY}{dZ}}{1 - \exp\left(\dfrac{G c_{p,v}\dfrac{dY}{dZ}}{h_G a_I}\right)} \tag{9}$$

An energy balance over the entire segment (control volume III, Fig. 2(*b*)) gives the change in desiccant temperature:

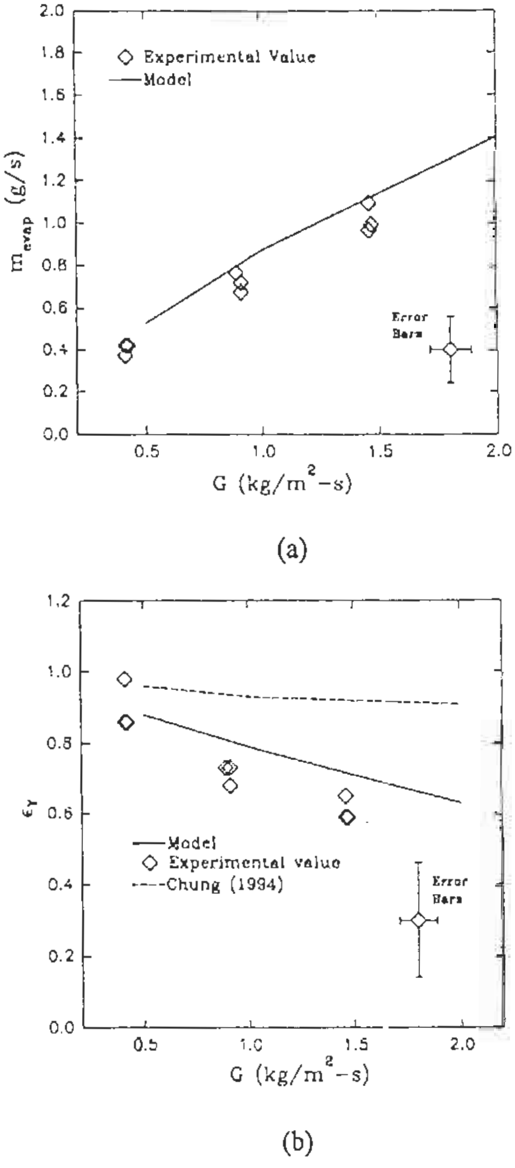
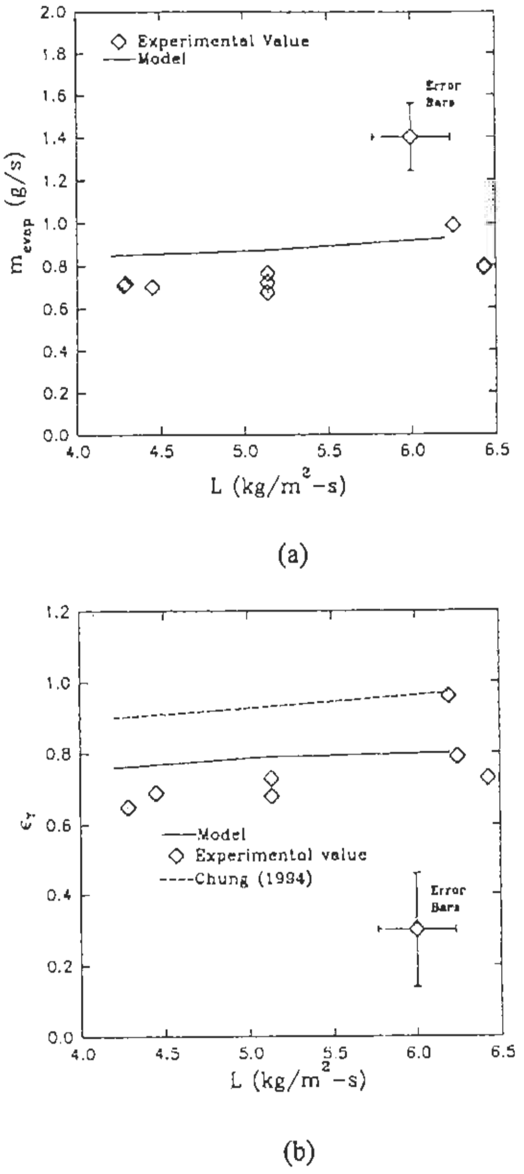


Fig. 3 Influence of air flow rate on: (*a*) water evaporation rate; (*b*) humidity effectiveness



(a)

(b)

Fig. 4 Influence of desiccant flow rate on: (*a*) water evaporation rate; (*b*) humidity effectiveness

$$dT_L = \frac{G}{c_{p,L}L}\{(c_{p,a} + Yc_{p,v})dT_a + (c_{p,v}[T_a - T_0] - c_{p,L}[T_L - T_0] + \lambda_0)dY \tag{10}$$

A water mass balance across the segment (control volume III, Fig. 2(*b*)) yields the change in desiccant concentration.

$$dX = -\frac{G}{L}XdY \tag{11}$$

Finally, an overall mass balance over control volume III (Fig. 2) gives the change in desiccant flow rate.

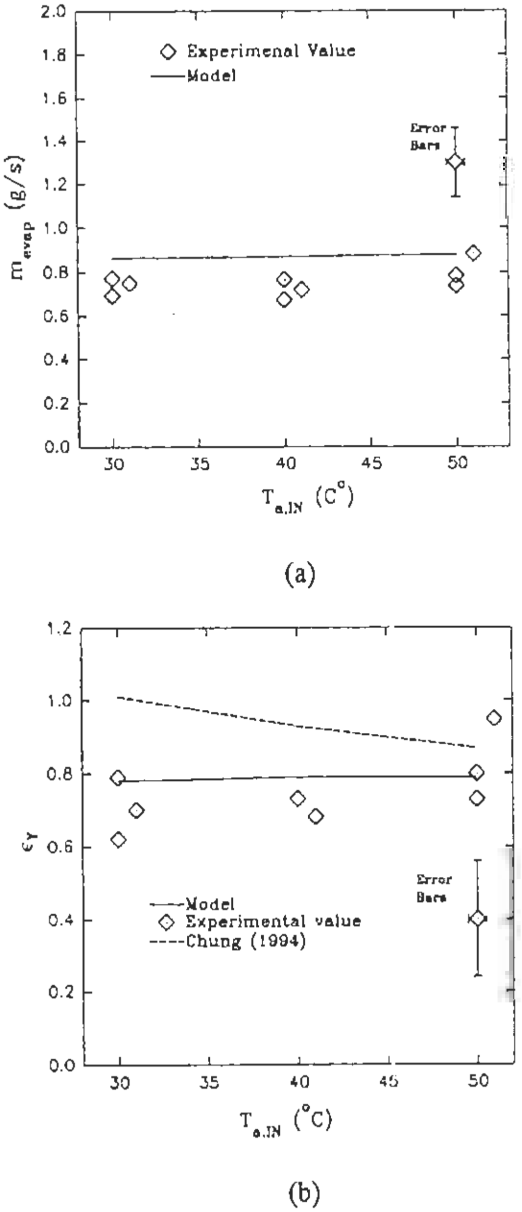
$$dL = GdY \tag{12}$$

A FORTRAN computer program was written to carry out the finite difference analysis with the bed height Z divided into 1000 segments. An under-relaxation iterative procedure was utilized to promote convergence. The criteria for convergence was ±0.05°C for the inlet desiccant temperature, and ±0.0001 kg TEG/kg solution for the inlet desiccant concentration.

Results and Discussion

The results from the experimental study and theoretical modeling are shown graphically in Figs. 3 to 9. These figures show the water evaporation rate, m_{evap}, and the humidity effectiveness, ϵ_Y, as a function of air and desiccant flow rates and inlet temperatures, desiccant concentration, inlet air humidity ratio, and packed bed height. In addition, performance predictions from Chung's correlation (Eq. (3)) are shown along with the experimental results.

Uncertainties of the experimental measurements were calculated using the method by Kline and McClintock (1953). Error bars obtained from these uncertainty calculations are shown in the figures. Further details on the uncertainty analysis are given elsewhere (Öberg, 1998). The repeatability of the experimental measurements is also indicated in the figures as three experimental data points are shown for each set of variables. To further cross-check the consistency of the data, a water mass balance across the regenerator was calculated, yielding ±5 percent deviation between the amount of water entering and leaving the regenerator. Similarly, an energy balance across the regenerator gave deviations of ±10 percent.



(a)

(b)

Fig. 5 Influence of inlet air temperature on: (*a*) water evaporation rate; (*b*) humidity effectiveness

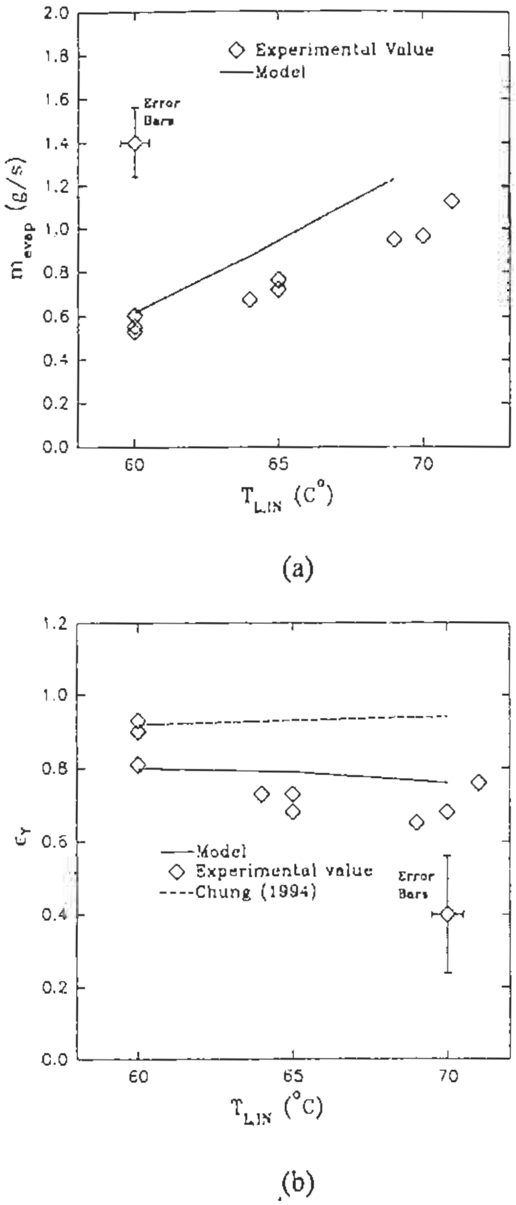


Fig. 6 Influence of inlet desiccant temperature on: (*a*) water evaporation rate; (*b*) humidity effectiveness

The pressure drop across the packed bed varied between 30 and 210 Pa/m packing, depending on the air flow rate. Typically, packed bed absorbers/desorbers are designed for a pressure drop between 200 and 400 Pa/m packing (Treybal, 1980). Hence, even at the highest air flow rate, the regenerator operated at the lower end of the typical design conditions.

The finite difference model presented herein has previously been found to give good performance predictions for air dehumidification in a packed bed (Öberg and Goswami, 1998c). Figures 3 to 9 show that the experimental findings for desiccant regeneration also agree well with the predictions from the finite difference model. Only a slight discrepancy can be seen (approximately ±15 percent), and the difference is within the error bars of the experiments. Also, the repeatability of the experiments for each set of variables is better than what the error bars indicate. In cases where there is a discrepancy, the finite difference model generally overpredicts the performance of the regenerator. One explanation for this is the assumption that the area available for heat and mass transfer is equal to the total specific surface area of the packing. Even though the liquid flow rate is high as compared to the air flow rate, complete wetting of the packing is difficult to obtain. Therefore, the mass transfer area is less than the packing surface area. Also, it should be kept in mind that the correlations used for the transfer coefficients are empirical, and they were obtained for liquid-gas systems and packings other than those used in the present study.

Chung's correlation greatly overpredicts the performance of the regenerator, and the influence of design variables is not accurately shown from this correlation. For instance, the humidity effectiveness obtained from the finite difference model and the experiments shows a larger dependency on the air flow rate and packed bed height than what is predicted by Chung's correlation (Figs. 3(*b*) and 9*b*)). Since this correlation was obtained from experimental data on packed bed dehumidifiers, accurate predictions for desiccant regeneration would not be expected.

The experimental study on the packed bed regeneration tower showed the following variables to significantly influence the regeneration performance: air flow rate, inlet desiccant temperature, inlet air humidity ratio, inlet desiccant concentration, and the packed bed height. The water evaporation rate increases with the air flow rate (Fig. 3(*a*)). However, the humidity effectiveness

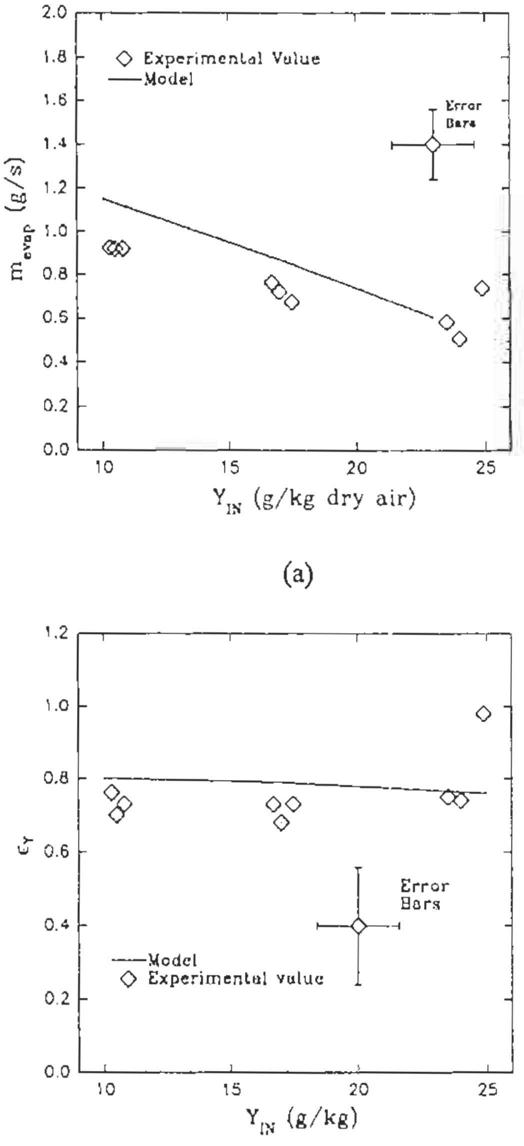
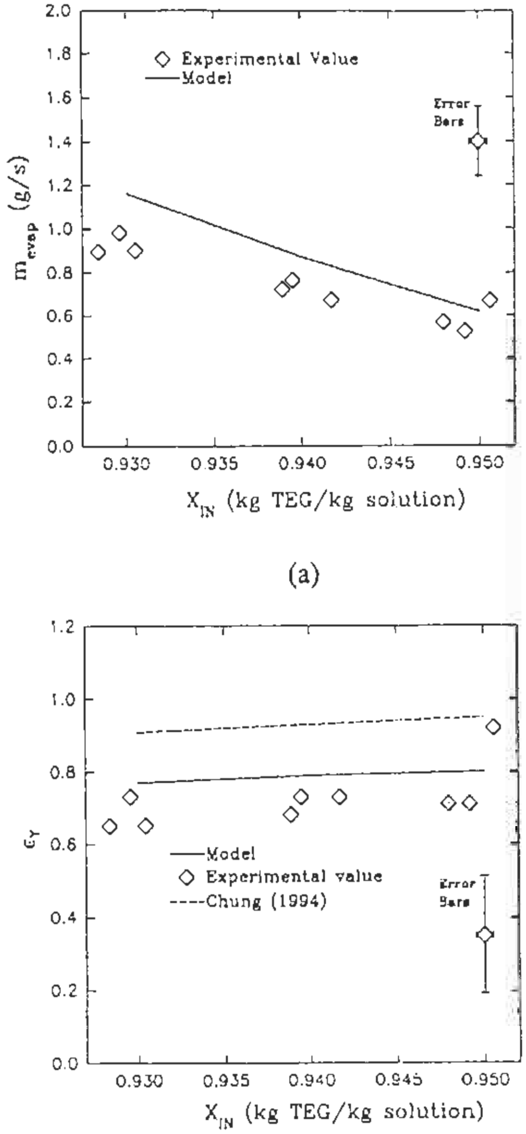


Fig. 7 Influence of inlet air humidity ratio on: (*a*) water evaporation rate; (*b*) humidity effectiveness



(a)

(b)

Fig. 8 Influence of inlet desiccant concentration on: (*a*) water evaporation rate; (*b*) humidity effectiveness

decreases with the air flow rate (Fig. 3(*b*)) since the change in humidity ratio across the tower decreases as the air flow rate increases.

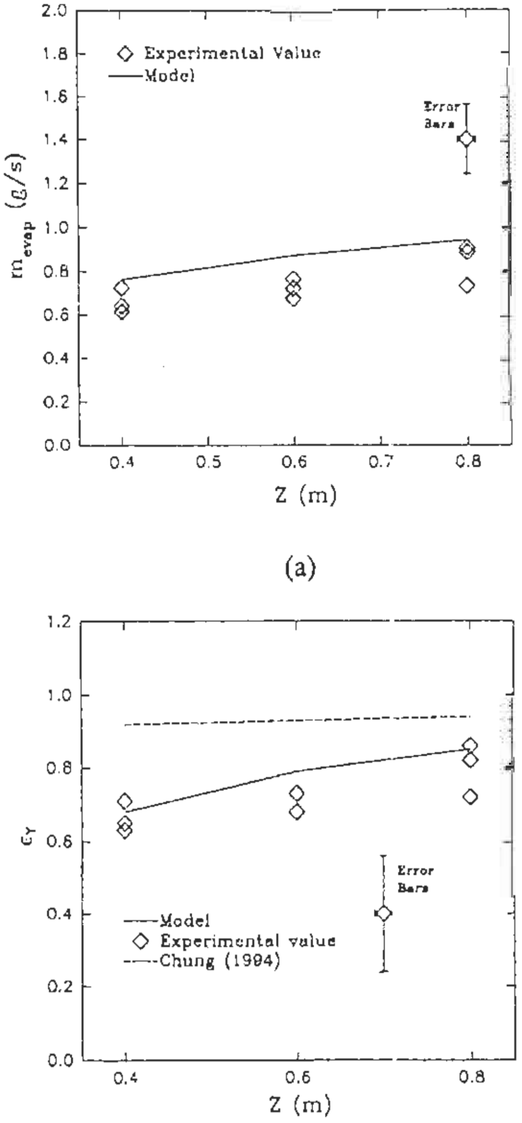
In the regeneration process, the water vapor pressure in the liquid is higher than the vapor pressure in the air so that water is evaporated from the desiccant to the air. Therefore, as the liquid vapor pressure increases with the desiccant temperature, the potential for mass transfer increases. Hence, the water evaporation rate increases with the liquid temperature (Fig. 6(*a*)). However, the effectiveness shows only a slight dependency on the inlet desiccant temperature (Fig. 6(*b*)). This is because the highest possible humidity ratio that can be obtained at the air outlet, Y_{equ}, is dependent on $T_{L,IN}$, making the effectiveness somewhat normalized with respect to the desiccant temperature.

By similar reasoning it may be explained why the water evaporation rate decreases with increasing desiccant inlet concentration, X_{IN}, while the desiccant concentration did not influence the humidity effectiveness significantly (Fig. 8). Increasing X_{IN} decreases the driving force for mass transfer, and thus lowers the water evaporation rate. On the other hand, Y_{equ} is dependent on X_{IN} so that the humidity effectiveness is normalized with respect to the desiccant concentration. Therefore, the humidity effectiveness is not significantly influenced by X_{IN}.

An increase in the inlet humidity ratio increases the vapor pressure in the air, decreasing the potential for mass transfer between the desiccant and the air. Therefore, the water evaporation rate decreases with increasing inlet air humidity (Fig. 7(*a*)). By definition, the humidity effectiveness is already normalized with respect to the inlet humidity ratio (Eq. (2)). This explains why the humidity effectiveness is not significantly dependent on the inlet humidity ratio as shown in Fig. 7(*b*).

Increasing the bed height increases the water evaporation rate, as well as the effectiveness (Fig. 9). This is because a taller bed increases the area for heat and mass transfer so that a humidity ratio closer to the equilibrium value, Y_{equ}, may be reached at the air outlet.

A comparison between the findings in this investigation and experimental findings from studies previously reported in the literature is given in Table 1. The table shows the desiccant used, the parameters describing the performance, the independent variables and the ranges examined. Under each variable, up- and



(a)

(b)

Fig. 9 Influence of packed bed height on: (*a*) water evaporation rate; (*b*) humidity effectiveness

Table 1 Packed bed regenerator performance

<table>
<tr><th>Reference</th><th>Desiccant</th><th>Performance Parameter</th><th colspan="7">Independent Variable</th></tr>
<tr><td rowspan="4">present study</td><td rowspan="4">TEG</td><td></td><td>L
(kg/m^2-s)</td><td>X_{IN}
(kg/kg)</td><td>$T_{L,IN}$
(°C)</td><td>G
(kg/m^2-s)</td><td>$T_{a,IN}$
(°C)</td><td>Y_{IN}
(g/kg)</td><td>Z
(m)</td></tr>
<tr><td></td><td>4.2-6.5</td><td>0.93-0.95</td><td>60-70</td><td>0.4-2.0</td><td>30-50</td><td>10-25</td><td>0.4-0.8</td></tr>
<tr><td>m_{evap}</td><td>↑↓</td><td>↓</td><td>↑</td><td>↑</td><td>↑↓</td><td>↓</td><td>↑</td></tr>
<tr><td>ϵ_Y</td><td>↑↓</td><td>↑↓</td><td>↑↓</td><td>↓</td><td>↑↓</td><td>↑↓</td><td>↑</td></tr>
<tr><td rowspan="4">Ertas et al. (1994)</td><td rowspan="4">mixture of LiCl and $CaCl_2$</td><td></td><td colspan="2">L*
(kg/m^2-s)</td><td colspan="2">X_{IN}
(kg/kg)</td><td>$T_{L,IN}$
(°C)</td><td colspan="2">Y_{IN}*
(g/kg)</td></tr>
<tr><td></td><td colspan="2">0.8-3.1</td><td colspan="2">0.32-0.46</td><td>60-90</td><td colspan="2">18-25</td></tr>
<tr><td>X_{OUT}</td><td colspan="2">↓</td><td colspan="2">↑</td><td>↑</td><td colspan="2">↓</td></tr>
<tr><td>$T_{L,OUT}$</td><td colspan="2">↑</td><td colspan="2">↑</td><td>↑</td><td colspan="2">↑</td></tr>
<tr><td rowspan="3">Löf et al. (1984)</td><td rowspan="3">LiCl</td><td></td><td colspan="7">G*
(kg/m^2-s)</td></tr>
<tr><td></td><td colspan="7">0.7-0.74</td></tr>
<tr><td>h_Ga</td><td colspan="7">↑</td></tr>
<tr><td rowspan="3">Patnaik et al. (1990)</td><td rowspan="3">LiBr</td><td></td><td colspan="2">L*
(kg/m^2-s)</td><td>$T_{L,IN}$
(°C)</td><td>X_{IN}
(kg/kg)</td><td colspan="2">$T_{a,IN}$
(°C)</td><td>Y_{IN}
(g/kg)</td></tr>
<tr><td></td><td colspan="2">1.1-1.5</td><td>40-56</td><td>0.57-0.60</td><td colspan="2">55-75</td><td>5-9</td></tr>
<tr><td>m_{evap}</td><td colspan="2">↑</td><td>↑</td><td>↓</td><td colspan="2">↑</td><td>↓</td></tr>
<tr><td rowspan="3">Potnis and Lenz (1996)</td><td rowspan="3">LiBr</td><td></td><td colspan="7">L*
(kg/m^2-s)</td></tr>
<tr><td></td><td colspan="7">1-3</td></tr>
<tr><td>m_{evap}</td><td colspan="7">↑</td></tr>
<tr><td colspan="10">* Values converted to this unit by present authors.
↑ performance parameter increases with increasing variable
↓ performance parameter decreases with increasing variable
↑↓ variable has no significant effect on the performance parameter</td></tr>
</table>

down-arrows indicate the influence of the variable on the performance parameter. Table 1 shows that a limited amount of experimental data on packed bed regenerators is available in the literature. Thus, the present detailed investigation provides valuable insights into the design of the desiccant regeneration process, especially for the use of triethylene glycol as the desiccant.

In general, findings from all the studies agree well. However, Ertas et al. (1994), Patnaik et al. (1990), and Potnis and Lenz (1996) found that the water evaporation rate increases with desiccant flow rate, whereas the present study found only a slight dependency on the desiccant flow rate. Patnaik et al. (1990) and Potnis and Lenz (1996) explained the large dependency on desiccant flow rate as being due to the large resistance to mass transfer in the liquid phase. In the present investigation TEG was used as the desiccant whereas salt solutions were used in the other investigations, and it may be that the resistance to mass transfer in the liquid phase is not as important in the TEG-water-air system. Also, Patnaik et al. (1990) explained part of the dependency on the desiccant flow rate as being due to increased wetting of the packing with increasing flow rate. That is, if the liquid flow rate is low, an increase may provide better wetting of the packing, and therefore increase the performance of the regenerator. In the present study, higher desiccant flow rates were used than in the other studies. At a certain desiccant flow rate, maximum wetting of the packing is obtained and a further increase of the flow rate will not improve the wetting. Therefore, in addition to a large resistance to mass transfer in the liquid phase, the performance improvement reported in the previous investigations (Ertas et al., 1994; Patnaik et al., 1990; Potnis and Lenz, 1996) is also explained by the increased wetting of the packing with increasing flow rate. Since no significant dependency was obtained in the present investigation, it may be concluded that the flow rates used were sufficient to obtain maximum wetting in the system used here.

In the study by Patnaik et al. (1990), the evaporation rate increases with air temperature. In the present study, no dependency on the air temperature was obtained. Again, this discrepancy can be explained by the higher desiccant flow rates used in the present study. The performance of the regeneration process will increase with increased heat addition since this will increase the average temperature in the regenerator, which in turn increases the driving force for mass transfer. With a higher desiccant flow rate, the relative amount of heat added to the regenerator by the air stream is lower. Thus, the inlet air temperature is not as important when using high desiccant flow rates.

Finally, provided that the desiccant flow rate is high enough to ensure adequate wetting of the packing, only the air flow rate, G, and the tower height, Z, significantly influence the humidity effectiveness, ϵ_Y. Hence, the knowledge of a functional relationship between ϵ_Y, G, and Z opens up the possibility for a greatly simplified model of the desiccant regeneration in a packed bed. However, such a model would be system specific and would only apply to the specific packing, desiccant, etc., for which the relationship was obtained.

Conclusions

As the largest energy requirement associated with desiccant cooling is low temperature heat for desiccant regeneration, the performance of the regeneration process greatly influences the overall system performance. Therefore, to advance solar-based liquid desiccant cooling technology, the many design variables affecting the performance of a packed bed regenerator have been experimentally investigated. In addition, performance predictions from a theoretical model, and empirical correlations previously available in the literature, have been compared to the experimental findings.

Design variables found to have the greatest impact on the performance of the regenerator are the air flow rate and the humidity ratio, the desiccant temperature and concentration, and the packed bed height. The liquid flow rate and the inlet air temperature did not have a significant effect on the regenerator performance; however, the liquid flow rate must be high enough to ensure wetting of the packing. In this study, the liquid flow rate was higher as compared to the flow rates used in the studies previously reported.

The results obtained in this study compare reasonably well with other experimental investigations. Contrary to the findings of this study, some studies have found that the liquid flow rate and air temperatures influence the performance. One explanation for this is the lower liquid flow rate used in those investigations.

The regenerator performance predicted with the finite difference model described in this paper shows a good agreement with the experimental findings. Thus, for a detailed study of the regeneration process, the finite difference model gives accurate performance predictions based on fundamental equations, minimizing the assumptions and use of empirical correlations.

Correlations for the effectiveness of the absorption/desorption process in a packed bed dehumidifier/regenerator as a function of design variables are very useful for quick performance estimates, and for incorporating into system simulation models. The most general correlation currently available in the literature is the one by Chung (1994) which is based on experimental data for air dehumidification in a packed bed. From the present study it is evident that this correlation is not applicable to desiccant regeneration in a packed bed. Hence, it would be valuable if correlations valid for both dehumidification and regeneration were derived.

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