Study the performance of dehumidification packed bed tower using liquid desiccant

دراسة اداء برج تجفيف الهواء ذي مهد يعمل بمادة سائلة ماصة للرطوبة

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الملخص العربي:

يعرض في هذا البحث تصميم لمجفف للهواء الرطب ، يعتمد علي المجففات السائلة و يمكن استعماله في منظومات تكييف الهواء التي تعمل بمثل هذه السوائل وبالطاقة الشمسية أو أى مصدر طاقة حرارية منخفضة. هذا المجفف يتكون من برج غير اديباتيكي معبأ بقطع من مادة polypropylene مساحتها 167م^2/م^3 هذة القطع ملصوقة في الجدران الداخلية للبرج بشكل مبعثر.

تمت دراسة عملية إنتقال الحرارة والمادة وتداخل عمليتي تجفيف الهواء وتشبع المحلول النشط عبر نموذج يعتمد على فوارق الخواص الحرارية للموائع المستعملة (الهواء الرطب والمحلول النشط) وقد تم مقارنة هذة الدراسة بالنتائج العملية التي اجريت. التنبؤ باداء المجفف وقع عبر دراسة مدي تأثير مختلف العوامل واستعمال الحاسب الآلى . النتائج تؤكد على أن بزيادة رطوبة الهواء الداخل وتقليل درجة حرارة الهواء والمحلول وزيادة معدل تدفق الهواء وتركيز المحلول ومعدل تدفقه عملية التجفيف تتحسن كفاءتها.

Abstract

The application of desiccant air conditioning systems is proposed as an alternative solution that reduces energy consumption and greenhouse gas emissions in hot and humid locations. This paper presents the results from a study of the performance of a packed tower absorber for calcium chloride desiccant dehumidification system. The rate of dehumidification was assessed under the effects of variables such as air and desiccant flow rates, air temperature and humidity, and desiccant temperature and concentration.

Key words: liquid desiccant –dehumidifier –heat and mass transfer.

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Nomenclature:

W	Air humidity ratio, kg_v/kg_{da}.
C_p	Specific heat, kJ/kg.^{0}C
$m^{\cdot}$	Mass flow rate, kg/s.
L	Desiccant flow rate, kg/m^2.s.
G	Air flow rate, kg/m^2.s.
N_v	Specific interfacial mole flow rate, kmol/m^2.s.
T	Temperature, ^{o}C .
X	Desiccant concentration, kg salt /kg solution.
h	Heat transfer coefficient, kW/m^2. ^{0}C .
q_a	Heat transfer from air to solution, kW/m^2.
a_t	Specific surface area of packing, m^2/m^3.
a_w	The effective interfacial area of packing, m^2/m^3.
M	The molecular weight, kg/kmol .
F	Mass transfer coefficient, kmol / m^2.s
P	The partial vapor pressure, Pa .
P	The total pressure in humid air, Pa.
dZ	The differential length in flow direction, m.
$h'_a \cdot a_t$	The corrected heat transfer coefficient .
Dp	Nominal diameter of packing, m.
D	Diffusivity, m^2/s.
Pr	Prandtl number.
Sc	Schmidt number.
K	The mass transfer coefficient, m/s .
R	Universal gas constant, kJ /kmol .
$m^{\cdot}_{deh}$	The rate of absorbed mass, kg/s
MR	The percentage moisture removed, % .

Greek letters

σ	Surface tension, N/m^2.
μ	Viscosity, N.s/m^2.
ρ	Density, kg/m^3.
λ	Latent heat of condensation, kJ/kg .

Subscripts

a	Air.
L,s	Desiccant solution.

o	Reference or outside.
W,v	Water vapor.
c	Critical.
e	Equilibrium.
deh	Air dehumidification.

1- Introduction

Use of liquid desiccant offers several design and performance advantages over solid desiccant , especially when solar energy is used for regeneration. Air may be dehumidified when it is brought into contact with a suitable liquid desiccant. Different types of liquid desiccants are available in the market and the application of the proper desiccant in hot humid climates would improve the dehumidification effectiveness. The driving potential for a dehumidification process is the difference in the pressure of the water vapor in the air and the water vapor saturation pressure corresponding to the air-desiccant solution interfacial temperature and concentration of water above the desiccant. Among the various desiccants available, lithium chloride, lithium bromide, calcium chloride, and tri ethylene glycol have received much attention.

Both solid and liquid desiccants are extensively used for dehumidification and cooling. Some of the merits of liquid desiccant systems include improved indoor air quality, acting as disinfectants, being single regenerator for multiple conditioners and flexibility in its location. However, common problems involving carryover of solutions into air stream, crystallization of salts and corrosion by salts are expected. Never the less, the liquid desiccant cooling systems is used to control air humidity especially in hot and humid areas.

Chung et al. [1] compared random Flexi Rings and Berl Saddles to cross corrugated cellulose and PVC structured packing in dehumidification testes with LiCl solution. Gandhidasan P. [2] developed a prediction procedure for air side pressure drop in a apacked column valid both for random and structured packings.

Zurigat et al [3] and Abdul-Wahab et al. [4,5] analysed the effect of operating conditions and structured packing density on the dehumidification performance with tri ethylene glycol (TEG) desiccant.

Elsarrag [6] experimentally investigated the effect of air and liquid flow rates, air humidity, desiccant temperature and concentration on tri ethylene glycol (TEG) regeneration in a packed column filled with structured packing. Fumo and

Goswami [7] modeled and experimentally measured the performance of packed-bed, lithium chloride heat, and mass exchangers that used a random, polypropylene packing with a volumetric surface area of 210 m^2 per m^3. It was also noticed that the dehumidification or regeneration process was almost not affected by the air temperature and the desiccant solution flow rate. Liu and Jiang [8] and Liu et al. [9] presented analytical solutions for the coupled heat and mass transfer within liquid- desiccant packed- bed systems under assumptions that included minimal change in desiccant concentration through the packed bed and a Lewis number of one. Both groups of [8] and [9] researchers showed that their analytical solutions closely agree with more exact numerical solutions and with experimental data from other studies. Salarian H. et al. [10] studied the performance of a packed bed absorber LiCl desiccant dehumidification system. The packings of the absorber tower was predicted using a finite difference model. The experimental study was carried out to evaluate the dehumidification rate of air. The influence of the design variables on the dehumidification rate, is studied.

The present study uses a mathematical model to compare the experimental results of a packed bed.

2. Experimental Set- Up and Procedure

A experimental apparatus is designed for studies on a packed bed liquid desiccant absorber, based on the results of a finite difference model, is shown in Figure1.

A schematic of the experimental rig is shown in Figure 1and 2. The packed bed absorption tower has a 35x35 cm cross section . The height of the tower is constant and equal to 60cm. The Packings used are polypropylene with specific surface area of 167 m^2/m^3. The experimental rig consists of an air line and a desiccant loop. In the first loop ambient air is blown past an air heater coil (800W) and through a humidifying chamber to achieve the set conditions at the inlet of the packed tower. The air goes through the packed tower, where the heat and mass transfer take place in a counter flow configuration (air up-flow and desiccant down-flow) . An air dehumidification process or a desiccant absorption process occurs depending on the relative values of the partial vapor pressure on the air and desiccant side. Fresh unused calcium chloride ($CaCl_2$) solution is stored in a tank, and its temperature is adjusted by an electric heater (1200W) submerged in it. After the desiccant solution reaches its adjusted temperature, it is pumped and sprayed over the top of the dehumidifier. A circulation pump was used to circulate the solution. To study dehumidification, the rate of moisture removal from the air (water condensation rate) is studied experimentally and theoretically as a function of the following variables: air and desiccant flow rates; air temperature and humidity ratio; and desiccant temperature and concentration.

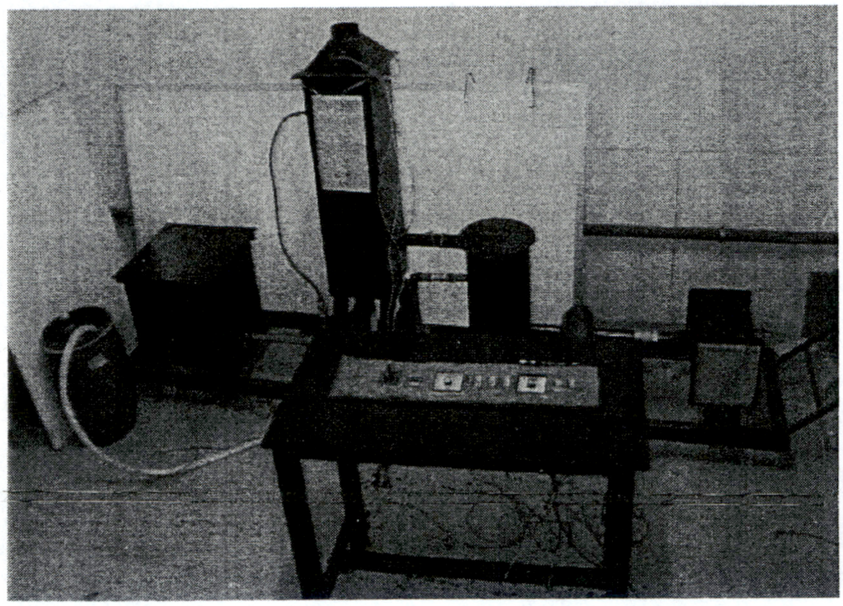
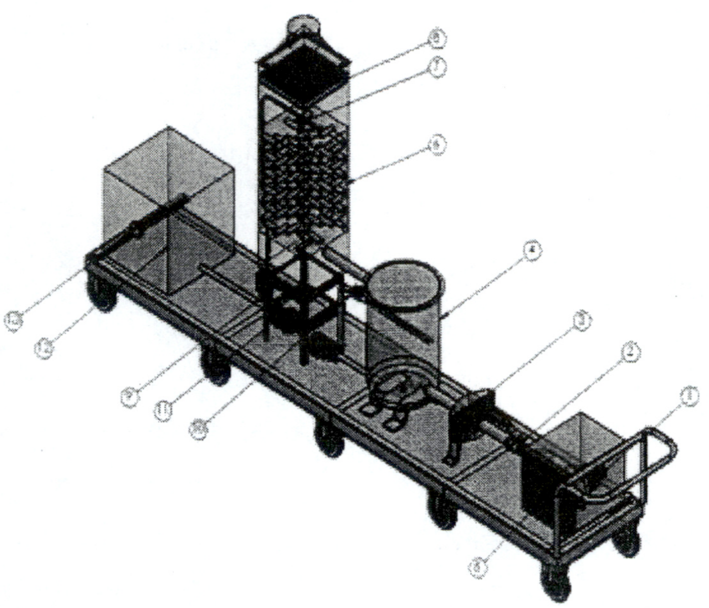


Fig. 1-The experimental test rig for liquid desiccant dehumidification system.



1- Air Blower.
2- Air Control Value.
3- Air Heater.
4- Humidifying Chamber .
5- Air Filter .
6- Random Packing .
7- Liquid Distributor.
8- Eliminator .
9- Solution Control Valve .
10- Water Pump.
11- Desiccant Solution Pump .
12- Fresh Desiccant Storage.
13- Desiccant Solution Heater.

Fig. 2- A schematic diagram of the experimental setup.

2.1. Measuring locations:

As shown in figure 1 the air duct contains two measurement sections located at the inlet and at the outlet of the tower to measure the temperature and humidity ratio. Each measuring station consists of two temperature taps.

2.2. The used instruments:

Concentration of $CaCl_2$ solution at a given point is determined by calculating its density and temperature at this point using the data available in tabular form by Zaertsev and Aseev [12]. The density of the solution is calculated by collecting a sample of the solution and measuring its mass and volume. The partial vapor pressure on the desiccant solution surface is calculated using the correlations introduced by Gad et al. [13]which will be mentioned later. Digital air velocity meter with a resolution 0.1 is used to measure the air velocity . The temperature of the air and the liquid desiccant is measured by a K-Type thermocouple. This instrument is used for measuring the air-dry bulb, wet bulb, and desiccant temperatures. By using the wet bulb and dry bulb temperatures of the air, the humidity of the air can be obtained. A multi switch selector with six channels is used with the thermocouples to ensure measuring at the inlet and the outlet of tower .The desiccant flow rate is calibrated and adjusted constant during the experiment. The inlet temperature of air and solution is adjusted and recorded by a temperature controller with resolution 0.1 ^{0}C. The air and desiccant solution temperatures are varied by using electric heaters of 800W and 1200W respectively. The main features of the different measurement devices are shown in table 1.

Table (1) Specifications of different measurement devices.

Devices	Type	Accuracy	Range	% error
Thermometers	K-Type thermocouple 0412- YK90HT	± 0.1 ^{0}C	0-50 ^{0}C	±0.1K
Air velocity meter	HB2 T M 4010000	±0.2 m/s	0.4-25m/s	±0.2%
Temperature controller	Thermostat	± 1 ^{0}C	0-400 ^{0}C	±0.3%

3. Theoretical Heat and Mass Transfer Model of the Packed Bed Towers:

Assumptions:

The used model is based on the following assumptions:

- The system is adiabatic
- The thermal resistance in the liquid phase is negligible compared to the gas phase,
- The heat and mass transfers occur only in transversal direction to gas and liquid flows (Z-direction, referring to Fig.3B).

No axial dispersion exists. Therefore, a one-dimensional analysis can be used. The packed bed height z is divided into small segments, dZ (Fig.3B), 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 desiccant outlet conditions that give the known inlet conditions at the top of the packed bed. The column height, in which air flows upward at rate G and the desiccant solution flows downward at rate L.

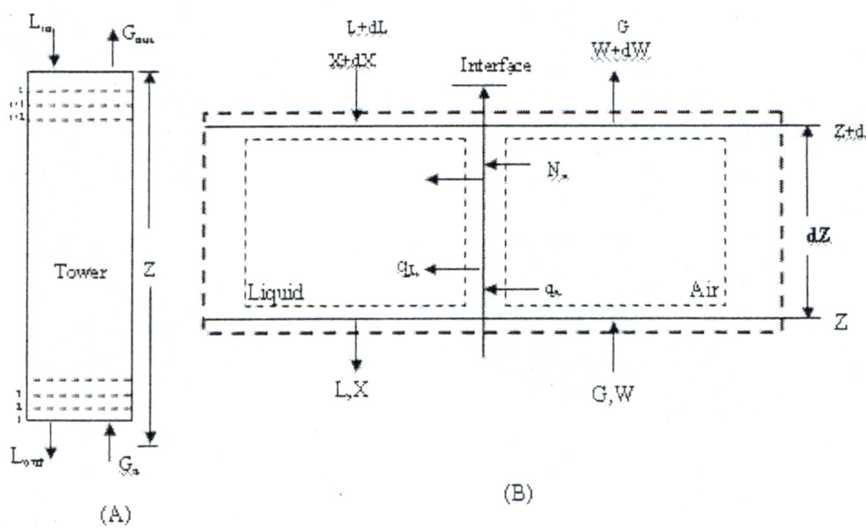


Fig.(3) Packed bed dehumidifier (A) over view; (B) differential segment.

3.1. Governing Equations:

Heat and mass balances for the dehumidifier will be carried out to derive the governing equations for the variation of air humidity and temperature, desiccant temperature, concentration and flow rate across a differential segment, based on the above assumptions.

The governing equations for the proposed system can be written as follows. [7]:

The Change in Air Humidity:

$$\frac{dW}{dZ} = -\frac{M_W F_a a_w}{G} Ln\left(\frac{1-P_{VL}/P}{1-P_{Va}/P}\right) \quad (1)$$

Where:

W is the absolute humidity of air kg_{wv}/kg_{da}; dZ is the differential length in flow direction in m; M_W is the molecular weight of water vapor in kg/kmol; F_a is the air side mass transfer coefficient in kmol/m^2.s; a_w is the wetted surface (the effective interfacial) area of packing in m^2/m^3; G is superficial air flow rate in kg/m^2.s;

P_{VL} is the partial vapor pressure on the desiccant solution surface in pa; P_{va} is the partial vapor pressure on the air in Pa; P is the total pressure in humid air in Pa.

The Change in Air Temperature:

$$\frac{dTa}{dZ} = \frac{h'_a a_t.(T_L - T_a)}{G.(C_{pa} + W.C_{pv})} \quad (2)$$

Where:

T_a and T_L are the temperature of air and liquid; respectively in ^{0}C; C_{pa} and C_{pv} are the specific heat of air and water vapor; respectively in kJ/kg^{0}C; $h'_a \cdot a_t$ is the heat transfer coefficient corrected for simultaneous heat and mass transfer [7]:

$$h'_a a_t = \frac{-G.C_{pv}.\frac{dW}{dZ}}{1-\exp\left(\frac{G.C_{PV}.\frac{dW}{dZ}}{ha\ a_t}\right)} \quad (3)$$

Where:

h_a is the air side heat transfer coefficient in kW/m^{2}.^{0}C; a_t is the total specific surface area of packing in m^2/m^3.

The Change in Desiccant Flow Rate:

$$\frac{dL}{dZ} = G.\frac{dW}{dZ} \quad (4)$$

Where:

L is superficial desiccant flow rate in kg/m^2.s; G is superficial air flow rate in kg/m^2.s.

The Change in Desiccant Concentration:

$$\frac{dX}{dZ} = -\frac{G}{L}.X.\frac{dW}{dZ} \quad (5)$$

Where:

X, is desiccant concentration in kg_{salt} /$kg_{solution}$.

The Change in Desiccant Temperature:

$$\frac{dT_L}{dZ} = \frac{G}{C_{pL} \cdot L}\{(C_{pa} + WC_{pv})\frac{dT_a}{dZ} + [C_{pv}.(T_a - T_o) - C_{pL}(T_L - T_o) + \lambda_o]\frac{dW}{dZ}\} \quad (6)$$

Where:

C_{pd} , C_{Pa} , C_{pv} are the specific heat of desiccant, air and water vapor; respectively in kJ/kg^0C; T_o is the reference ,environment, outside temperature; λ_O is latent heat of condensation at the reference temperature in kJ/kg.

The heat and mass transfer area is held to be identical and is equal to the specified surface area of the packing. However, since the high surface tension of the desiccant solution, the surface of the packing is often wetted insufficiently. This phenomena resulted in reduction of the mass transfer area, So that, in the study of N. Fumo and D. Y. Goswami in 2000 [7], the surface tension of the desiccant solution is taken into account by adopting the equation for wetted surface area proposed by Onda et al. (1968) [14].

$$\frac{a_W}{a_t} = 1 - \exp[-1.45(\frac{\sigma_C}{\sigma_L})^{0.75}(\frac{L}{a_t \mu_L})^{0.1}(\frac{L^2 a_t}{\rho_L^2 g})^{-0.05}(\frac{L^2}{\rho_L \sigma_L a_t})^{0.2} \quad (7)$$

Where:

σ is the surface tension in N/m; μ is the dynamic viscosity in kg/m.s ; ρ is the density in kg/m^3; g is the acceleration due to gravity in m/s^2.

Note that:

σ_C is the critical surface tension of packings which equal to 0.035 N/m^2; σ_L is the surface tension of desiccant solution which equal to 0.095 N/m^2 [14].

Where:

a_w and a_t are the wetted and specific surface area of packing ; respectively (m^2/m^3); σ_C and σ_L are the critical and desiccant solution surface tension; respectively (N/m), μ_L is the desiccant viscosity (N/m^2); ρ_L is the desiccant density (kg/m^3). This equation was used by

Oberg and Goswami in the definition of K-type mass transfer coefficients [11]:

$$K_a = 5.23(\frac{a_t.D_a}{R.T_a})(\frac{G}{a_t\mu_a})^{0.7}(\frac{\mu_a}{\rho_a.D_a})^{1/3}.(a_t.D_p)^{-2} \qquad (8)$$

Where:

K_a is the air side mass transfer coefficient in kmole /m^2.s.Pa; g is acceleration of gravity in m/s^2; D_a is the diffusivity of air in m^2/s; D_P is nominal size of packing in m; R is the universal gas constant in kJ/kmol °C (R= 8.314 kJ/ kmol/°C).

The K-type mass transfer coefficient for air side can be converted to F-type coefficients by :

$$F_a = K_a.\ P \qquad (9)$$

Where

F_a is the air side mass transfer coefficient in kmol/m^2 .s; P is the total pressure in humid air in Pa .

By apply the heat and mass transfer analogy; it is found that the air side heat transfer coefficient is [7]:

$$h_a = F_a.M_a.(C_{pa}+WC_{pv}).\frac{Sc^{2/3}}{\Pr^{2/3}} \qquad (10)$$

The Schmidt number is given by:

$$Sc = \mu_a/(\rho_a.D_a) \qquad (11)$$

Where:

h_a is the air side heat transfer coefficient in kW/m^2.^{0}C; M_a is the molar mass of air in kg/kmol.

The air contact with a desiccant solution is said to be in equilibrium state when there is no heat abs mass transfer between the air and the solution . The humidity ratio (HR) of the air at the equilibrium with the desiccant solution can be evaluated from [13].

$$W_e = \frac{0.622P_{VL}}{1.013\times10^5 - P_{VL}} \qquad (12)$$

Where:

w_e is the HR air in equilibrium with $CaCL_2$ solution at the interfacial area in kg_V/Kg_{da} , P_{VL} is in pa which is calculated using the correlations introduced by Gad et al. [13]

$$Ln(P_{VL}) = A(X_L) - \frac{B(X_L)}{T_L+111.96} \qquad (13)$$

Where:

P_{VL} is in mmHg, T_L is in ^{0}C A (X_L) and B(X_L) are regression dependent parameters, which can be expressed as linear functions of concentration according to the following relations:

$$A(X_L) = a_0 + a_1X \qquad (13a)$$

$$B(X_L) = b_0 + b_1 X \quad (13b)$$

Where:

a_0= 10.0624, a_1= 4.4674

b_0=739.828, b_1=1450.96

The value of P_{vL} in the above equation is within a temperature range of 10-65 ^oC and a concentration range of 20-50%

4. The Performance of the Dehumidifier:

The moisture removal rate (MRR)

The MRR is defined as the rate of which moisture is removed from process air. It can be calculated from.

$$MRR. = \dot{m}_{deh} = \dot{m}_a (W - W_e) \quad (14)$$

Where:

$\dot{m}_{deh}$ is the rate of absorbed mass from the air into the desiccant solution, it is referred as, moisture removal rate (MRR), $\dot{m}_a$ is the mass flow rate of air in kg/s. The percentage of moisture removed (M.R.) is defined as following:

$$M.R. = \frac{inlet\ air\ humidity\ ratio - outlet\ air\ humidity\ ratio}{inlet\ air\ humidity\ ratio} x100 \quad (15)$$

5. Model Validation

To check the consistency and reliability of the present theoretical analysis, comparisons of the present model predictions are made with experimental results performed by Fumo and Goswami [7] which are illustrated in figures 4 and.5

The effect of inlet air humidity ratio, W Kg $_{w.v}$/ Kg $_{d.a}$. on the moisture removed ,M.R.% for X=0.35, Ta=30.2 ^0C, G=1.5 Kg/m^{2}s, L= 6 Kg/m^2.s and T_L=30 ^0C is illustrated in Fig.4. It is noticed from figure that the moisture removed M.R. increases with the increasing the inlet air humidity ratio.

The effect of the desiccant solution temperature, T_L,^0C on the M.R.% is illustrated in Fig. 5. It is noticed from the figure that the M.R. decreases with increasing the desiccant solution temperature.

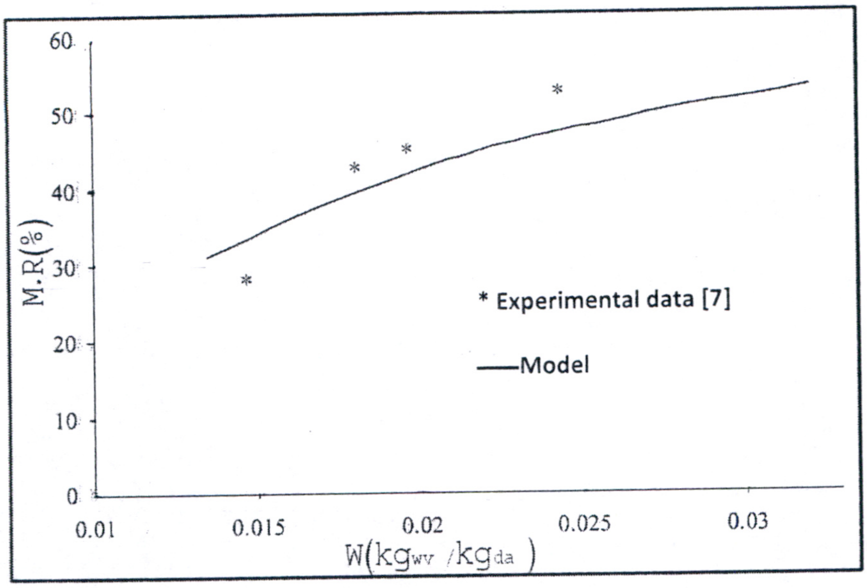


Fig. 4 - Effect of inlet air humidity ratio on dehumidification.

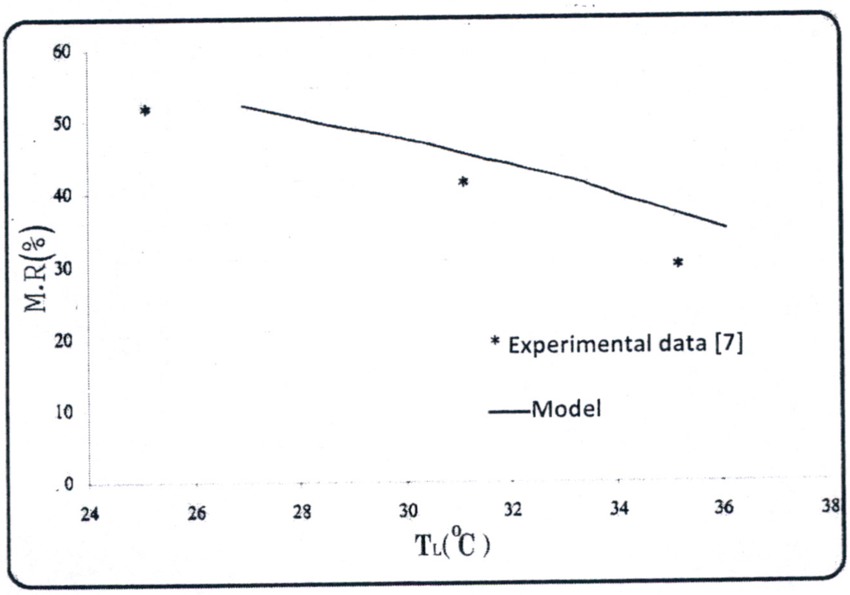


Fig. 5 - Effect of liquid desiccant temperature on dehumidification.

6. Results and Discussion

Numerical simulation is performed for different parameters. The effect of various parameters of air and desiccant solution, namely, air inlet temperature, inlet air humidity ratio, air mass flow rate, desiccant solution temperature, desiccant solution mass flow rate and desiccant concentration is investigated and studied experimentally. The effect of any parameter is studied by varying its value while the other parameters are kept constant. The effect of each parameter is analyzed as follows:

6.1. Effect of Desiccant Flow Rate:

Fig.6 shows the influence of the desiccant solution flow rate on the moisture removed M.R. % from the air stream of the absorber. The desiccant flow rate does not cause significant variation in the moisture removed. However, the liquid flow rate must be high enough to ensure wetting of the packing, good contact between the air and the desiccant and also to increase the heat and mass transfer coefficients.

6.2. Effect of Desiccant Concentration

The influence of the desiccant solution concentration on the moisture removed is shown in Fig.7. Partial vapor pressure of the desiccant solution is reduced with increasing desiccant solution concentration, and it raises the mass transfer potential between the desiccant solution and the moisture in the air. Hence, the moisture removed increases with increasing desiccant solution concentration. Increasing of the concentration increases the surface tension in the desiccant solution , which reduces the wettability of the desiccant solution.

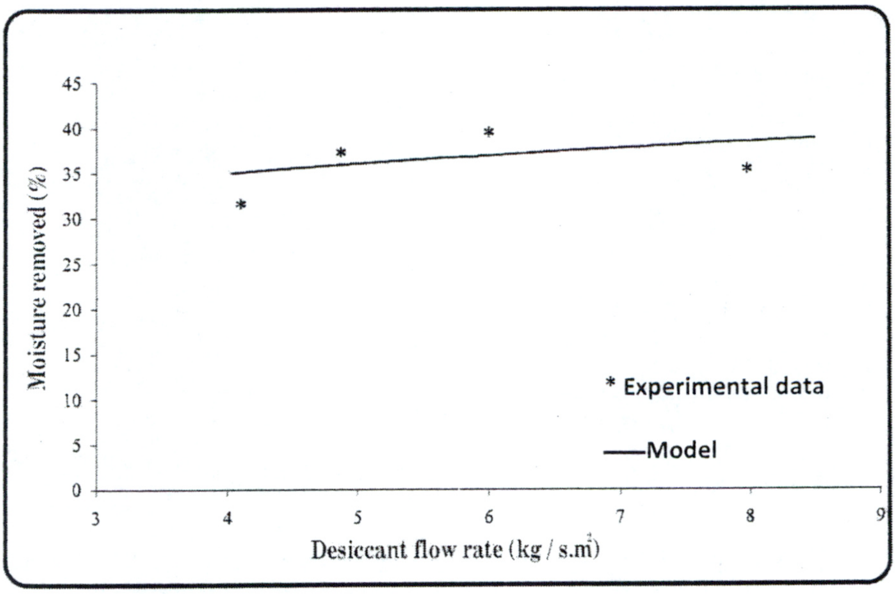


Fig. 6 - Effect of the desiccant flow rate on the moisture removed.

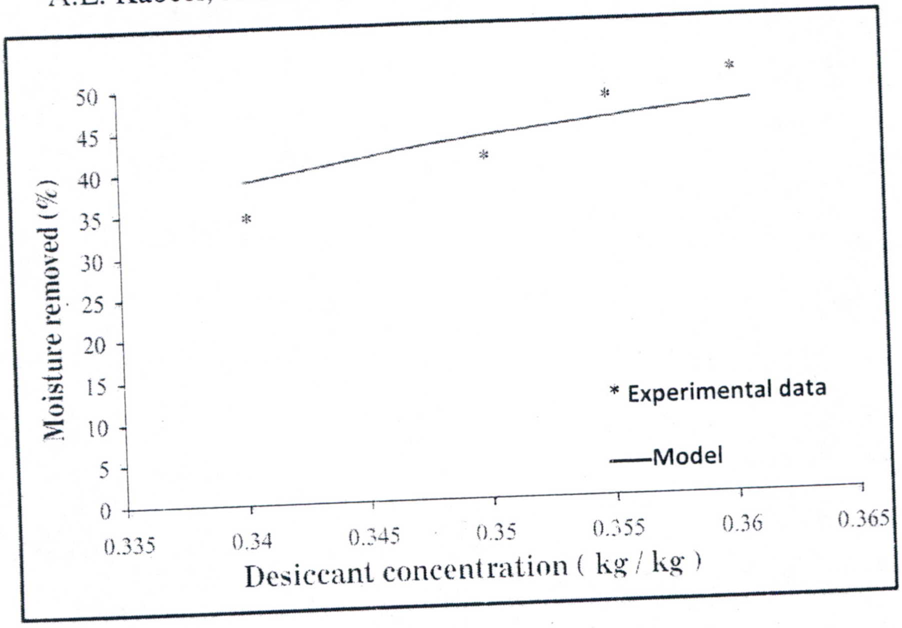


Fig. 7- Effect of the liquid desiccant concentration on the moisture removed.

6.3. Effect of Desiccant Inlet Temperature

Fig. 8 shows the influence of the solution temperature on the moisture removed, M.R%, from the air stream of the absorber. The moisture removed is reduced as the desiccant solution temperature increases because the latter raises the vapor pressure of the desiccant solution, and reduces the mass transfer potential between the desiccant solution and the moisture in the air. Surface tension of the desiccant solution is reduced as the desiccant solution temperature increases, which enhances the wettability and the wet area.

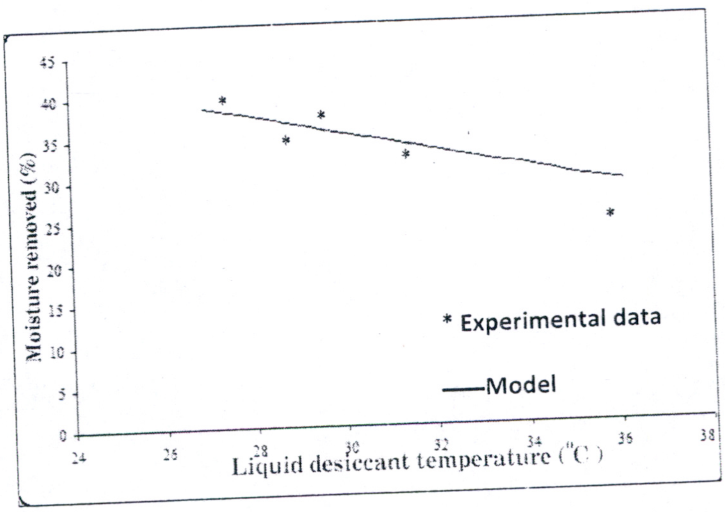


Fig. 8 - Effect of the liquid desiccant temperature on moisture removed.

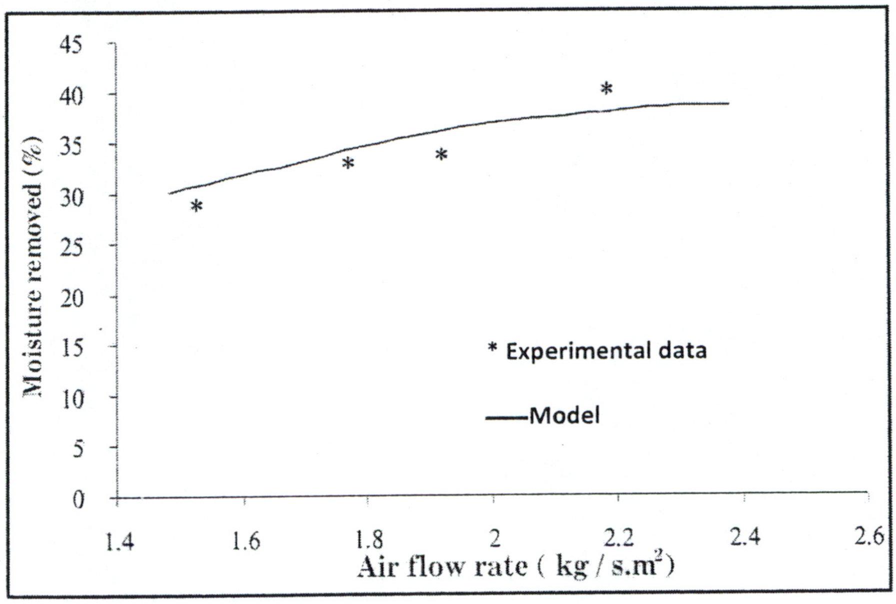
6.4. Effect of Air Flow Rate.

As is expected, the air flow rate affects the dehumidifier performance. The moisture removed increases with increasing air flow rate, Fig.9. Higher air flow rate increases the mass transfer coefficient between the desiccant solution and the air stream and incoming moisture rate into the dehumidification bed, but reduces the contact time.

The equilibrium humidity of solution tends to increase due to higher moisture removal. Higher mass transfer coefficient is not high enough to remove all the increased moisture rates. Hence , average humidity ratio of the air passing through the dehumidification bed is higher at higher air flow rates.

6.5. Effect of Air Inlet Humidity Ratio

It is shown in Fig.10 that increasing the air inlet humidity ratio increases the amount of moisture removed in the dehumidifier. The partial water vapor pressure of the air increases with increasing air inlet humidity ratio , which increases the mass transfer potential.



`Fig. 9 - Effect of the air flow rate on moisture removed.

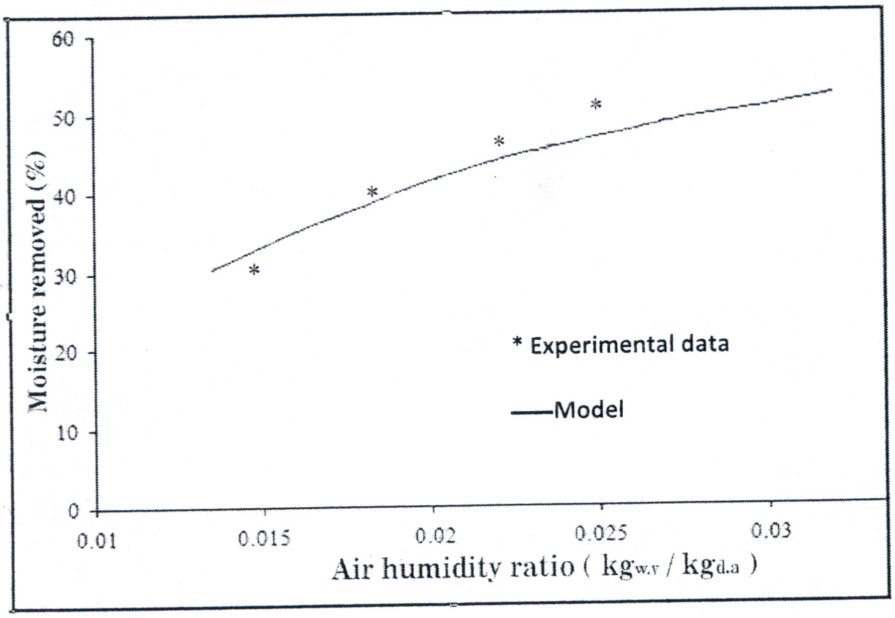


Fig. 10 - Effect of the inlet air humidity ratio on moisture removed.

6.6. Effect of Air Inlet Temperature

The effect of the air inlet temperature on the moisture removed is shown in Fig.11. Heat is transferred from the hot air to the desiccant solution, which increase in the solution temperature due to the raising in the partial vapor pressure of the desiccant solution. Hence, the amount of the moisture removal is reduced with increasing the air inlet temperature.

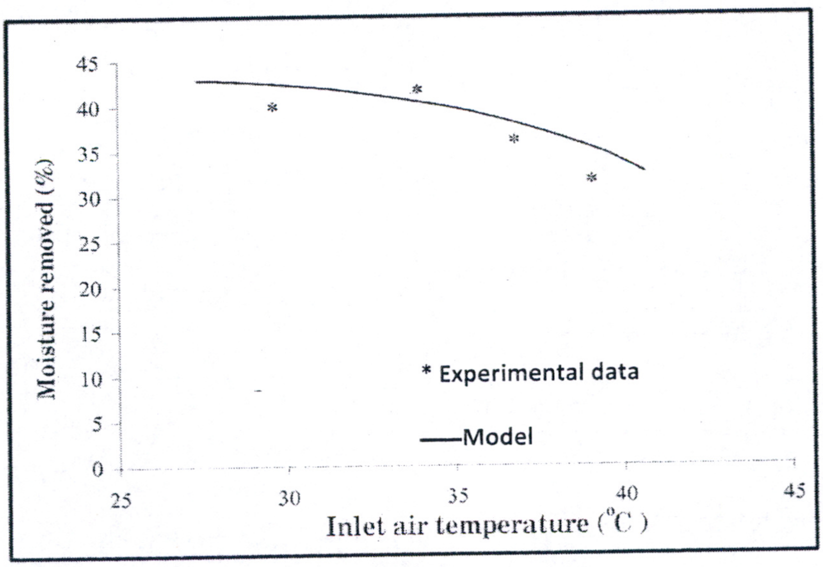


Fig.11- Effect of the inlet air temperature on moisture removed.

7. Conclusion

The present analysis was used by Oberg and Goswami [7] for deriving the governing equations to predict the variation of the humidity ratio, flow rate and temperature of air, desiccant solution temperature, concentration and flow rate along the dehumidifier height in the dehumidifier, packing height as a function of moisture removed. The theoretical study is carried out to evaluate the dehumidification rate of air in a dehumidifier packed tower.

The experimental study is carried out to evaluate the dehumidification rate of air in a dehumidifier packed tower . Results of the model are plotted and compared with experimental data. Also, the theoretical results of the presented model are compared with other investigator for validation purpose whereas good agreement is found.

From the experimental data and analysis of theoretical results the following conclusions can be summarized:

1- The air humidity ratio decreases along the dehumidifier height with decreasing of desiccant solution temperature.
2- The desiccant solution moisture content decreases along the dehumidifier height with increasing the desiccant solution temperature, but with decreasing the inlet humidity ratio.
3- The air temperature decreases along the dehumidifier height with increasing the inlet humidity ratio, but with decreasing the desiccant solution inlet temperature.
4- The desiccant solution moisture content gain increases with the increase of each of the desiccant solution concentration and the inlet humidity ratio, but it increases with the decrease of the desiccant solution temperature and the mass flow rate.
5- The increase of the liquid desiccant solution flow rate leads to an increase of the dehumidifier performance slightly.
6- Comparison between theoretical and experimental results shows that difference of the order of 4 % is found.

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