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

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ABSTRACT

In the present work, the application of a thick layer of cloth in a honeycomb form for the absorption of water vapor 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 (CaCl₂), 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 results 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 vapor of about 14000 Km³, while the amount of water on the earth is only about 1200 Km³ [2]. The extraction of fresh water from the atmospheric air can be carried out by two different processes. 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 onto a solid absorbent or over hygroscopic solution with subsequent heating of these substances 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. Ghandhi et al. [12], studied the theoretical relation for selection of optimum cooling temperature. Sofata [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
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 (CaCl₂) 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 CaCl₂ 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 absorption. 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 CaCl₂ 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

\[
\frac{dM}{dt} = \beta A (P_\text{in} - P_\text{v})
\]

(1)

where \(M\) is the mass of absorbed water in the bed, \(t\) is the absorption time, \(\beta\) is the mass transfer coefficient, \(A\) is the absorption area, \(P_\text{in}\), and \(P_\text{v}\) is the water vapour pressure in the air stream and on the bed surface.

The mass transfer coefficient, \(\beta\) is dependent on the coefficient in gas side and in desiccant side,

\[
\frac{1}{\beta} = \frac{1}{\beta_g} + \frac{1}{\beta_h}
\]

(2)

where \(\beta_g\), \(\beta_h\) are the values of mass transfer coefficient in the gas side and bed side, respectively. Values of \(\beta\) can be evaluated from the experimental results. The enthalpy of the absorbent can be evaluated from the energy balance of the bed.

\[
\frac{dT_a}{dt} = U A (T_a - T_v) + \beta A L (P_\text{in} - P_\text{v})
\]

(3)

where \(U\) is the heat transfer coefficient from the air stream to the bed, \(T_a\) and \(T_v\) 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,
\[ X = \frac{M_i}{M_s + M_i} \]  

where \( M_s \) is the mass of water in the solution.

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

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

\[ \dot{X} = \dot{P} - \left( \dot{P} - \dot{X}_e \right) \exp\left( -\dot{A} \right) \]  

where:

\[ \dot{X} = \frac{1 - X}{X} \]  

\[ \dot{X}_e = \frac{1 - X_e}{X_o} \]  

\[ A = \frac{p \beta \xi \tau}{M_A / A} \]  

\[ \dot{P} = \frac{1 - X_e}{X_e} \]  

where \( X_e \) 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 descent concentration on the vapour pressure at different temperatures with accuracy in the range from 20-31%. However the relation between the vapour pressure, concentration and temperature is more precisely expressed by [6] with accuracy of about 6% is given as,

\[ \log(P_e) = A(x) - \frac{B(x)}{t + 111.96} \]  

\[ A(x) = a_x + a_r X \]  

\[ B(x) = b_x + b_r X \]  

where \( a_x = 10.0624 \), \( a_r = 4.4674 \), \( b_x = 759.828 \), \( b_r = 1450.96 \), \( t \) is the solution temperature in °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)
where \( c = 111.96 \), substituting equation 1 in equation 12

\[
\frac{dM_w}{dt} = \beta A (P_v - e) \frac{M(X)}{i + c} \frac{B(X)}{i + c} 
\]  

(13)

\[
\frac{dM_w}{dt} = \frac{a_0 + a_1 X - ((b_0 + b_1 X)/(i + c))}{P_v - e} = \beta A dt 
\]  

(14)

from equation (4) in equation (14)

\[
\frac{dM_w}{dt} = \frac{a_0 + a_1 X - ((b_0 + b_1 X)/(i + c))}{P_v - e} = \beta A dt 
\]  

(15)

Assume

\[
Y_1 = P_v - e 
\]  

(16)

\[
\frac{dY_1}{dM_w} = \frac{X^2}{M_s} + b_1 \frac{X^2}{M_s (i + c)} a_0 + a_1 X - ((b_0 + b_1 X)/(i + c)) 
\]  

(17)

from equation 17, assume

\[
Y_2 = \frac{X^2}{M_s} - (a_0 + b_1 X)/(i + c) 
\]  

(18)

from equation 15, 16, 17 and 18

\[
\frac{1}{Y_2} \log Y_2 = \beta A \tau + c, 
\]  

(19)

at \( \tau = 0 \), \( X = X_0 \), \( i = i_0 \)

\[
Y_3 = P_v - e 
\]  

(20)

\[
Y_4 = \frac{X^2}{M_s} - (a_0 + b_1 X)/(i_0 + c) 
\]  

(21)
\[ c_i = \frac{1}{Y_i} \log Y_i \]  
from equation 19

\[ Y_i \log Y_i + Y_i \log Y_i = Y_i \beta \Delta \tau \]  

**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 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 give 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, 0.06395 Kg/s) and at different inlet temperatures to cells (21, 22, 23, 25, 27 °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.

![Diagram of experimental setup](image)

Fig. 1: Experimental set up
EXPERIMENTAL PROCEDURE

Since CaCl₂ salt is not volatile, the concentration of the solution can be calculated from the following equation:

\[ X_0 M_0 = X M_i \]  \hspace{1cm} (24)

where:

- \( X_0 \) is the initial concentration,
- \( M_0 \) is the initial mass of solution in the bed.

\[ M_i = M_0 \cdot M_b \]  \hspace{1cm} (25)

where \( M_0 \) is the mass of the dry bed, \( M_i \) is the total mass of bed and solution.

The humidity ratio of air can be calculated at bed exit from the following equation:

\[ W_i = W_r \frac{\Delta m}{\Delta t m_a} \]  \hspace{1cm} (26)

The vapour pressure in the air calculated from this equation:

\[ P_v = \frac{W_{ai} P}{0.622 + W_{ci}} \]  \hspace{1cm} (27)

\( P_{atm} \) is the atmospheric air pressure, mm Hg.

The mass transfer coefficient \( \beta \) can be evaluated from the following relation,

\[ \beta = \frac{\Delta m}{\Delta t \Delta P A} \]  \hspace{1cm} (28)

where, \( \Delta m \) is mass of absorbed water and \( \Delta t \) is absorption period.

\[ \Delta P = P_i - P_r \]  \hspace{1cm} (29)

RESULTS AND DISCUSSIONS

The experimental tests are carried out at different inlet air temperatures and different mass flow rates. Experiments aim 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, 0.00124, 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 the bed at different temperatures for the three cells of the bed at constant flow rate of 0.06395 kg/s. It can be observed that the mass of absorbed solution increases 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 proves that the accumulated mass of absorbed water decreases 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 minutes at inlet temperature 27°C and reached to 100 minutes 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 does not effect on the vapour pressure in ambient air but decreases the desiccant temperature and consequently decreases the vapour pressure on the desiccant surface which result in increase in vapour pressure difference between air and desiccant.

The variation of absorbed mass of solution versus time for different flow rates at constant air inlet temperature to the cells is presented in Fig. 5, 6 and 7. It can be seen from the figures that the absorption rate increases 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 3: Variation of the mass of solution absorbed in the bed for middle cell at constant mass flow rate 0.0639 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 cell at constant temperature 19°C.

Fig 8: Variation of the concentration of solution of a sodium salt 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 the 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 middle 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 external cell absorbed in the bed at constant temperature 21 C.
Comparison between experimental results with the present theoretical results and the previous theoretical results [11] are given in Fig. 16. The differences between the experimental results and theoretical data can be explained as follows: During the experimental tests humidity ratio of air stream varies from 7 to 9 gm/Kg dry. However, in theoretical calculations it is assumed that the inlet humidity of air is constant. This assumption results in constant values of \( X_w \) which actually variable during the experiments. Also, the mass transfer coefficient is assumed constant in theoretical calculations. The value of \( \beta \)
however, depends on air stream velocity and the variable thermo-physical properties of the Calcium Chloride solution. Also results show good agreement between present theoretical and experimental results.

The theoretical and experimental study on the transient adsorption characteristics of vertical packed porous bed was studied by Hamed [13]. Figure 17 shows the comparison between the experimental results of previous work [13] and the present work for the variation of solution concentration. 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 minutes for the previous work. Which means that the rate of absorption can be enhanced with application of honeycomb bed as desiccant carrier.

CONCLUSIONS
An investigation on the application of honeycomb bed as a desiccant 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 CaCl₂ 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 honeycomb bed.

REFERENCES:
1- Obreiskova, V. E., “Hydro-energy”, Energoatomizdat, Moscow, 1988
13-Hamed A. M. Theoretical and experimental study on the transient adsorption characteristics of vertical packed porous bed Mansoua third international Engineering Conference, Egypt, 2000, pp.61-76.

NOMENCLATURE
A  absorption area, m²
α, c  empirical constants of equation (4)
θ  integration constant of equation (6)
I  initial of absorbent, J/kg
l  latent heat of water vapour, J/kg
M  mass of absorbed water in the bed, gm
M₀  initial mass of solution in the bed, gm
Mₜ  total mass of bed and solution, gm
Mₜₐ  mass of water in solution, gm
Mₚ  mass of salt in solution, gm
mₚ  air flow rate, Kg/s
P  atmospheric pressure, mm Hg
Pₚ  water vapour pressure in the air stream, mm Hg
Pₚₜ  water vapour pressure on the bed surface, mm Hg
Tₐ  temperatures of the air stream, K
Tₜ  temperatures bed surface, K
U  heat transfer coefficient from the air stream to the bed, W/m.K
W₀  humidity ratio of air at exit section
Wₜ  humidity ratio of air at exit section
X  sorbent concentration,
X₀  initial concentration
Xₜ  concentration at the end of absorption.
τ  is the absorption time, sec
β  mass transfer coefficient, Kg/sec.m².mm Hg
βₜ  mass transfer coefficient in the gas side, Kg/sec.m².mm Hg
βₜₐ  mass transfer coefficient in the bed side, Kg/sec.m².mm Hg
A  dimensionless time
X  dimensionless water content
P  dimensionless water content at equilibrium condition.