Mansoura Engineering Journal, (MEJ), Vol. 25, No. 3, September 2000.

APPLICATION OF HONEYCOMB BED AS A DESICCANT CARRIER FOR ABSORPTION OF WATER FROM AIR

امتصاص بخار الماء من الجو بواسطة طبقة من القماش على شكل خلية النحل

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خلاصة :

في هذا البحث تم عمل دراسة نظرية ومعملية حول استخدام طبقة من القماش مشكلة على هيئة شمع عسل النحل بعد تشريبها بمحلول كلوريد الكالسيوم بغرض امتصاص رطوبة الجو. في النموزج الرياضى تم تناول ومناقشة تأثير العوامل المختلفة على عملية الامتصاص وتشمل هذه العوامل كل من درجة حرارة وكمية السريان ورطوبة الجو بالاضافة الى خواص المحلول الملحى المستخدم في الجزء العملى من البحث تم تجهيز نماذج متشابهة كل نموزج على شكل شمع عسل النحل وتم وضعها في قناة هوائية على التوالى. اجريت التجارب عند درجات حرارة مختلفة ومعدلات متغيرة لسريان الهواء الجوى وتم مقارنة معدلات الامتصاص بالنسبة للوحدات الثلاثة وقد تم عمل مقارنة بين نتائج النموزج الرياضى والقياسات المعملية ومناقشة النتائج.

ABSTRACT

In the present work, the application of a thick layer of cloth in a honeycomb form for the absorption of water vapour from atmospheric air is investigated. Three equivalent cells are arranged in series and the air stream is allowed to flow through them. Liquid Calcium Chloride is applied as the absorbing material. Each cell is impregnated with the desiccant ($CaCL_2$) where the cloth layer functions as a desiccant carrier. In the theoretical model, the effect of various parameters on the absorption process is analyzed. Dimensionless variables are also presented with the corresponding physical meanings. Comparison between the experimental resuls and the theoretical model show that the agreement is reasonable.

INTRODUCTION

The rapid increase of population and the industrial development has raised the demand of fresh water. The atmospheric air contains a higher quantity of water vapour of about 14000 Km^3, while the amount of water on the earth is only about 1200 Km^3 [1]. The extraction of fresh water from the atmospheric air can be carried out by two different process. The first process by passing the moist air over a cooling coil of an air conditioner, moisture is separated if the effective coil temperature is lower than the dew point. In the second process, water is extracted by absorption on-to a solid absorbent or over hygroscopic solution with subsequent heating of these substance in order to evaporate water. The cooling/dehumidification process is analyzed and the parameters controlling the heat and mass transfer rate are studied by Khalil [2]. Awad et al, [3] described the application of a simple vapour- compression refrigeration cycle for cooling moist air to a temperature lower than its dew point where condensation of moisture occurs. Gandhidasan et al [12], studied the theoretical relation for selection of optimum cooling temperature. Sofrata, [4] described the operation of a system extracting the water from outdoor air based on adsorption-desorption process using a solid desiccant. Analysis of transient heat/mass

Accepted September 11, 2000

transfer and adsorption-desorption interaction can be found in ref. [5]. Hamed [6] carried a theoretical study to extract the water from the atmospheric air using solar energy by using Calcium Chloride ($CaCl_2$) solution as a liquid desiccant. Gad et al, [7] presented theoretical and experimental investigation on the application of corrugated surface of desiccant bed, which is made of a thick layer of cloth carrying $CaCl_2$ solution as the absorbent solution and evaluate the effect of solar radiation intensity and ambient temperature on the system productivity..

However, the effect of shape of the bed carrier is less investigated. On the other hand, enhancing the mass transfer area is expected to increase the rate of absorbtion. In the present work, investigation the process of absorption of water from air is carried out on a honeycomb bed, which is made of a thick layer of a cloth impregnated with $Ca.Cl_2$ desiccant. The bed consists of three cells arranged in series. The aim of this study is to evaluate the effect of the different parameters (air flow rate and inlet temperature) on the absorption rate and study the effect of this variables on the three cells.

THEORETICAL ANALYSIS

The rate equation describing the absorption process can be given as

$$\frac{dM}{d\tau} = \beta.A.(P_v - P_s) \qquad (1)$$

where M is the mass of absorbed water in the bed, τ is the absorption time, β is the mass transfer coefficient, A is the absorption area, P_v and P_S is the water vapour pressure in the air stream and on the bed surface.

The mass transfer coefficient, β is dependent on the coefficient in gas side and in desiccant side.

$$\frac{1}{\beta} = \frac{1}{\beta_v} + \frac{1}{\beta_b} \qquad (2)$$

where β_v . β_b are the values of mass transfer coefficient in the gas side and bed side, respectively. Values of β can be evaluated from the experimental results.
The enthalpy of the absorbent can be evaluated from the energy balance of the bed.

$$\frac{dI_b}{d\tau} = U.A.(T_a - T_b) + \beta.A.L.(P_v - P_s) \qquad (3)$$

where U is the heat transfer coefficient from the air stream to the bed, T_a and T_b are the temperatures of the air stream and bed surface, respectively and L is the latent heat of water vapour.

The solution concentration is generally defined as the ratio between the mass of salt M_S in solution to the mass of sorbent as,

$$X = \frac{M_s}{M_w + M_s} \qquad (4)$$

where M_w is the mass of water in the solution.

The theoretieal analysis of the process of water absorption from the air is presented by Hamed and Proselkov [11]. The model describes the variation of the effect of operating paramters on the absorption process.

The final solution of system of equations can be given in the following dimensionless form [11],

$$\bar{X} = \bar{P} - \left(\bar{P} - \bar{X}_o\right) EXP\left(-\bar{A}\right) \qquad (5)$$

where:

$$\bar{X} = \frac{1 - X}{X} \qquad (6)$$

$$X_O = \frac{1 - X_O}{X_O} \qquad (7)$$

$$\bar{A} = \frac{p.\beta.c.\tau}{Ms / A} \qquad (8)$$

$$\bar{P} = \frac{1 - X_\infty}{X_\infty} \qquad (9)$$

where X_∞ is the concentration at the end of absorption.

In the analysis presented by [11] is based on the approximate relation, which defines the effect of desceent eoncentration on the vapour pressure at different temperatures with accurcy in the range from 20-30%. However the relation between the vapour pressure, concentration and temperature is more precisely expressed by [6] with aceurey of about 6% is given as,

$$Log(P_v) = A(x) - \frac{B(x)}{t + 111.96} \qquad (10)$$

$$\left.\begin{aligned} A(x) &= a_o + a_1 X \\ B(x) &= b_o + b_1 X \end{aligned}\right. \qquad (11)$$

where $a_o = 10.0624$, $a_1 = 4.4674$, $b_o = 739.828$, $b_1 = 1450.96$. t is the solution temperature in ^{0}C, X is the concentration of the solution in the cell. Equation (10) is applicable in range of water from 6.62 mmHg to 76.2 mmHg.

Accordingly the effect of various parameters on the absorption process can be presented in the following analysis, considering equation (10)..

From equation (11)

$$P_s = e^{A(X) - \frac{B(X)}{t+c}} \tag{12}$$

where e=111.96, substituting equation 1 in equation 12

$$\frac{dM_w}{dt} = \beta .A.(P_v - e^{A(X) - \frac{B(X)}{t+c}}) \tag{13}$$

$$\frac{dM_w}{P_v - e^{a_0 + a_1.X - ((b_0 + b_1.X)/t+c)}} = \beta.A.dt \tag{14}$$

from equation (4) in equation (14)

$$\frac{dM_w}{P_v - e^{a_0 + a_1 \cdot \frac{M_s}{M_s + M_w} - ((b_0 + b_1 \cdot \frac{M_s}{M_s + M_w})/t+c)}} = \beta.A.d\tau \tag{15}$$

Assume

$$Y_1 = P_v - e^{a_0 + a_1 \cdot \frac{M_s}{M_s + M_w} - ((b_0 + b_1 \cdot \frac{M_s}{M_s + M_w})/t+c)} \tag{16}$$

$$\frac{dY_1}{dM_w} = a_1 \cdot \frac{X^2}{M_s} + b_1 \cdot \frac{X^2}{M_s(t+c)} e^{a_0 + a_1.X - ((b_0 + b_1.X)/t+c)} \tag{17}$$

from equation 17, assume

$$Y_2 = \frac{X^2}{M_s}(a_1 + \frac{b}{t+c}) e^{a_0 + a_1.X - ((b_0 + b_1.X)/t+c)} \tag{18}$$

from equation 15,16,17 and 18

$$\frac{1}{Y_2} \log Y_1 = \beta.A.\tau + c_1 \tag{19}$$

at $\tau = 0$ $X = X_0$, $t = t_o$

$$Y_3 = P_v - e^{a_0 + a_1 \cdot \frac{Xo2}{M_s} - ((b_o + b_1 \cdot \frac{Xo2}{M_s})/t_o+c)} \tag{20}$$

$$Y_4 = \frac{X_0{}^2}{M_s}(a_1 + \frac{b}{t_o+c}) e^{a_0 + a_1.X_o - ((b_0 + b_1.X_o)/t_o+c)} \tag{21}$$

$$c_1 = \frac{1}{Y_4} \log Y3 \tag{22}$$

from equation 19

$$Y_4 \log Y_1 + Y_2 \log Y_3 = Y_2 \, Y_4 \beta A \tau \tag{23}$$

EXPERIMENTAL SET UP

Figure (1) shows a schematic of the experimental system. The aim of the experimental work is to study the performance of the honeycomb bed saturated by the Calcium-Chloride and compare the results with the output of the theoretical model. The system consists of centrifugal fan with variable velocity from 0 to 1450 r.p.m in order to control the amount of air stream, variable power heater to control of the temperature of the inlet air to the cells, measuring instruments and test section. The test section consists of three identical cells (18 cm x 18 cm x 5 cm) in arranged series. Each cell is made of aluminum wire which is welded together to gave honeycomb cross section. A thick layer of cloth around the honeycomb was used as a bed carrying the desiccant solution Each cell is weighed and then impregnated in the desiccant solution. The ambient humidity ratio is determined with the measured dry -bulb and wet-bulb temperatures of the air stream. During the absorption, the mass of each cell is recorded during the experimental test every 5 minutes in order to evaluate the mass of absorbed water during this time. The experiments were carried out at different values of air flow rate (0.00324, 0.029, 0.0389, 0.04536, .06395 Kg/s) and at different inlet temperatures to cells (21, 22, 23, 25, 27 ^{0}C). Variation of solution concentration is evaluated by knowledge the mass of absorbed water at different time. The air stream velocity is measured with a hot wire anemometer. Temperatures at inlet and outlet sections are measured at different points using thermocouples and the average value is evaluated.

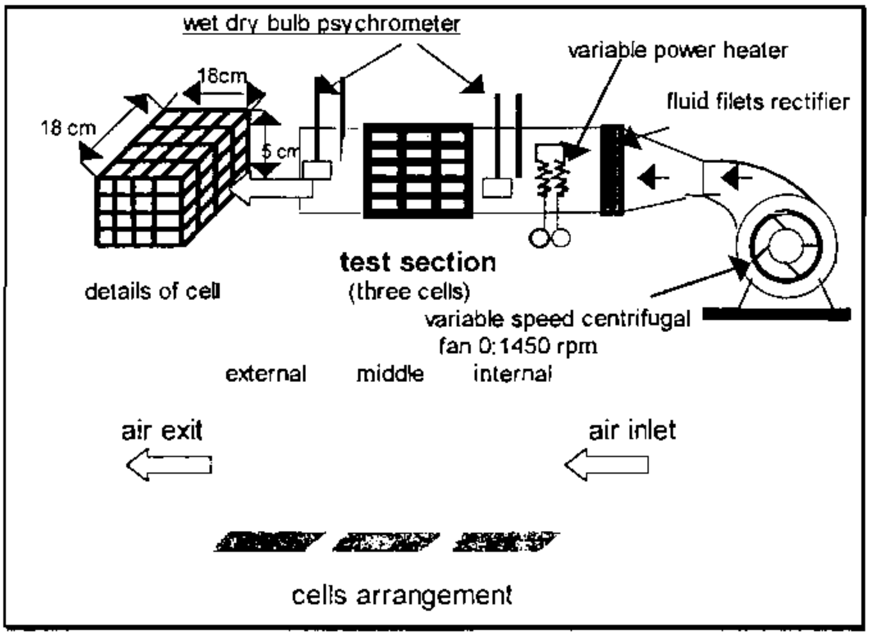

Fig. 1: experimental set up

EXPERIMENTAL PROCEDURE

Since $Ca.Cl_2$ salt is not volatile, the concentration of the solution can be calculated from the following equation:

$$Xo.M_o = X_t.M_t \tag{24}$$

where:
X_o is the initial concentration, M_o is the initial mass of solution in the bed.

$$M_t = M_t - M_b \tag{25}$$

where M_b is the mass of the dry bed, M_t is the total mass of bed and solution.
The humidity ratio of air can be calculated at bed exit from the following equation:

$$\dot{W}_O = W_i - \frac{\Delta m}{\Delta \tau . m_a} \tag{26}$$

The vapour pressure in the air calculated from this equation:

$$P_v = \frac{W_O . P}{0.622 + W_O} \tag{27}$$

P_a is the atmospherie air pressure, mm Hg.

The mass transfer coefficient β can be evaluated from the following relation,

$$\beta = \frac{\Delta m}{\Delta \tau \; \Delta P \; A} \tag{28}$$

where, Δm is mass of absorbed water and $\Delta \tau$ is absorption period.

$$\Delta P = P_v - P_s \tag{29}$$

RESULTS AND DISCUSSIONS

The experimental tests are carried out at different inlet air temperatures and different mass flow rates. Experiments aims at studying the absorption characteristics of a honeycomb bed impregnated with liquid desiccant. Also, the effect of air temperature and mass flow rate on the absorption are demonstrated. Comparison between the experimental results and theoretical results is also discussed.

Two groups of the experimental tests are carried out on the honeycomb section. In the first group, at different values of the inlet air temperature and fixed mass flow rate. The second group of the experimental work is carried out at different mass flow rates, 0.00324, 0.029 , 0.0389 . 0.04536 and 0.06395 Kg/s at fixed inlet air temperature..

Figures, 2,3 and 4 illustrate the variation of the absorbed mass of solution in bed at different temperatures for the three cells of the bed at constant flow rate of 0.06395 Kg/s. It can observed that the mass of absorbed solution increase with decreasing the temperature , the maximum value is about 27 gm for the external cell, 28 gm for the middle cell, and 30.5 gm for the internal cell is recorded, which provs that the accumlated mass of absorbed water decrease with the duct depth. Also, it is found that increasing the value of the absorbed water due to temperature decrease of 27 C to 21 C is about 10.5 gm. The time required to reach equilibrium with ambient air increases with decreasing the temperature. It reached to 30 minute at inlet temperature 27 C and reached to 100 minute at temperature equals 21 C. Comparing the experimental results of the three cells, it can be observed that the rate of absorption of water increases with decrease in air stream temperature. This can be explained by the fact that, the decrease in air stream temperature, however dos not effect on the vapour pressure in ambient air but decreases the desiccant temperature and conceguantly decreases the vapour pressure on the desiccant surface which result in increase in vapour pressure diffence between air and desiccant.

The variation of absorbed mass of solution versus time for different flow rate at constant air inlet temperature to the cells is presented in Fig. 5. 6 and 7.. It can seen from the figures that the absorption rate increase with the increasing amount of the flow rate. It reached to 27 gm for the external cell, 28 gm for the middle cell and 30.5 gm for the internal cell.

Figures 8, 9 and 10 show the variation of the concentration of the solution at different temperatures with the constant flow rates (0.06395 Kg/s) for the three cells. It can be observed that the concentration decreases with the time. The concentration reached to about 40 % for cell and for the internal. cell reached to about 37.5%

Also, the transient value of solution concentration at different flow rates and constant temperature is presented in Fig. 11, 12 and 13.. For a given absorption period, the final concentration of the desiccant is show to be highly dependent on the flow rate. For example (Fig. 9), for the middle cell, the concentration reached about 40% when the flow rate is 0.06395 Kg/s and reached to 54 % at flow rate decreased to 00324 Kg/s.

Figure. (14) shows the variation of the vapour pressure on the solution surface with time at flow rate equals 0.06395 Kg/s for the three cells. It can be seen that the value increases with time and changes from about 1.5 mm Hg to 7.8 mm Hg. The variation of the vapour pressure in the air versus time at flow rate equals 0.06395 Kg/s is illustrated in Fig. (15). The value decreases with time and changes from 7.4 mm Hg to 6.6 mm Hg after 100 minutes for the internal cell..

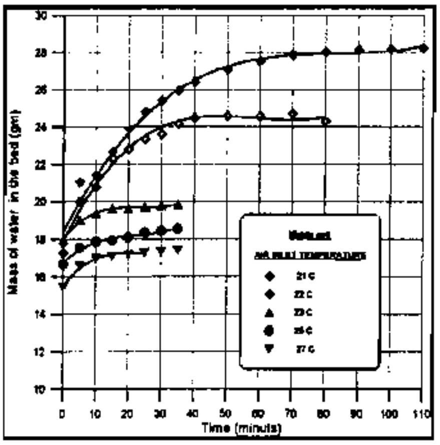

Fig 2: Variation of the mass of solution absorbed in the bed for middle cell at constant mass flow rate 0.0639 kg/s

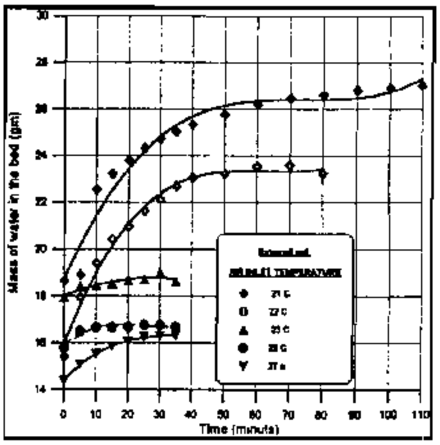

Fig 3: Variation of the mass of water absorbed in the bed for external cell at constant mass flow ral .0639 kg/s

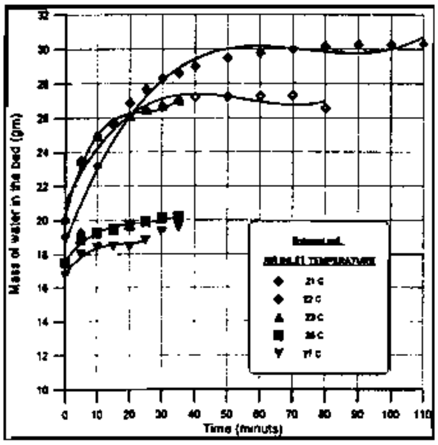

Fig 4: Variation of the mass of solution absorbed in the bed for internal cell at constant mass flow rate 0.0639 kg/s

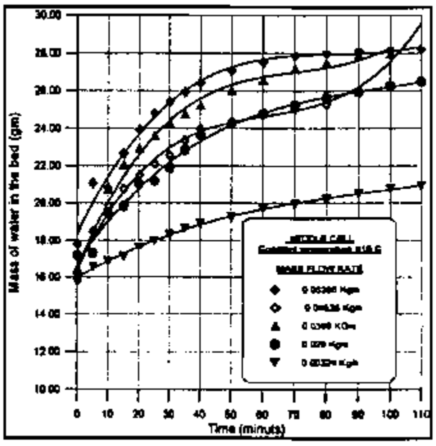

Fig 5: Variation of the mass of solution absorbed in the bed for middle cell at constant temperature 19 C

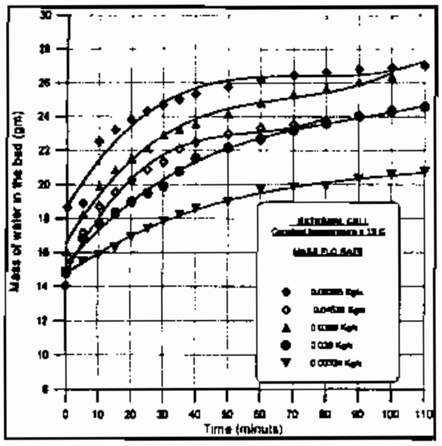

Fig 6: Variation of the mass of water absorbed in the bed for external cell at constant temperature 19 C

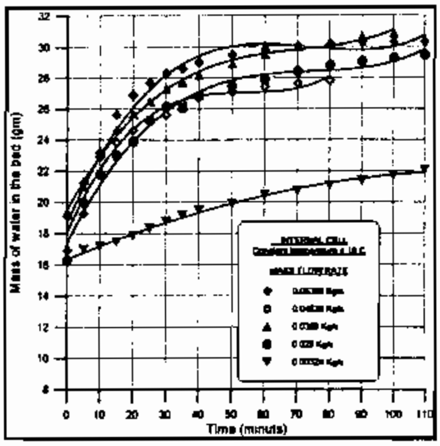

Fig 7: Variation of the mass of water absorbed in the bed for internal cel at constant temperature 19 C

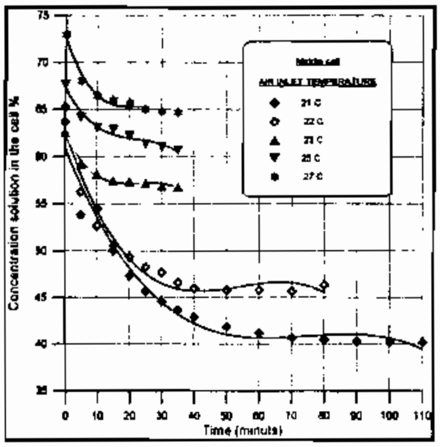

Fig 8: Variation of the concentration of solution of a meddle cell absorbed in the bed at constant mass flow rate 0.0639 kg/s

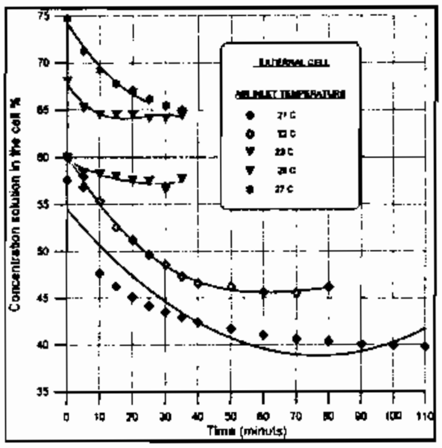

Fig 9: Variation of the concentration of solution of the external cell absorbed in the bed at constant mass flow rate 0.0639 kg/s

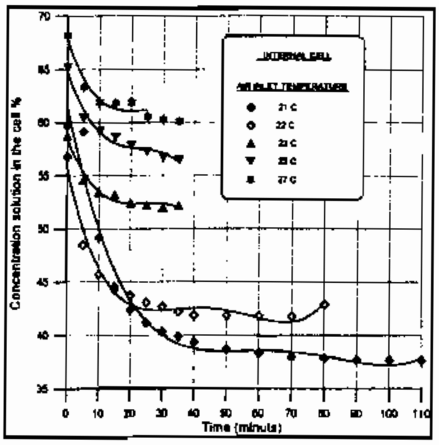

Fig 10: Variation of the concentration of solution of he internal cell absorbed in the bed at constant mass flow rate 0.0639 kg/s

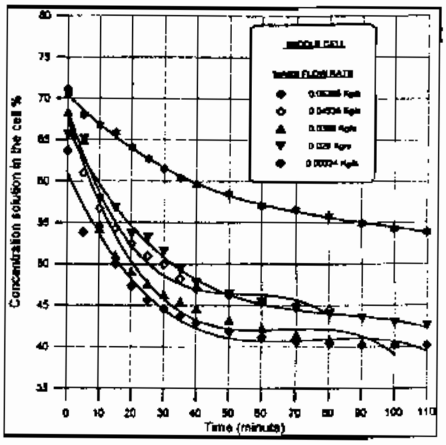

Fig 11: Variation of the concentration of solution of the meddle cell absorbed in the bed at constant temperature 21 C

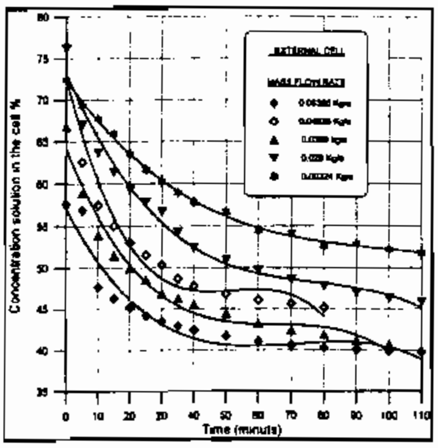

Fig 12: Variation of the concentration of solution of the external cell absorbed in the bed at constant temperature 21 C

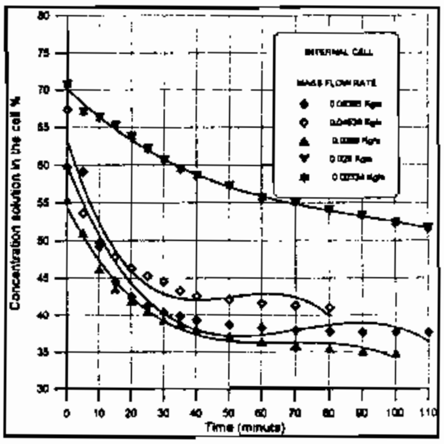

Fig 13: Variation of the concentration of solution of the internal cell absorbed in the bed at constant temperature 21 C

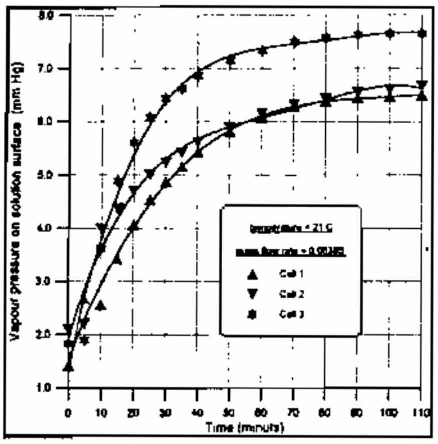

Fig 14: Variation of the vapour pressure on solution surface in the cells at flow rate equal 0.06395 Kg/s

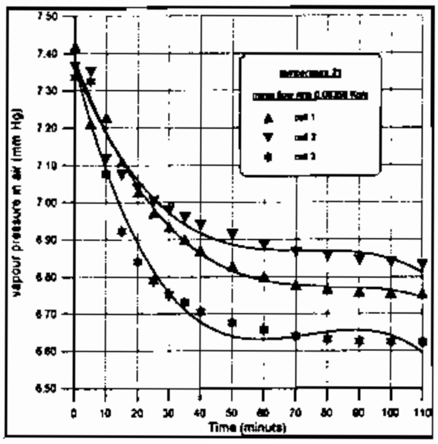

Fig 15: Variation of the vapour pressure in air for the cells at flow rate equal 0.06395 Kg/s

Comparison between experimental results with the present theoretical results and the previous theoretical results [11] are given in Fig. 16. The difference between the experimental results and theoretical data can be explained as follows: During the experimental tests humidity ratio of air stream varies of from 7 to 9 gm/Kg$_{air}$. However, in theoretical calculations it is assumed that the inlet humidity of air is constant. This assumption results in constant values of X_∞ which actually variable during the experiments. Also, the mass transfer coefficient is assumed constant in theoretical calculations. The value of β,

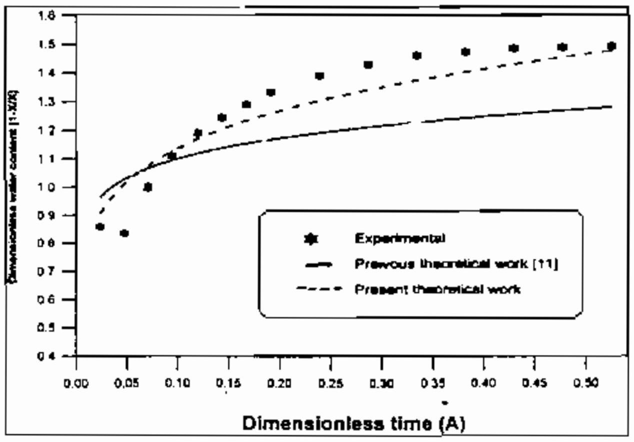

Fig 16: Variation of the dimensionless water content with dimensionless time

however, depends on air stream velocity and the variable thermo-physical properties of the Chalcium Chloride solution. Also results show good agreement between present theoretical and experimental results.

The theoretical and experimental study on the transient adsorption characterists of vertical packed porous bed was studied by Hamed [13]. Figuer 17 shows the comparison between the experimental results of previous work [13] and the present work for the variation of solution consentration. It can be observed that the time required for change in the concentration from 55 % to 40% is about 90 minutes for the present work and about 300 minuts for the previous work. Which means that the rate of absorption can be inhanced with application of honycomb bed as desiccent carrier .

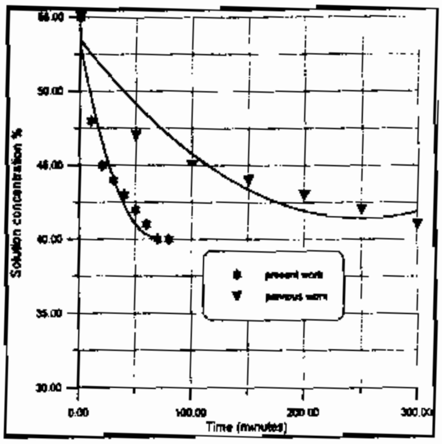

Fig. 17:Comparison between this work and previous work

CONCLUSIONS

An investigation on the application of honeycomb bed as a desiceant carrier for absorption of water from atmospheric air is carried out. The effect of operating conditions; inlet temperature and flow rate of the air stream on the absorption process of $CaCl_2$ desiccant was studied. The average values of the mass transfer coefficient for the different cells are evaluated. Also results show good agreement between theoretical and experimental results. Results shows that the absorption rate can be enhanced with application of honycomb bed.

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NOMENCLATURE

A	absorption area, m^2
a,c	empirical constants of equation (4)
c_o	integration constant of equation (6)
I	inthalpy of absorpent, J/Kg
L	latent heat of water vapour, J/Kg
M	mass of absorbed water in the bed, gm
M_o	initial mass of solution in the bed, gm
M_t	total mass of bed and solution, gm
M_w	mass of water in solution, gm
M_s	mass of salt in solution, gm.
m_a	air flow rate, Kg/s
P	atmospheric pressure, mm Hg
P_v	water vapour pressure in the air stream, mm Hg
P_S	water vapour pressure on the bed surface, mm Hg.
T_a	temperatures of the air stream, K
T_b	temperatures bed surface, K
U	heat transfer coefficient from the air stream to the bed, W/m.K
W_O	humidity ratio of air at exit section
W_I	humidity ratio of air at exit section
X	sorbent concentration,
X_o	initial concentration.
X_∞	concentration at the end of absorption.
τ	is the absorption time, sec
β	mass transfer coefficient, Kg/sec.m^2.mm Hg
β_v	mass transfer coefficient in the gas side, Kg/sec.m^2.mm Hg
β_b	mass transfer coefficient in the bed side, Kg/sec.m^2.mm Hg
$\bar{A}$	dimesionless time
$\bar{X}$	dimensionless water content
$\bar{P}$	dimensionless water content at equilibrium condition .