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STUDY OF AN AQUEOUS LITHIUM CHLORIDE DESICCANT SYSTEM PART I: AIR DEHUMIDIFICATION

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ABSTRACT

Desiccant systems have been proposed as energy saving alternative to vapor compression air conditioning for handling the latent load. Use of liquid desiccants offers several design and performance advantages over solid desiccants, especially when solar energy is used for regeneration. For liquid-gas contact, packed towers with low pressure drop have offered good heat and mass transfer characteristics for compact designs. This paper presents the results from a study of the performance of a packed tower absorber for an aqueous lithium chloride desiccant dehumidification system. The rate of dehumidification, as well as the effectiveness of the dehumidification process were assessed under the effects of variables such as air and desiccant flow rates, air temperature and humidity, and desiccant temperature and concentration. A variation of the Öberg and Goswami mathematical model was used to predict the experimental findings given satisfactory results.

Keywords: Liquid desiccant, lithium chloride, dehumidification, packed tower, absorber, desiccant cooling.

INTRODUCTION AND BACKGROUND

Liquid desiccant cooling systems have been proposed as an alternative to the conventional vapor compression cooling systems to control air humidity, especially in hot and humid areas. Research has shown that a liquid desiccant cooling system, can reduce the overall energy consumption, as well as shift the energy use away from electricity and toward renewable and cheaper fuels (Öberg and Goswami, 1998a). Burns et al (1985) found that utilizing desiccant cooling in a supermarket reduced the energy cost of air conditioning by 60% as compared to conventional cooling. Öberg and Goswami (1998a) modeled a hybrid solar cooling system obtaining an electrical energy savings of 80%, and Chengchao and Ketao (1997) showed by computer simulation that a solar liquid desiccant air conditioning has advantages over vapor compression air conditioning system in its suitability for hot and humid areas and high air flow rates.

Use of liquid desiccants offers several design and performance advantages over solid desiccants, especially when solar energy is used for regeneration (Öberg and Goswami, 1998c). Several liquid desiccants are commercially available: triethylene glycol, diethylene glycol, ethylene glycol, and brines such as calcium chloride, lithium chloride, lithium bromide, and calcium bromide which are used singly or in combination. The usefulness of a particular liquid desiccant depends upon the application. At the University of Florida, Öberg and Goswami [1998a, 1998b] conducted a study of a hybrid solar liquid desiccant cooling system using triethylene glycol (TEG) as the desiccant. Their experimental work concluded that glycol works well as a desiccant. However, pure triethylene glycol does not have zero vapor pressure and this causes some of the glycol to evaporate into the air. Although triethylene glycol is nontoxic, any evaporation into the supply air stream makes it unacceptable for use in air conditioning of an occupied building. Therefore, there is a need to evaluate other liquid desiccants for solar hybrid cooling desiccant systems. Lithium chloride (LiCl) is a good candidate material since it has good desiccant characteristics and does not vaporize in air at the ambient conditions. A disadvantage with LiCl is that it is corrosive. This paper presents an experimental study of aqueous solution of lithium chloride as a desiccant for a solar hybrid cooling system.

A number of experimental studies have been carried out on packed bed dehumidifiers using salt solutions as desiccants. Chung et al (1992, 1993), and Chen et al (1989) used lithium chloride (LiCl); Ullah et al (1999), Kinsara et al (1998), and Lazzarin et al (1999) used calcium chloride ($CaCl_2$); while Ahmed et al (1997), and Patnaik et al (1990) used lithium bromide (LiBr). Other experiments for absorbers using LiCl were carried out by Kessling et al (1998), Kim et al (1997), and Scalabrin and Scaltriti (1990).

In any thermodynamic system, the conditions of the working fluids and parameters of the physical equipment define the overall performance of the system. In a liquid desiccant cooling system variables such as air and desiccant flow rate, air temperature and humidity, desiccant temperature and concentration are of great interest on the performance of the dehumidifier. The mass ratio of air to desiccant solution $MR = m_{air}/m_{sol}$ is an important factor for absorber efficiency and system capacity. In previous works it have been studied the performance of packed bed absorbers and regenerators with MR between 1.3 and 3.3. The range of MR varies with the type of absorber/regenerator, but in general better results are obtained for small MR.

For simulation purposes, validated models are required for modeling the absorber in a liquid desiccant system. Models using lithium chloride have been described by Khan and Martinez (1998), Ahmed et al (1997), and Kavasogullari et al (1991). Due to the complexity of the dehumidification process, theoretical modeling relies heavily upon experimental data. Öberg and

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Goswami (1998b) developed a model for a packed bed liquid desiccant air dehumidifier with triethylene glycol as liquid desiccant which was validated satisfactorily by the experimental data. The present study uses a modified version of the mathematical model developed by Öberg and Goswami to compare the experimental results of a packed bed dehumidifier using lithium chloride as a desiccant. A companion paper describes the experimental and simulation results for regeneration of lithium chloride.

EXPERIMENTAL FACILITY AND PROCEDURE

A schematic of the experimental facility is shown in Fig. 1. The packed bed absorption tower was constructed from a 25.4 cm (24 cm ID) diameter acrylic tube to allow for flow visualization. The height of the tower is constant and equal to 60 cm. The packing used was 2.45 cm (1 in) polypropylene Rauschert Hiflow® rings with specific surface area of 210 m^2/m^3. Fresh, unused lithium chloride was stored in a tank, and its temperature was adjusted by circulating cold or warm water through a submerged stainless steel coil. Air was blown past an air heater or a cooling coil, and through a humidifying chamber to adjust its temperature and relative humidity before it enters the packed tower. 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. Once steady state was obtained, measurements were taken 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 humidity probes. In addition, samples of the desiccant entering the dehumidifier were taken during the experiment and analyzed for water content using Karl Fischer titration.

The rate of moisture removal from the air (water condensation rate, m_{cond}) was studied experimentally as a function of the following variables: air and desiccant flow rates; air temperature and humidity ratio; and desiccant temperature and concentration. For the same variables an analysis of the tower efficiency was done using humidity effectiveness. Experiments were conducted for each variable at three levels (low, intermediate, and high value) while keeping the other variables constant. Three experiments were conducted at each level, and an average was used in the results.

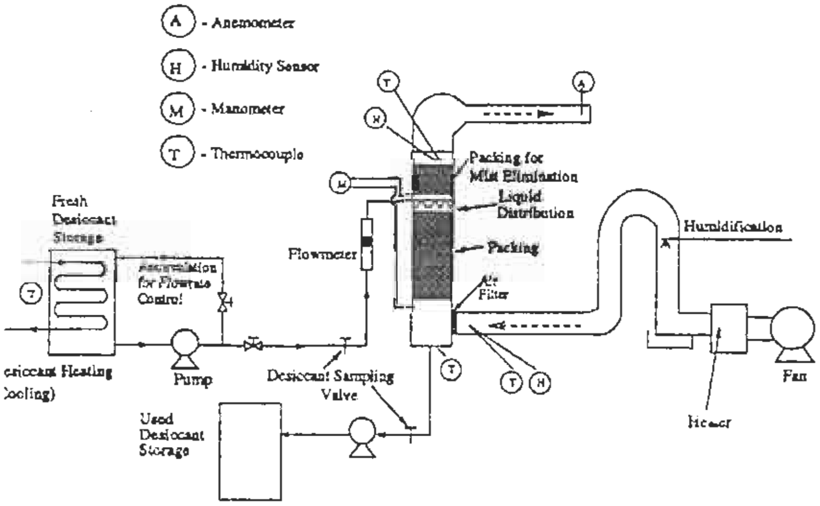

Fig. 1 Experimental facility.

THEORETICAL MODEL OF THE PACKED BED ABSORPTION TOWER

Öberg and Goswami [1998b] developed a finite difference model based on the model for adiabatic gas absorption presented by Treybal (1969) with the exception that the resistance to heat transfer in the liquid phase was neglected. For their model they assumed 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, that for their case, the interfacial surface area is the same for heat transfer and mass transfer, and equal to the specific surface area of the packing; the heat of mixing is negligible as compared to the latent heat of condensation of the water; and the resistance to heat transfer in the liquid phase is negligible. For the finite difference model, the packed bed height Z is divided into small segments, dZ (Fig. 2b), and the mass and energy balances are solved for each segment, from the bottom to the top of the tower. Since only the inlet conditions of the desiccant are known, the outlet conditions must initially be guessed, and iterations are required to find the

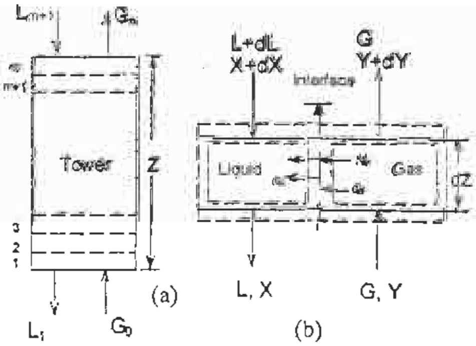

Fig. 2 Packed bed: (a) overview; (b) differential segment

desiccant outlet conditions that give the known inlet conditions at the top of the packed bed.

Öberg and Goswami's finite difference model, which worked well for TEG as the desiccant, required two modifications to account for the higher surface tension of LiCl and higher water concentration in brines as compared to water concentration in TEG. The modifications and governing equations that describe the changes in air humidity and air temperature, desiccant temperature and desiccant concentration, and desiccant flow rate across a segment are given below.

Öberg and Goswami assumed that the interfacial surface area is the same for heat and mass transfer, and is equal to the specific surface area of the packing. Because of the high surface tension of LiCl solutions, twice that of glycol, the packing is wetted insufficiently causing a considerable reduction of the area for mass transfer. Therefore, to estimate the wet area, an equation for wetted surface area proposed by Onda et al (1968) was used:

$$\frac{a_w}{a_t} = 1 - \exp\left[-1.45\left(\frac{\gamma_c}{\gamma_L}\right)^{0.75}\left(\frac{L}{a_t \cdot \mu_L}\right)^{0.1}\left(\frac{L^2 \cdot a_t}{\rho_L^2 \cdot g}\right)^{-0.05}\left(\frac{L^2}{\rho_L \cdot \gamma_L \cdot a_t}\right)^{0.2}\right] \quad (1)$$

This equation takes into account the liquid surface tension and the surface energy of packing materials, and was used by Öberg and Goswami in the definition of the k-Type mass transfer coefficients[2]:

$$k_L = 0.0051\left(\frac{\mu_L \cdot g}{\rho_L}\right)^{1/3}\left(\frac{L}{a_w \cdot \mu_L}\right)^{2/3}\left(\frac{\rho_L \cdot D_L}{\mu_L}\right)^{1/2}\left(a_t \cdot D_P\right)^{0.4} \quad (2)$$

$$k_G = 5.23\frac{a_t \cdot D_G}{R \cdot T_a}\left(\frac{G}{a_t \cdot \mu_G}\right)^{0.7}\left(\frac{\mu_G}{\rho_G \cdot D_G}\right)^{1/3}\left(a_t \cdot D_P\right)^{-2} \quad (3)$$

Then, the change in air humidity across the differential segment is defined by:

$$\frac{dY}{dZ} = -\frac{M_w \cdot F_G \cdot a_w}{G} \cdot \ln\left(\frac{1-y_i}{1-y}\right) \quad (4)$$

Where the interfacial gas phase concentration is given by:

$$y_i = 1 - (1-y) \cdot \left(\frac{x}{x_i}\right)^{\frac{F_L}{F_G}} \quad (5)$$

Equation (5) was used with the vapor-liquid equilibrium curve for LiCl to solve for the interfacial concentrations in the gas and liquid phases.

The k-Type mass transfer coefficients for liquid phase can be converted to F-Type coefficients by:

$$F_L = k_L \cdot x_{SM} \cdot \frac{\rho_L}{M_L} \quad (6)$$

Where x_{SM} may be considered equal to 1 for very dilute solutions. For lithium chloride the logarithmic mean desiccant mole fraction difference between the bulk liquid and interface values must be calculated as:

$$x_{SM} = \frac{x - x_i}{\ln\left(\frac{x}{x_i}\right)} \quad (7)$$

The k-Type mass transfer coefficient for gas phase can be converted to F-Type coefficients by:

$$F_G = k_G \cdot P \quad (8)$$

The change in air temperature across the differential segment is given by:

$$\frac{dT_a}{dZ} = \frac{h'_G a_t \cdot \left(T_L - T_a\right)}{G \cdot \left(c_{P,a} + Y \cdot c_{P,v}\right)} \quad (9)$$

Where $h'_G a_t$ is the heat transfer coefficient corrected for simultaneous heat and mass transfer:

$$h'_G a_t = \frac{-G \cdot c_{P,v} \cdot \frac{dY}{dZ}}{1 - \exp\left(\frac{G \cdot c_{P,v} \cdot \frac{dY}{dZ}}{h_G \cdot a_t}\right)} \quad (10)$$

Applying the heat and mass transfer analogy, it is found that the gas phase heat transfer coefficient is:

$$h_G = F_G \cdot M_a \cdot \left(C_{P,a} + Y \cdot C_{P,v}\right) \cdot \frac{Sc^{2/3}}{P_r^{2/3}} \quad (11)$$

With Schmidt number $Sc = \frac{\mu_G}{\rho_G \cdot D_G}$.

The change in desiccant flow rate, concentration and temperature across the differential segment are given by equations 12, 13 and 14 respectively:

$$\frac{dL}{dZ} = G \cdot \frac{dY}{dZ} \quad (12)$$

$$\frac{dX}{dZ} = -\frac{G}{L} \cdot X \cdot \frac{dY}{dZ} \quad (13)$$

$$\frac{dT_L}{dZ} = \frac{G}{c_{P,L} \cdot L}\left\{\left(c_{P,a} + Y \cdot c_{P,v}\right)\frac{dT_a}{dZ} + \left[c_{P,v} \cdot \left(T_a - T_o\right) - c_{P,L}\left(T_L - T_o\right) + \lambda_o\right]\frac{dY}{dZ}\right\} \quad (14)$$

Vapor pressure is an important property which determines the air humidity ratio in equilibrium with the desiccant at the interface. In this study a second order polynomial was used and the coefficients were obtained from a curve fit using data from Uemura (1967):

$$p_V = \left(a_o + a_1 \cdot T + a_2 \cdot T^2\right) + \left(b_o + b_1 \cdot T + b_2 \cdot T^2\right) \cdot X + \left(c_o + c_1 \cdot T + c_2 \cdot T^2\right) \cdot X^2 \quad (15)$$

$a_o=4.58208$, $a_1=-0.159174$, $a_2=0.0072594$ $b_o=-18.3816$ $b_1=0.5661$, $b_2=-0.019314$ $c_o=21.312$, $c_1=-0.666$ $c_2=0.01332$; T (°C), X (kg_{LiCl}/kg_{sol}).

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A sensitivity analysis comparing the data from Uemura (1967), and Zaytsev and Aseyev (1992) has shown that the deviation in water condensation rate can be of the order of 11%.

The efficiency of the tower was evaluated through a humidity effectiveness defined as:

$$\in_Y = \frac{Y_{IN} - Y_{OUT}}{Y_{IN} - Y_{equ}} \qquad (16)$$

For this relation, Y_{IN} and Y_{OUT}, are the humidity ratios of the air at the inlet and outlet of the tower, respectively. Y_{equ} is the humidity ratio of the air, which is in equilibrium with the desiccant solution at the local solution temperature and concentration.

An additional consideration was introduced in the model to account for the non-uniform liquid distribution at the top of the tower. The packing volume that is dry is estimated by using geometric relations allowing the calculation of a correction factor for unwetted packing fraction, CF. This correction factor was used to modify the relation a_w/a_t in equation (1), by $a_w/(a_t \cdot CF)$.

RESULTS AND DISCUSSION

Table 1 presents the experimental results, while figures 3 to 8 show the experimental results together with the theoretical modeling results. Uncertainties of the experimental measurements were calculated using the method by Kline and McClintock (1953). Error bars obtained from these calculations are also shown in the figures. It is seen from the figures that the adapted finite difference model shows very good agreement with the experimental findings. The variables found to have the most significant effect on the dehumidifier performance are: air flow rate, humidity ratio, desiccant temperature, and desiccant concentration. Figures 3 to 8 show that the influence of these variables may be assumed linear. Therefore, the slope of the condensation rate curve (% change in m_{cond} / % change in variable) in these figures gives an estimation of the influence of these variables on the water condensation rate. The water condensation rate increases with the air flow rate with a slope of 0.9 (Fig. 3). It may be explained that a high air flow rate will remove the dehumidified air more rapidly from the interface, thereby reducing the humidity gradient between the interface and bulk air, and maintaining a higher potential for mass transfer. The water condensation rate increases with the inlet air humidity ratio with a slope of 2.5 (Fig. 5). It happens because a higher humidity ratio implies a higher air vapor pressure and consequently higher potential for mass transfer. The water condensation rate decreases with the desiccant temperature with a slope of –1.4 (Fig. 7). A higher desiccant temperature gives a lower potential for mass transfer in the dehumidifier resulting in a lower condensation rate. The water condensation rate increases with the desiccant concentration with a slope of 2.7 (Fig. 8). A higher desiccant concentration gives a higher potential for mass transfer in the dehumidifier resulting in a greater condensation rate. It may be pointed out that if the air temperature is considerably higher than the desiccant temperature, the desiccant temperature will increase, resulting in a reduction of the potential for mass transfer (Fig. 4). The desiccant flow rate does not cause significant variation in the water condensation rate (Fig. 6); however, the liquid flow rate must be high enough to ensure wetting of the packing.

For the range of the variables studied, humidity effectiveness for the absorber remains mostly stable, no variation higher than 6% was found. The only clear trends observed were: slight decrease of the humidity effectiveness with air flow rate and air temperature; and slight increase of the humidity effectiveness with desiccant flow rate. The lower value of humidity effectiveness was 75% and the higher 84%.

Table 1: EXPERIMENTAL RESULTS

INLET						OUTLET				
G	Ta	Y	L	TL	X	Ta	Y	TL	X	m_{cond}
0.890	30.1	0.0180	6.124	30.1	34.6	31.3	0.0104	32.3	34.5	0.32
1.180	30.1	0.0181	6.227	30.3	34.7	32.2	0.0108	32.6	34.6	0.40
1.513	30.2	0.0181	6.113	30.0	34.3	32.2	0.0108	32.7	34.1	0.52
1.189	35.5	0.0188	6.290	30.3	34.5	32.8	0.0112	32.6	33.7	0.42
1.183	40.1	0.0180	6.287	30.5	34.4	33.1	0.0115	32.9	34.3	0.36
1.214	30.3	0.0142	6.273	30.1	33.9	31.1	0.0103	31.5	33.8	0.23
1.187	29.9	0.0215	6.272	30.3	33.9	33.4	0.0120	33.1	33.7	0.53
1.190	30.1	0.0180	5.019	30.2	34.4	32.2	0.0113	32.7	34.2	0.38
1.182	30.2	0.0181	7.420	30.2	34.4	32.0	0.0110	32.5	34.3	0.39
1.198	29.9	0.0177	6.269	25.0	34.7	28.2	0.0088	28.4	34.5	0.50
1.176	29.9	0.0178	6.309	35.2	34.9	35.7	0.0140	36.2	34.8	0.21
1.182	29.9	0.0179	6.164	30.1	33.1	32.4	0.0114	32.2	33.0	0.36
1.192	29.9	0.0179	6.267	30.2	33.8	32.5	0.0112	32.6	33.7	0.38
1.176	30.0	0.0181	6.206	30.2	34.8	32.0	0.0107	32.5	34.7	0.41

CONCLUSIONS

Reliable sets of data for air dehumidification using lithium chloride were obtained. The influence of the design variables studied on the water condensation rate can be assumed linear. Therefore, the slope of the condensation rate curve in Figures 3 to 8 gives a measurement of the impact of the variable on the water condensation rate. Design variables found to have the greatest impact on the performance of the dehumidifier are: desiccant concentration (slope=2.7), desiccant temperature (slope= -1.4), air flow rate (slope=0.9), and air humidity ratio (slope=2.5). In this study the mass flow ratio of air to desiccant solution (MR) was varied between 0.15 to 0.25 which is lower than the MR values of 1.3 to 3.3 used in most other studies. The adapted finite difference model shows very good agreement with the experimental findings.

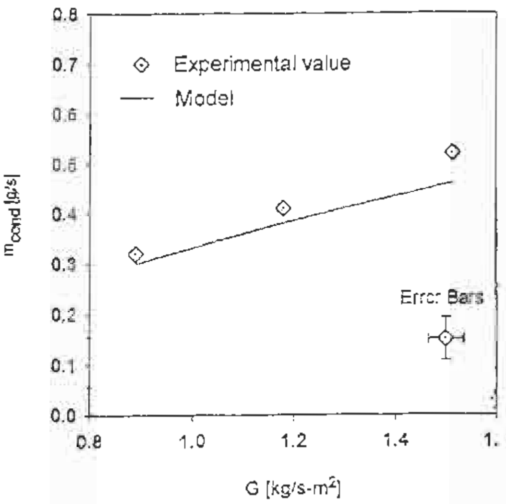

Fig 3: Influence of air flow rate

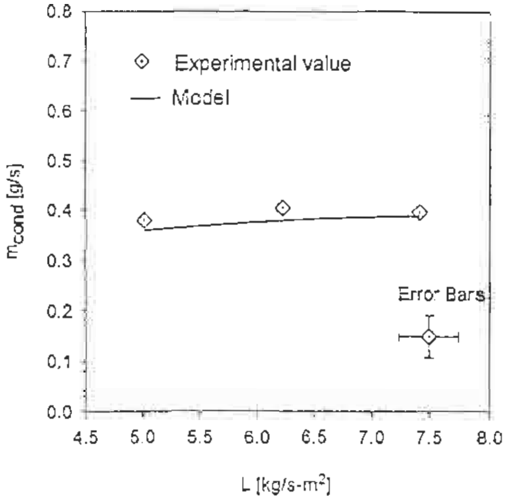

Fig. 6: Influence of desiccant flow rate

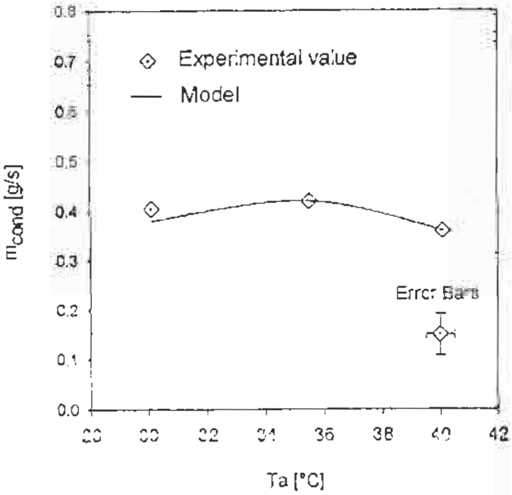

Fig. 4: Influence of inlet air temperature

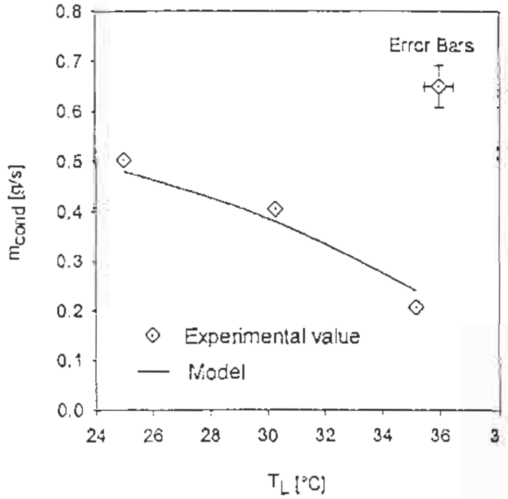

Fig. 7: Influence of inlet desiccant temperature

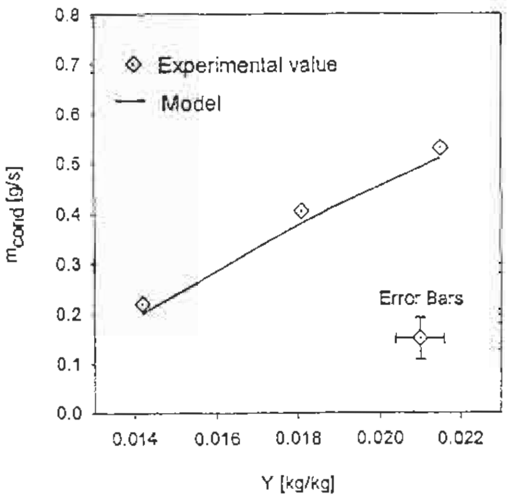

Fig. 5: Influence of inlet air humidity ratio

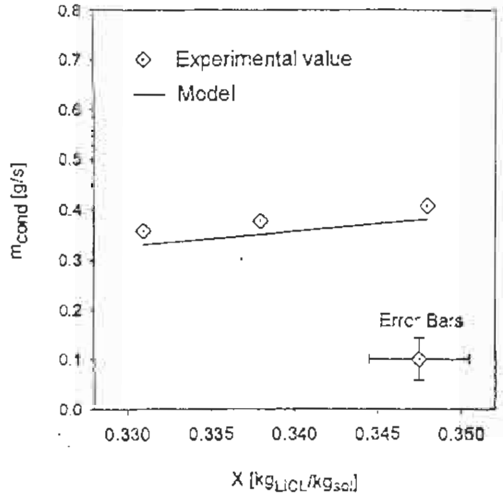

Fig. 8: Influence of inlet desiccant concentration

NOMENCLATURE

a_t = specific surface area of packing (m^2/m^3)
a_w = wetted surface area of packing (m^2/m^3)
specific heat (kJ/k_g-°C)
diffusivity (m^2/s)
D_p = nominal size of packing (m)
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)
= acceleration of gravity (m/s^2)
gas side heat transfer coefficient (kJ/m^2-s)
= gas phase mass transfer coefficient ($kmol/m^2$-s-Pa)
= liquid gas phase mass transfer coefficient (m/s)
L = superficial desiccant flow rate (kg/m^2-s)
M = molar mass (kg/kmol)
m = flow rate (g/s) or (kg/s)
P = total pressure (Pa)
Pr = Prandtl number
p_v = vapor pressure (Pa)
T = Temperature (°C)
= desiccant concentration (kg_{LiCl} / $kg_{solution}$)
x = desiccant mole fraction ($kmol_{LiCl}$ / $kmol_{solution}$)
x_{SM} = logarithmic mean solvent mole fraction difference between the bulk liquid and interface values ($kmol_{LiCl}$ /$kmol_{solution}$)
Y = air humidity ratio (kg water/kg dry air)
y = water mole fraction (kmol water / kmol air)
Z = tower height (m)
γ = surface tension (N/m)
λ = latent heat of condensation (kJ/kg)
μ = viscosity (N/m^2)
ρ = density (kg/m^3)

Subscripts:

a = air
c = critical
G = gas phase
i = interface
L = desiccant or liquid phase
o = reference state

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