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ADSORPTION DESORPTION OPERATIONS OF MULTILAYER DESICCANT PACKED BED FOR DEHUMIDIFICATION APPLICATIONS

عمليات الأمتزاز وإعادة التوليد لمهد ثابت مشبع بالمحلول و متعدد الطبقات لتطبيقات ازالة الرطوبة

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الملخص

فى هذا البحث تم دراسة تأثير عوامل التصميم والتشغيل المختلفة على عملية الأمتزاز وإعادة التوليد نظريا وعمليا على مهد ثابت متعدد الطبقات وذلك فى محاولة للوصول الى الطول الفعال للمهد عند الظروف المختلفة للتشغيل. تؤدى زيادة طول المهد الى زيادة الكمية الممتصة أو المتولدة الى حد معين وفى نفس الوقت تؤدى الزيادة في طول المهد الى زيادة فروق الضغط على طبقات المهد الثابت:

في الدراسة المعملية تم عمل جهاز معملي مكون من مهد ثابت ذو ثماني طبقات متساوية في الطول والوزن. ثم تم دراسة تأثير العوامل المختلفة للهواء الداخل للمهد كالسرعة والرطوبة ودرجة الحرارة على اداء الطبقات المختلفة للمهد في حالات الامتزاز وإعادة التوليد. واوضحت النتائج المعملية تغير الطول الفعال للمهد مع حالات الدراسة المختلفة.

وفى الدراسة النظرية تم وضع نموزج رياضي لاستنتاج معادلات لا بعدية لكمية المياه الممتصة وكذلك أعطى النموذج معادلات رياضية لابعدية لحساب درجات حرارة المهد عند الظروف المختلفة. أيضا تم استنتاج معادلة رياضية لحساب الطول الفعال للمهد عند ظروف التشغيل المختلفة وذلك مع الأخذ فى الاعتبار تأثير كلا من الطاقة المفقودة للتغلب على فروق الضغط بين الدخول والخروج من المهد والطاقة المستفادة نتيجة ازالة الحمل الكامن من الهوء عند مروره بالمهد.

أوضحت النتائج توافق جيد بين نتائج الدراسة النظرية والنتائج المعملية وبناء على ذلك يمكن استخدام المعادلات المستنتجة من النتائج المعملية مباشرة. كما أثبتت النتائج المستخدمة لحساب درجة حرارة المهد دقة النموذج المستخدم عن الدراسات السابقة.

Abstract

In this work, the effect of design and operating parameters on the performance of a multilayer desiccant packed bed was theoretically and experimentally studied. In the experimental work, a silica gel packed bed of eight layers has been studied. The transient value of the mass of adsorbed water and desorbed water were measured for different values of the bed length. The theoretical model shows the dependence of the dimensionless value of water content in the bed on the dimensionless time. Also the model shows that the dimensionless temperature depends on the bed characteristics and bed water content. The effect of inlet air humidity and velocity on the adsorption process for each bed layer was studied at different inlet velocity and at different air humidity. The effect of inlet temperature on desorption process for each packed bed layer was also studied at different inlet temperatures. The theoretical model also introduces an equation which can be used to predict the optimum bed length. Good agreement between experimental and theoretical results was found

Key Words: Adsorption, Desorption, Silica gel, Desiccant, Dehumidification

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1. Introduction

The use of desiccant and air dehumidification system is good alternative to the conventional vapor compression system for air conditioning. Also, the humidification and dehumidification processes of air are important operation in various industrial applications. The basic constituent of the desiccant cooling system is the desiccant bed.. Silica gel, activated alumina and molecular sieve can be desorbed at low temperature which makes it useful for use with solar energy [1]. An investigation on simultaneous dehumidification of silica gel showed that silica gel transfers about 30% more water per unit dry mass than activated alumina [2].

The regeneration of silica gel by an integrated desiccant/collector (IDC) has been studied by [3, 4 and 5]. Jiang [6] also tested the regeneration of a silica gel packed bed. The optimum operating time, after which the maximum amount of moisture had been removed, was determined at three regeneration temperatures, namely 65, 75 and 85 C. Singh and Singh [7] investigated the regeneration of silica gel in a multi-shelf regenerator (2–4 shelves) with air temperatures 42–72 C and air velocities 0.175–0.55 m/s. They found the values of the regeneration air temperature and bed air velocity for minimum energy input to be 52 C and 0.175 m/s irrespective of the number of shelves. An economic analysis on the operating cost of a silica gel bed was reported by Marciniak [8], and an adsorption performance analysis on the regeneration condition of the other adsorption process was reported by Kamiuto and Ermalina [9]. Effects of the regeneration temperature and the regeneration time for the specific moisture uptake in the adsorption dehumidification process using the commercial and the modified silica gels were observed by [10]. Theoretical and experimental study on the transient adsorption characteristics of vertical packed porous bed was studied by Hamed [11]. Kim et al [12] tested experimentally a coated sheet laminar flow silica gel packing for solar air conditioning applications. Hamed et al [13] studied experimentally the transient adsorption/desorption characteristics of solid desiccant in a vertical fluidized bed. The objective of the present theoretical and experimental study is the investigating the effect of the packed bed length on the bed performance for both adsorption and desorption process. The packed bed consists of eight equal layers. The experimental tests were carried at different operating conditions such as air velocity, humidity and temperature to evaluate the performance of each packed bed layer.

Theoretical model

The physical system considered in this work is illustrated in Figure 1. The system contains of solid packed bed. The granules of the packed bed are of silica gel that has the ability to absorb the moisture from the surrounding air. The theoretical model depends on the mass balance and energy balance of the packed bed. The following assumptions will be considered in the analysis.

1. There is no radial gradient of moisture content within the packed bed.
2. Equilibrium between exit gas and the solids in the bed is assumed.
3. The mass transfer process can be calculated using the bulk mean moisture concentration of air
4. The bed temperature gradient with time is assumed to be in axial direction only.

Mass balance

A mass balance for the whole packed bed in adsorption process gives:

(Rate of change of the weight of the water content in the bed) = (The difference weight between exit and inlet vapor flow rate)

$$\frac{d}{dt}(m_s W) = m_{vi} - m_{ve} \qquad (1)$$

Where

m_s is the weight of dry silica gel bed

W is the water content of Silica gel

m_{vi} is the mass flow rate of vapor inlet to the bed

m_{ve} is the mass of vapor exit from the bed

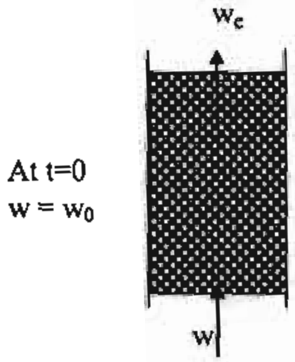


Fig. 1 : Adsorption of vapor by a batch of solids

From equation 1 substituting $m_v = m_g w$ yields

$$m_s \frac{dW}{dt} = m_g (w_i - w_e) \qquad (2)$$

Where:

w_i is the moisture fraction in air at inlet condition, kg water/kg dry air

w_e is the moisture fraction in air at exit condition, kg water/kg dry air

m_g is the air mass flow rate

$$\frac{dW}{dt} = \frac{m_g}{m_s}(w_i - w_e) \qquad (3)$$

Assuming that the exiting air which is in equilibrium with the silica in the bed, then

$$w_e = w^* \qquad (4)$$

Where:

w^* is the water content of air which is in equilibrium with silica that have a moisture fraction w

$$\frac{dW}{dt} = \frac{m_g}{m_s}(w_i - w^*) \qquad (5)$$

The relation between the adsorbed water W and the moisture fraction w for material depends on the thermo physical properties of the solid adsorbent- adsorbent pair. In silica gel the relation can be expressed as a linear function as [13]:

$$w^* = K_1 + K_2 W \qquad (6)$$

Where:

K_1 and K_2 are the regression constants and calculated from the physical properties of Silica gel. They depend on the air inlet temperature during the adsorption process. They are obtained from the following table1 [13]

Table 1: Evaluated values of regression constant with the inlet temperature.

Temperature, ^{0}C	K_1	K_2
25.2	-0.000483	0.0330948
27.9	-0.000556	0.0397986
28.8	-0.000582	0.0422896
31.4	-0.000663	0.0502858

From equation 6, in equation 5 and separating the variables

$$\frac{dW}{(W_i^* - W)} = \frac{m_g}{m_s} K_2 \, dt \qquad (7)$$

Solving Equation 7 with the initial condition

At $t=0$ $W = W_0$

$$\int_{W_0}^{W_t} \frac{dW}{(W_i^* - W)} = \int_0^t \frac{m_g}{m_s} K_2 \, dt \qquad (8)$$

$$\frac{(W_i^*-W)}{(W_i^*-W_o)} = Exp\left[\frac{-m_g}{m_s}K_2 t\right] \qquad (9)$$

Where

w_o is the initial value of weight fraction of adsorbed water on the silica on a dry basis, kg $_{water}$/ kg $_{dry}$ silica. Air flow rate per unit mass of solid desiccant in the bed $\frac{m_g}{m_s}$ can be expressed by,

$$\frac{m_g}{m_s} = \frac{\rho_g}{\rho_s}.\frac{1}{1-\varepsilon}.\frac{u_o}{L} \qquad (10)$$

$$\frac{(W_i^*-W)}{(W_i^*-W_o)} = Exp\left[\frac{-\rho_g}{\rho_s}.\frac{1}{1-\varepsilon}.\frac{u_o}{L}K_2 t\right] \qquad (11)$$

Where:

ρ_g and ρ_s are the air and dry silica gel density respectively.

L is bed length

u_o is the superficial air velocity flowing in the bed (exit velocity from the bed in the tube)

ε is the void fraction of silica gel particle. It depends on the type of arrangement rather than on the particle radius. Its value can be obtained from experimental measurements.

L is the bed length.

Equation (11) can be written as

$$\frac{(W_i^*-W)}{(W_i^*-W_o)} = Exp\left[-\beta \bar{T}\right] \qquad (12)$$

Where:

$$\beta = \frac{1}{1-\varepsilon}\left(\frac{\rho_g}{\rho_s}\right)K_2 \qquad (13)$$

$$\bar{T} = \frac{u_0 t}{L} \qquad (14)$$

and β is a dimensionless value that depends on the bed characteristic, and $\bar{T}$ is the dimensionless time,

Experimental measurements can be used to evaluate the values of β and $\bar{T}$ of equation 13 and 14.

In desorption process, the analysis will be similar with that in adsorption and the following equation can be obtained:

$$\frac{(W_i^*-W)}{(W_i^*-W_o)} = Exp\left[\frac{\rho_g}{\rho_s}.\frac{1}{1-\varepsilon}.\frac{u_o}{L}K_2 t\right] \qquad (15)$$

Energy balance

The process of moisture adsorption on the surface of the silica gel particles releases an amount of heat which is called the adsorption heat. This increases the bed temperature and will affect the properties of both of the bed and the flowing air in the bed, therefore, the process is not isothermal process, and the temperature variation with time can be obtained from the energy balance of the bed.

The energy balance depends on the energy balance of the whole packed bed in adsorption process as follows:

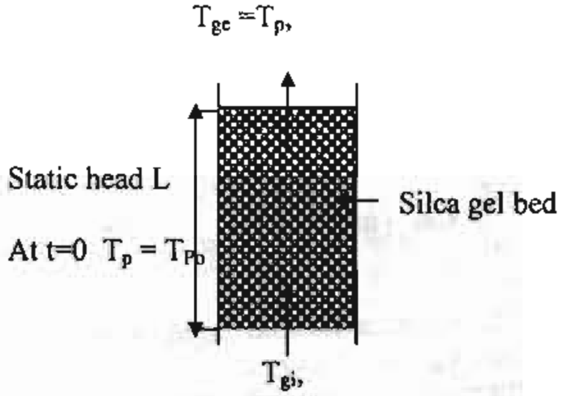


Figure 2 : Heat exchange between the packed bed and the flowing air

Heat given by the gas = heat gained by solids + heat gained by the water content in the bed

$$\rho_g C_{pg} u_o (T_{gi}-T_p)dt = \rho_s cp_s (1-\varepsilon) L\, dT_p + m_w cp_w\, dT_p \qquad (16)$$

$$\rho_g C_{pg} u_o \left(T_{gi} - T_p\right) dt = \rho_s cp_s (1-\varepsilon) L \, dT_p + W \rho_s cp_w (1-\varepsilon) L \, dT_p \qquad (17)$$

From equation 17 and separating the variables with the initial condition

$$T_p = T_{po} \text{ at } t = 0$$

$$\frac{T_{gi} - T_p}{T_{gi} - T_{po}} = \exp\left[- \frac{\rho_g C_{pg}}{\rho_s C_{ps} (1-\varepsilon) L} \frac{u_o t}{\left(1 + W \frac{cp_w}{cp_s}\right)} \right] \qquad (18)$$

Equation 18 shows the dependence of the temperature of the solid on the water content, air velocity, silica gel properties and bed length. W is determined from equation (11)

Where:

C_{ps} is the specific heat of silica gel

C_{pg} is the specific heat of air at constant pressure.

Pressure Drop in Packed Beds

Packed beds cause high pressure drop as a result of high turbulence of fluid flow through it. This pressure drop depends mainly on the depth of the bed, particle size, bed porosity, fluid viscosity, and flow velocity.

The pressure drop is translated to more blower power used to overcome the friction through the dehumidifier, which is a component of air conditioning system. This parameter is important for the dehumidifier designer to calculate the power consumed because increasing the bed length will increase the pressure drop and hence increase the power consumed. On the other hand, increasing of the bed length will improve the adsorption and desorption rate.

In vertical packed bed the flow velocity is constant through the whole points in the bed depth. The pressure drop suffered through a bed of packed solids such as spheres, cylinder, etc is dependent on bed height L, Porosity ε and reasonably well correlated by the Ergun equation [14]:

$$f = \frac{150}{\bar{\mathrm{Re}}} + 1.75 = \frac{\Delta P \, \rho_G d \, \varepsilon^3}{G^2 L (1-\varepsilon)} \qquad (19)$$

Where:

$$\bar{\mathrm{Re}} = \frac{\mathrm{Re}}{1-\varepsilon} \qquad (20)$$

f *is* the frication factor

Re is Reynolds number based on the gas superficial velocity in the bed and calculated from the following relation:

$$\mathrm{Re} = \frac{d\,G}{\mu} \qquad (21)$$

ΔP is the Pressure drop

d is the effective diameter of the particles

G is the mass velocity of air stream.

Optimization of the packed bed length.

Increasing the bed length will improve the state of the exit air (decreases humidity) but on the other hand increases the pressure drop and hence increasing the consumed power. An objective function must be stated to determine the required condition. In the present analysis the ratio of the latent heat removed from the dehumidifier to the power used for blowing air through the packed bed will be considered as the objective function for maximum energy utilization.

The latent energy E_w removed from the system is the same as that adsorbed by the bed, i. e

$$E_w = m_w \times L_e = m_s W \times L_e \qquad (22)$$

Le is the latent heat of evaporation for water at the bed temperature,

m_w is the adsorbed water and equals ms x W

The power consumed P_m due to the pressure drop in the bed can be calculated from the following equation

$$P_m = Q\,\Delta P \qquad (23)$$

Where Q is the volume flow rate and equals $u_o A$, A is the tube cross section area. Substituting from equation 11 in equation 22

$$E_w = \left\{ W_i^{\bullet} - \left(W_i^{\bullet} - W_o\right) Exp\left[\frac{-\rho_g}{\rho_s} \cdot \frac{1}{1-\varepsilon} \cdot \frac{u_o}{L} K_2 t\right]\right\} \times m_s Le \qquad (24)$$

Substituting from Equation 19 in Equation 24

$$P_m = u_o A \times \left(\frac{150}{\overline{\mathrm{Re}}} + 1.75\right) \frac{\rho v^2 L(1-\varepsilon)}{d\varepsilon^3} \qquad (25)$$

For maximum energy utilization, the ratio between the latent energy from dehumidified air to the power consumed must have maximum value, i. e..

$$\frac{d\dfrac{E_w}{P_m}}{dL} = 0 \qquad (26)$$

Substituting Equations 24 and 25 in Equation 26, the following relation is obtained

$$C_2 C_3 \frac{u_o t}{L} e^{c_3 \frac{u_o t}{L}} - C_1 + C_2 e^{c_3 \frac{u_o t}{L}} = 0 \qquad (27)$$

Where,

$$C_1 = W_i^{\bullet} m_s L_e \qquad (28)$$

$$C_2 = \left(W_i^{\bullet} - W_o\right) m_s L_e \qquad (29)$$

$$C_3 = \frac{-\rho_g}{\rho_s} \frac{K_2}{1-\varepsilon} \qquad (30)$$

From equation 27 it can be seen that the optimum bed length depends on the silica gel properties and inlet condition

The vapor pressure is calculated from the following equation

$$p_v = \frac{w P_{atm}}{0.622} \qquad (31)$$

The mass transfer coefficient is calculated from the following relation:

$$K = \frac{M_w}{V\,\Delta\rho} \qquad (32)$$

Where:

$$M_w = M_g(w_i - w_e) \qquad (33)$$

V is the bed volume

$\Delta\rho$ is the mean density difference between exit and inlet.

Experimental setup

The objective of the experiments was to study the performance of the different layers of the packed bed using silica gel as the desiccant. The adsorption and desorption process were studied for multi layer packed bed at different conditions such as flow rate and specific humidity. Fig. 3 shows the experimental setup used in this study. The system consists of different parts. The blower is used to introduce the atmospheric air to the system. The heater is used to regenerate the silica gel. To regenerate the desiccant bed, heated air is blown from the lower end of the layers at different temperatures and the exit parameters of the air are recorded with time. Two valves are used to control the amount of flow rate from the blower to the system. Valve 1 is opened in adsorption process while valve 2 is opened in desorption process. A glass pipe with a length of 100 cm, 0.5 cm thickness and 5 cm inner diameter; contains the column of silica gel layers with 80 cm height.

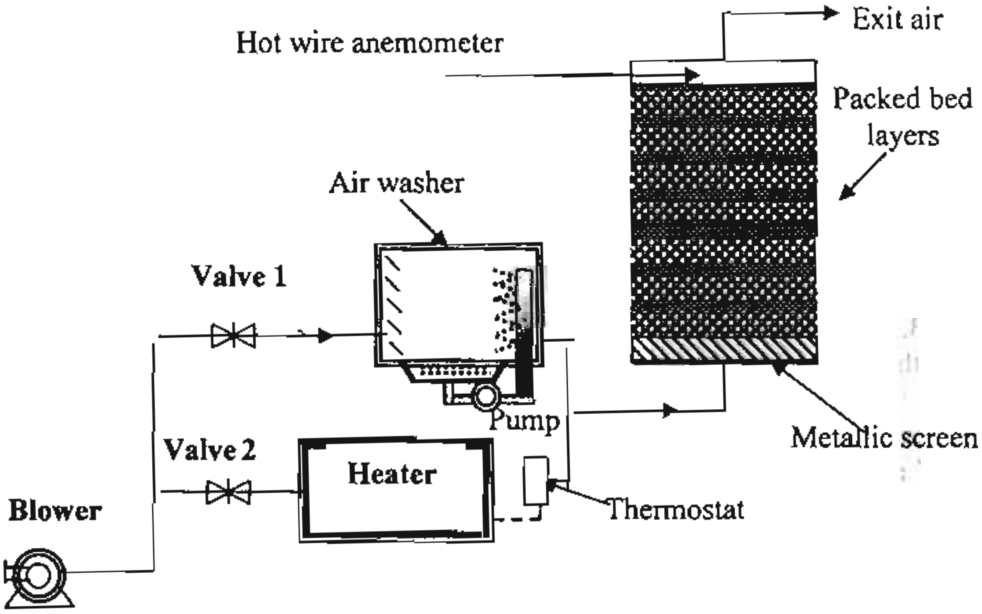


Fig. 3: Flow diagram of the experimental system

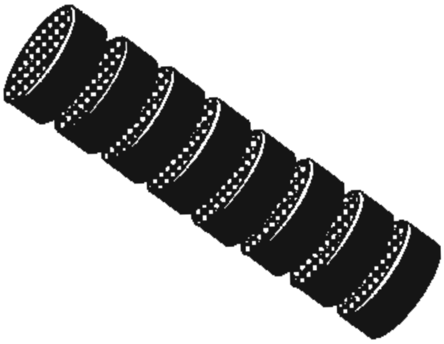


Fig 4: layers of the silica gel packed bed

The slice gel bed is divided into eight equal layers; each layer is of 10 cm thickness. An air washer is used in order to change the inlet humidity in adsorption process the set up as described above was provided with appropriate instruments for making the various measurements. The air velocity was measured by means of a hot wire anemometer giving the velocity directly in m/s. The temperature of air (DBT and WBT) was measured before and after the silica gel column in the adsorption and desorption processes. The specific humidity of air was calculated from its DBT and WBT. The density of silica gel was determined from weighing a known volume of it. The layers are removed from the bed with complete isolation from the atmospheric air, and then weighted. From the temperature of Silica gel and knowing density the concentration was obtained using the silica gel chart. The readings were taken at constant time intervals.

RESULTS AND DISCUSSION

The performance of desiccant packed bed layers during adsorption and desorption processes were evaluated by conducting a series of runs with different inlet conditions of air stream. The rate of adsorption, rate of desorption, total mass adsorbed and total mass desorbed were evaluated from the experimental analysis and recorded with time.

Figure 5 shows the effect of the velocity on the rate of adsorption at different layers of the packed bed for a time period of nearly 120 minutes at constant humidity inlet (w_i = 6.7 g water /kg air) and different flow velocities 3.9, 5.3, 5.6 and 9.6 m/s. Figure 5 presents the increase of the rate of adsorption with the increase of velocity (flow rate). Also it shows the decrease of the amount of adsorbed water in the direction from the first layer towards the last layer. The difference of the adsorbed rate between the first and last layers depends on the inlet velocity (flow rate). After 15 min this difference is about 0.16 g/min at air velocity 3.9 m/s while it increases to about 0.26 g/min at air velocity of 9.6 m/s at the same inlet humidity (w_i =6.7 g water /kg air). With the increase of time, the difference of the rate of adsorption between the first and last bed layer decreases; after 15 minutes and at velocity 3.9 m/s takes the value of 0.16 g/min, while it is about 0.05 g/min after 60 minuets and about 0.0023 g/min at 120 minutes. From the Fig. 5, it can be seen that the difference of the rate of adsorption between the first and last bed layer reaches its minimum value after nearly 90 minutes and nearly constant especially at higher velocity 9.6 m/s.

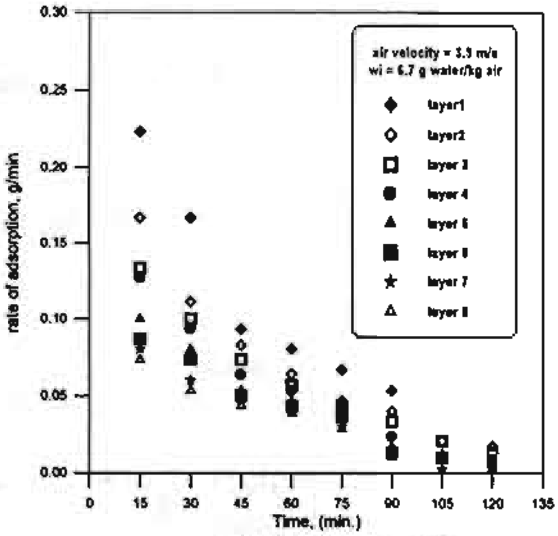


Fig. (5-a)

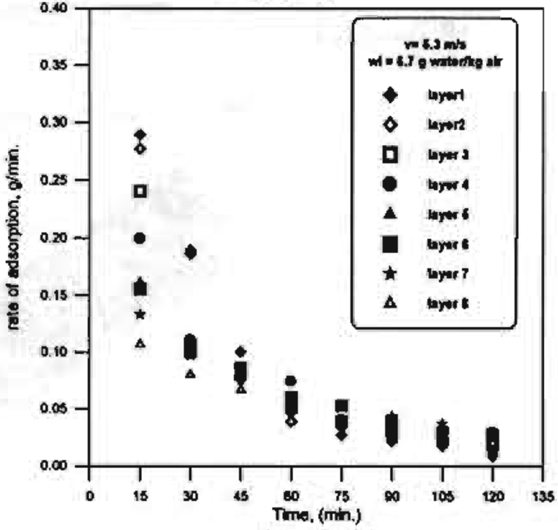


Fig. (5-b)

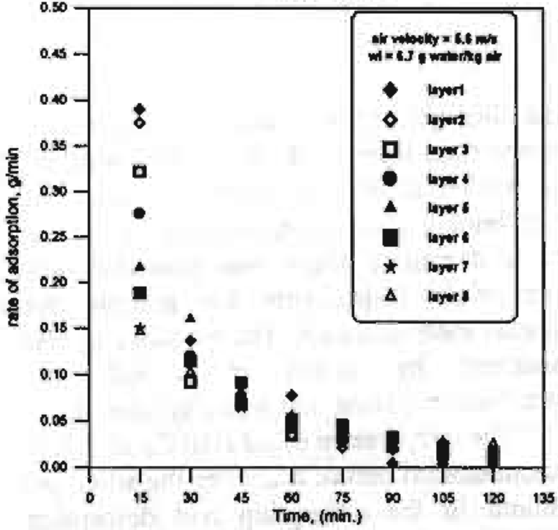


Fig. (5-c)

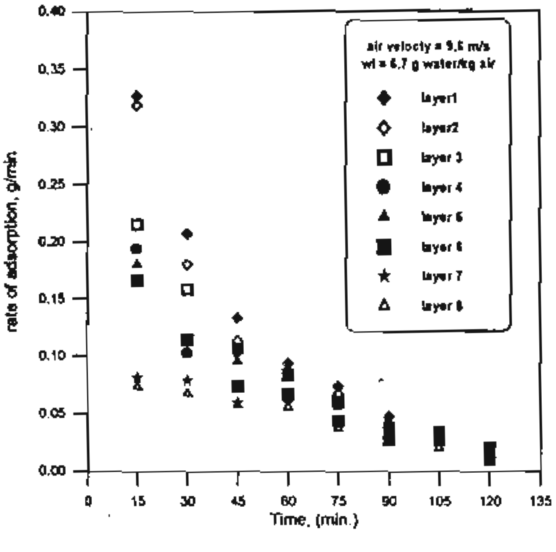


Fig. (5-d)

Fig. 5: Effect of velocity in the transient variation of the adsorption rate for the different layers of the packed bed

Figure 6 presents the effect of inlet humidity on the rate of adsorption at different layers of the packed bed for a time period of 120 min at constant air velocity v = 3.9 m/s and inlet humidity w_i =12.2, 14.2 and 17.5 g water/kg air. Figure 6 shows the increase of the rate of adsorption with the increase of inlet humidity. The rate of adsorption at the first layer after 30 minute are 0.23, 0.25 and 0.44 g/min at w_i =12.2, 14.2 and 17.5 g water/kg air respectively. It can be observed that the effect of inlet humidity on the rate of adsorption between the bed layers after 45 minutes is small for w_i =12.2 and 14.2 g water/kg air and is higher at an air humidity 17.5 g water/kg air.

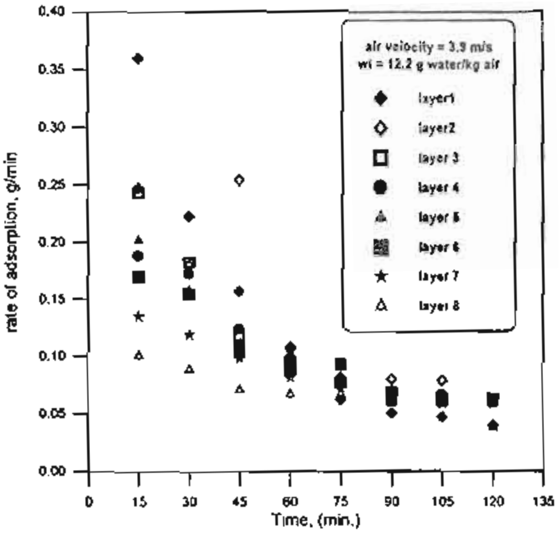


Fig. (6-a)

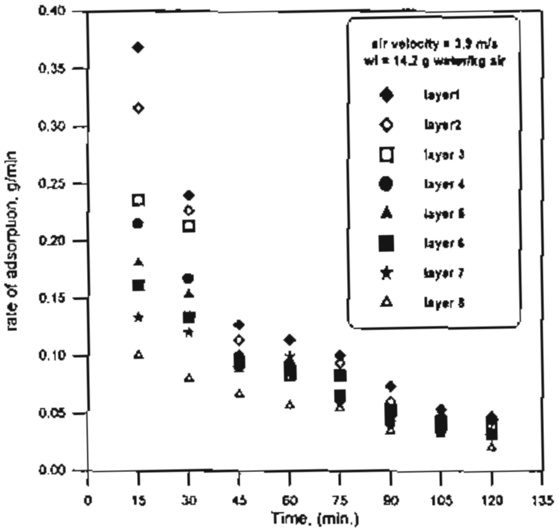


Fig. (6-b)

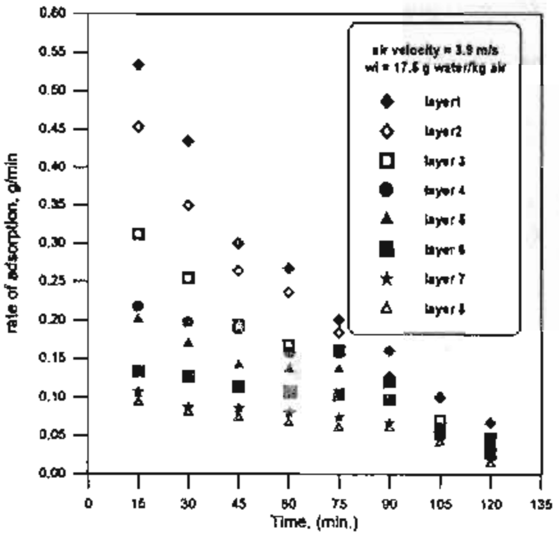


Fig. (6-c)

Fig. 6: Effect of inlet humidity on the transient variation of the adsorption rate for the different layers of the packed bed

Fig. 7 depicts the effect of inlet air temperature on the rate of desorption at the different packed bed layers for a time period nearly 60 min at constant air inlet velocity 3.9 m/s and at temperatures 30, 42, 60 and 70 C respectively. It can be seen that the dsorption rate increases with the increase of the inlet air temperature. Also the difference in the rate of desorption between the first layer and the last layer increases with the increase of flow inlet temperature. The values of the desorption rate for the first layer after 10 minutes are 0.06, 0.8, 0.9 and 1.1 g/min at air temperatures 30, 42, 60 and 70C, respectively.

For example the difference in the desorption rate after 10 min reaches 0.04 , 0.6,0.83 and 0.9 g/min at air temperatures 30, 42, 60 and 70 C respectively. After one hour the desorption rate at all layers tends to be the same specially at higher temperature (70 C).

Figure (7-a) shows that the desorption rate at low temperature (30 C) is very small. From this analysis, it can be seen that the desorption rate is highly dependent on the inlet air temperature.

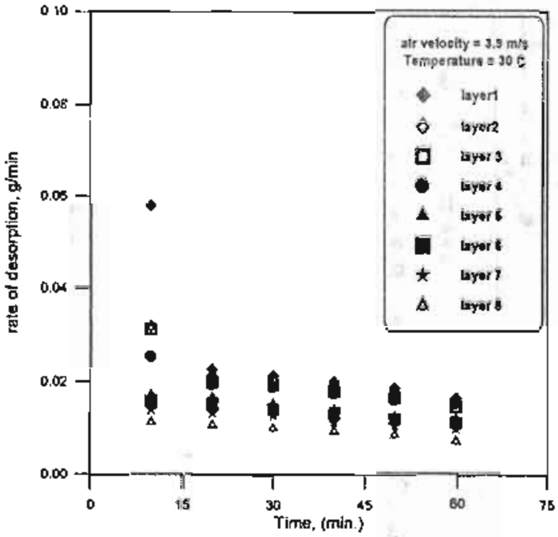


Fig (7-a)

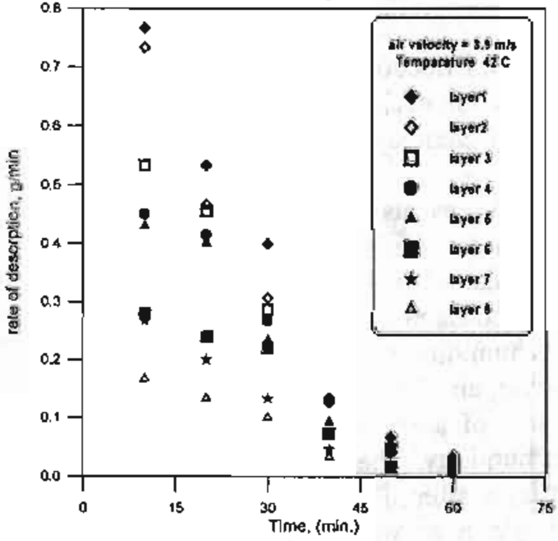


Fig (7-b)

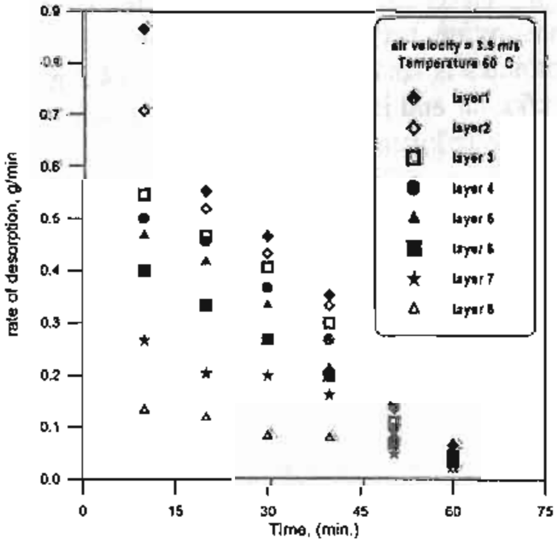


Fig (7-c)

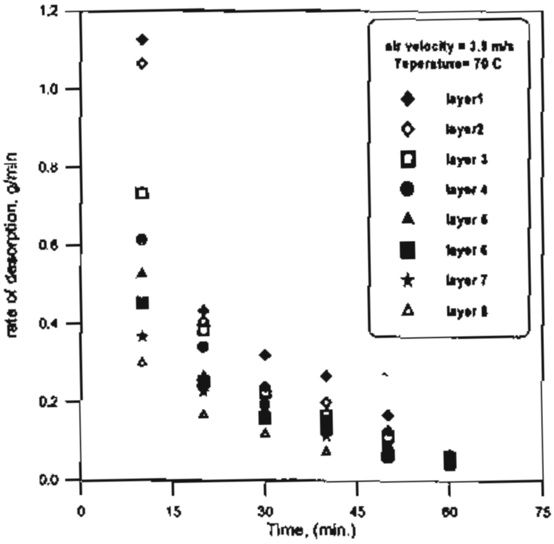


Fig (7-d)

Fig. 7: Transient variation of the desorption .rate of the different layers of the packed bed

The bed adsorption efficiency is expected to be dependent on the bed length. Spit of the bed layers are nearly identical, however, the mass of adsorbed waters is different from layer to layer. As seen from the Figures 5, 6 and 7, the rate of adsorption and desorption changes from layer to layer on the packed bed. This amount gives an indication of the effect of the packed bed length which can be considered at any condition.

The accumulated adsorbed water for the different layers of the packed bed during two hours at different inlet conditions (velocity and humidity) is shown in Fig 8. It can be seen that the accumulated adsorbed water decreases from the first layer towards the last layer with rates which depend mainly on the air velocity and inlet humidity conditions; the accumulated adsorbed water for the first layer is greater than the last layer varies from about 200-400% at the end of the experiment. This variation is depending on the inlet conditions (humidity and air velocity).

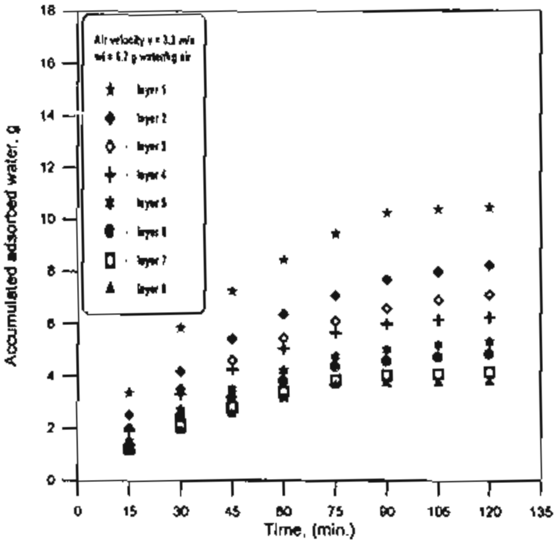


Fig. (8-a)

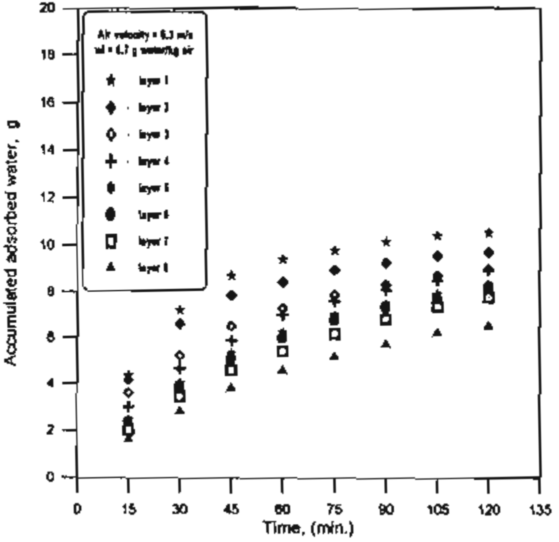


Fig. (8-b)

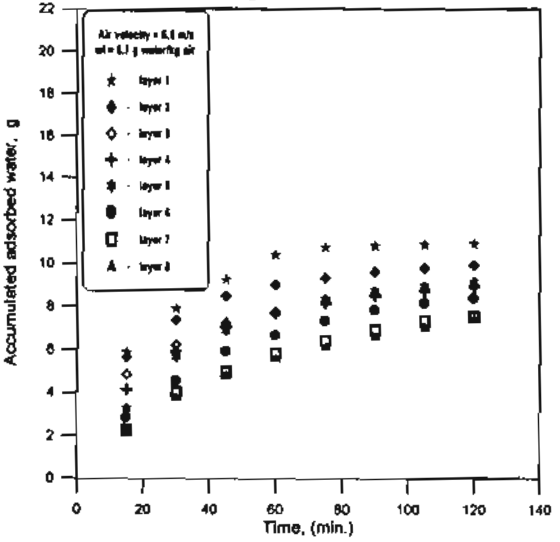


Fig. (8-c)

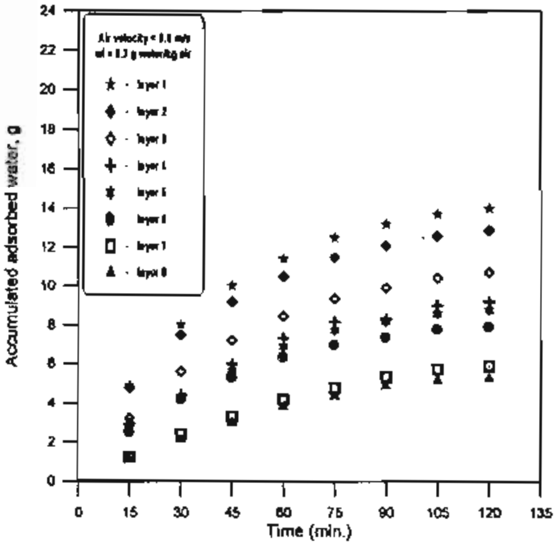


Fig. (8-d)

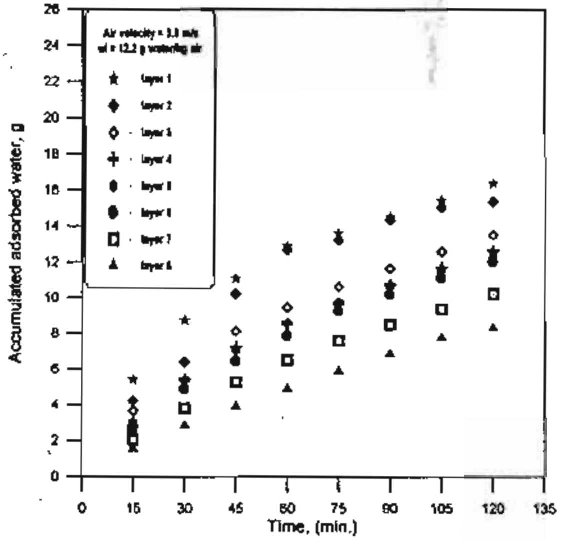


Fig. (8-e)

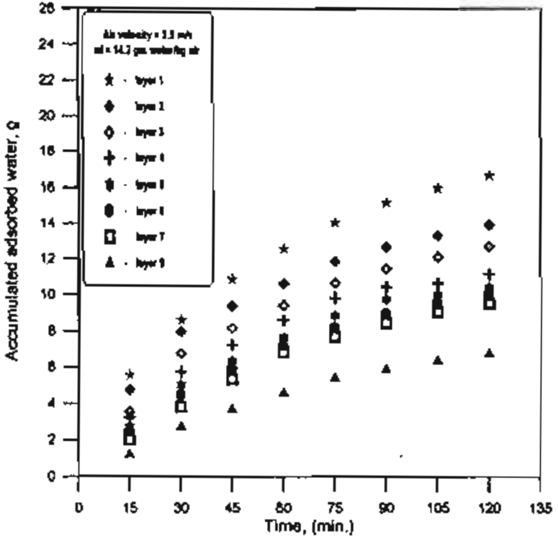


Fig. (8-f)

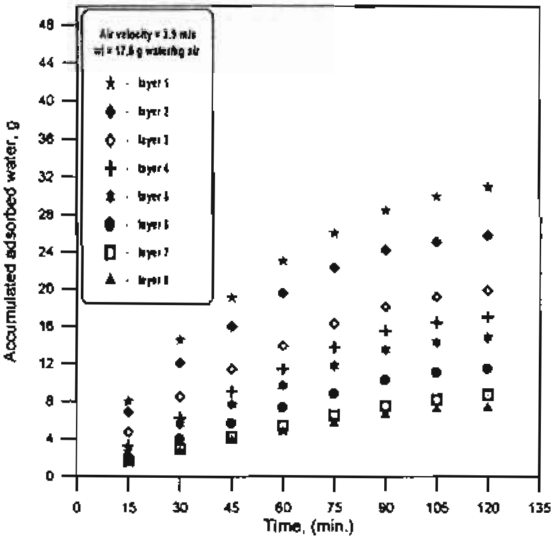


Fig. (8-g)

Fig. 8: Variation of the accumulated adsorbed water for the different layers

Fig. 9 shows the effect of the inlet air temperatures on the accumulated water for the different packed bed layers in desorbed process at constant velocity 3.9 m/s and different air temperatures 30, 42, 60, 70 C respectively.. The amount of desorbed water from the first layer is greater than that from the second layer and so on to the last layer. The ratio of the desorbed water from the first layer tends to be about 600% of that for the last layers

The accumulated desorbed quantities of water depend mainly on the inlet air temperature. The accumulated desorbed water from the first layer after one hour equal 2.5, 30, 35 and 35g at inlet air temperatures equal 30, 42, 60 and 70 C, respectively and at velocity 3.9 m/s.

It is noticed that, the amount of the accumulated desorpion water from the first layer after one hour remains nearly constant at velocity 3.9 m/s and at inlet air temperature equals 60 C and above. This means that the silica gel has lost all its carried water at 60 C after one hour at the velocity 3.9 m/s

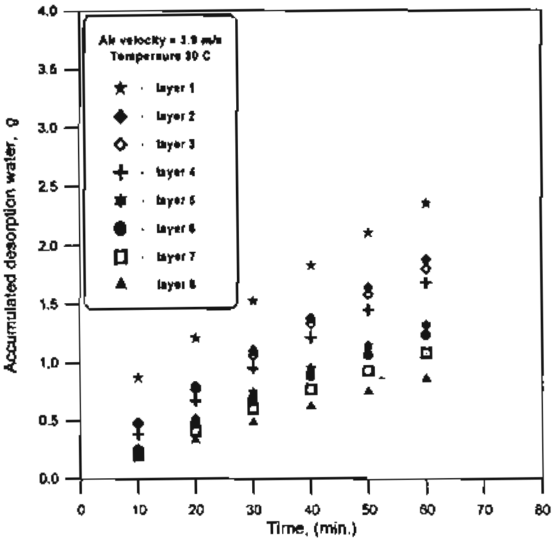


Fig. (9-a)

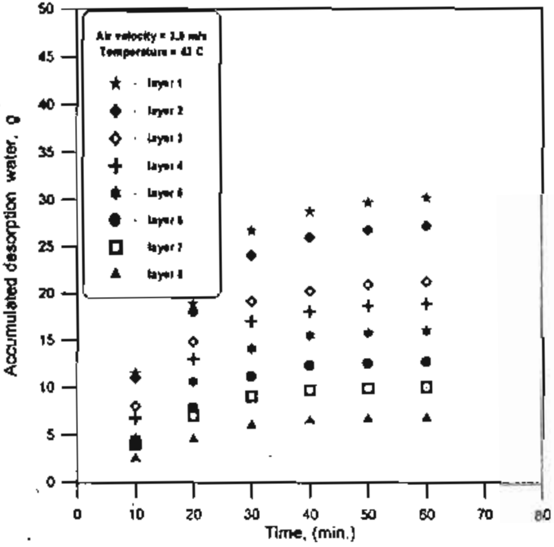


Fig. (9-b)

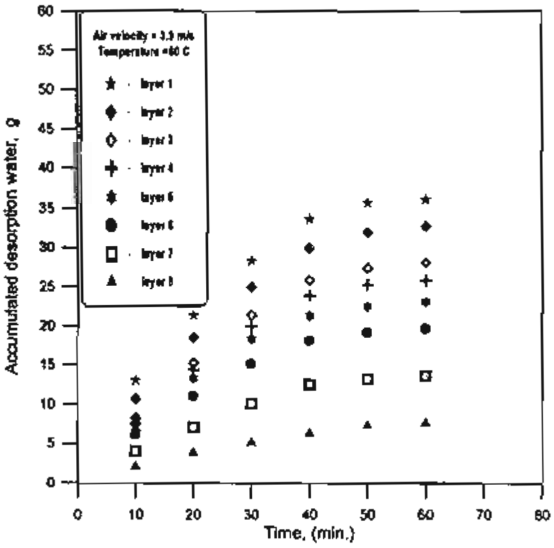


Fig (9-c)

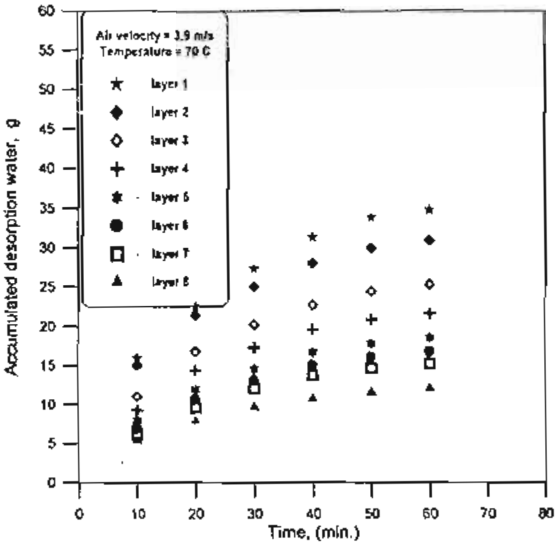


Fig. (9-d)

Fig. 9: Effect of inlet air temperature on the accumulated desorption water for the different layers at velocity3.9 m/s

Figure 10 shows the variation of the humidity of exit air stream from each layer of the packed bed with time during the adsorption process at air velocity 3.9 m/s. Transient variation of exit air humidity of each layer shows a gradual of humidity curve for different test, nearly the same irrespective of the inlet parameters. The difference between inlet and exit air humidity depends on the inlet conditions. Figure (10-a), (10-b), (10-c) and (10-d) show the variation of exit humidity at constant inlet humidity and different velocities while Figure (10-e), (10-f) and (10-g) show the variation at constant velocity and variable inlet humidity. The decrease in inlet humidity of air stream increases the potential of mass transfer. It can be observed that the difference between inlet and exit humidity increases with increases inlet humidity. The difference reached 2 g water/kg air at inlet humidity 6.7 g water/kg air , 3.5 g water/kg air at inlet humidity 12.2 g water /kg air , 3.8 g water/kg air at inlet humidity 14.2 g water/kg air and 4 g water /kg air at inlet humidity 17.54 water/kg air. From the figure it can be observed that the humidity difference between first layer and last layer is lower at the starting time of the experiments and then decreases with time till reaches a minimum value after 2 hours.

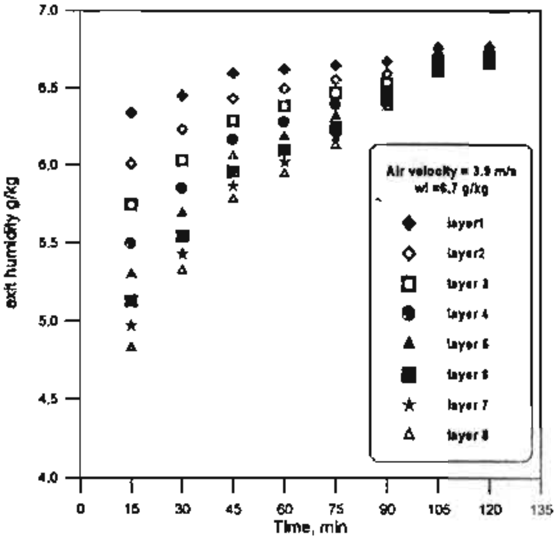


Fig. (10-a)

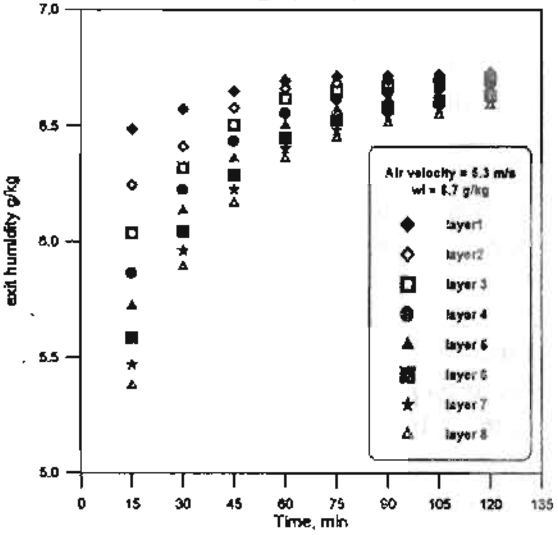


Fig. (10-b)

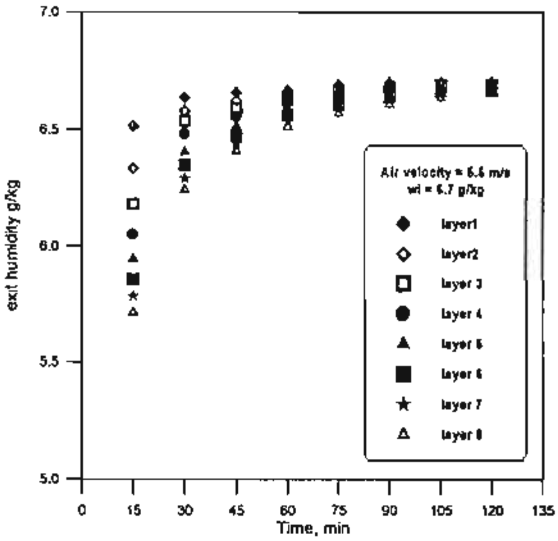


Fig. (10-c)

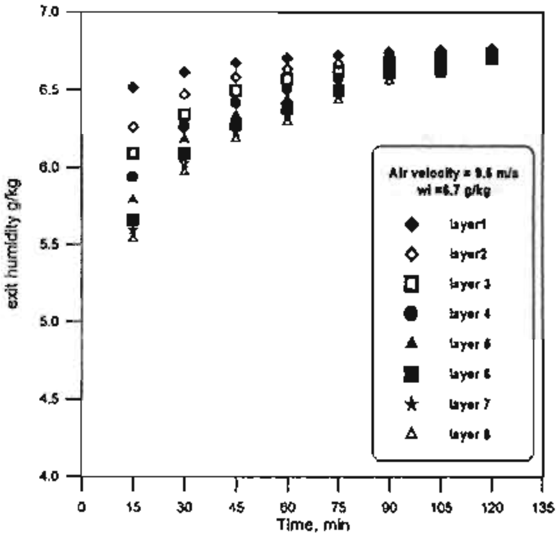


Fig. (10-d)

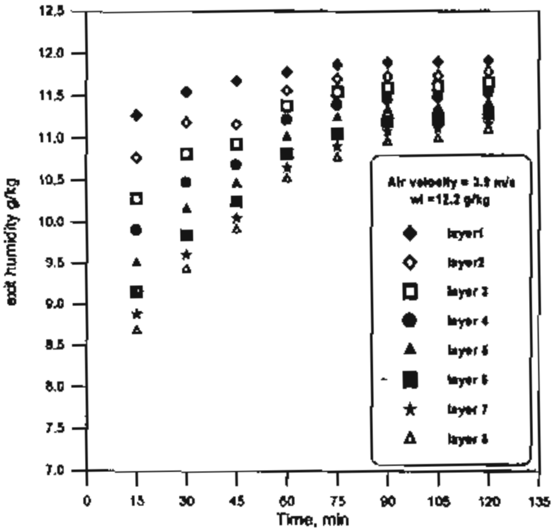


Fig. (10-e)

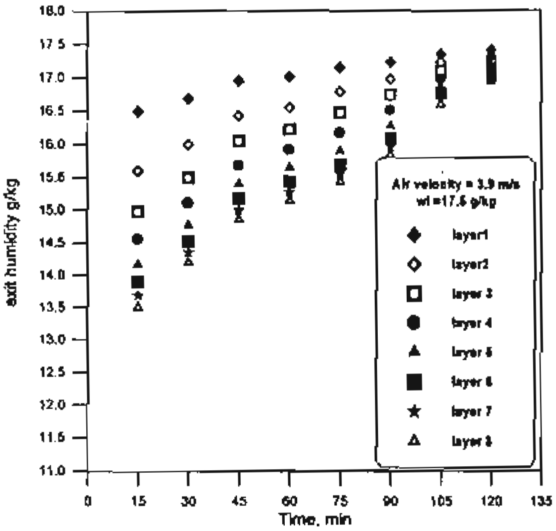


Fig. (10-g)

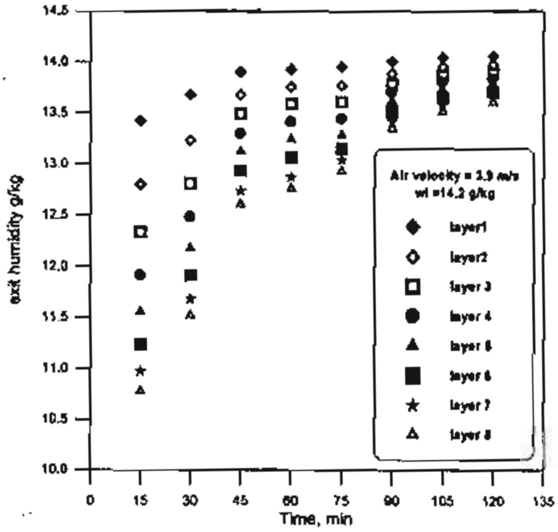


Fig. (10-f)

Fig. 10: Variation of the exit humidity for different layers of the packed bed during the adsorption process.

Figure 11 illustrate the variation in humidity of air at bed layers exit during the test period of the dsorption process. It can be seen that the exit humidly for each layer changed from layer to layer. The difference between exit and inlet humidity depends on the inlet humidity and desorption temperature. It reached 5.5 g water /kg air at temperature 42, 7 g water /kg air at temperature 60, 10 g water /kg air at temperature 70, and very small 0.3 g water /kg air at low temperature. From the figure it can be seen that the difference between exit and inlet humidity decreases with time because the bed temperature increases and the heat transfer rate from the flowing air to the silica gel particles decreases. It can be noted that, the difference between exit and inlet humidity reached a minimum value after one hour.

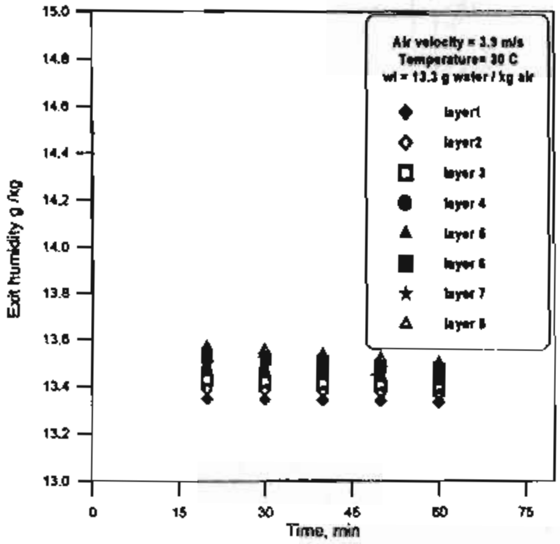


Fig. (11-a)

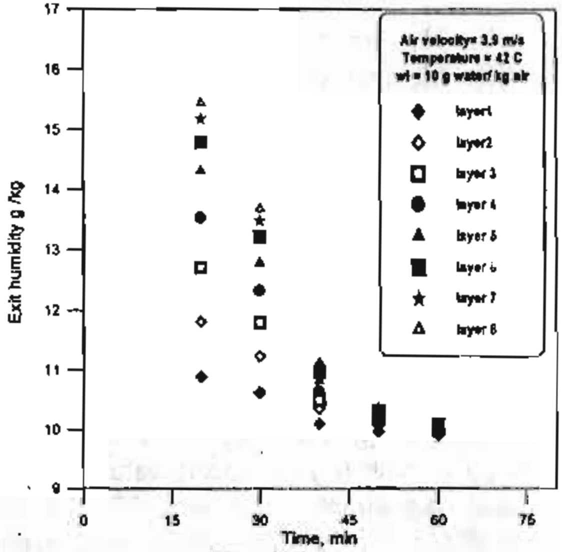


Fig. (11-b)

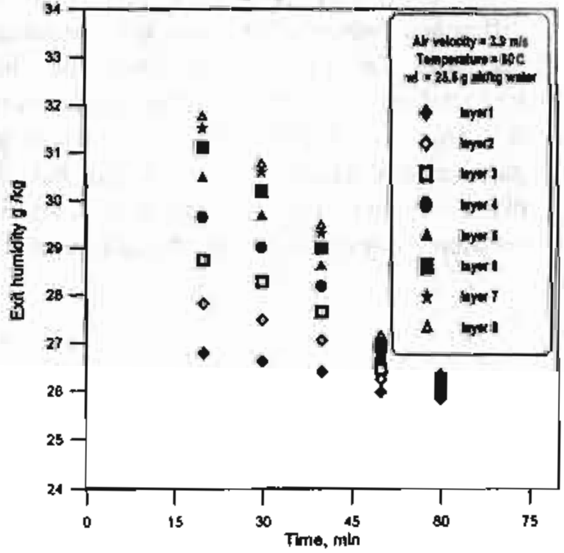


Fig. (11-c)

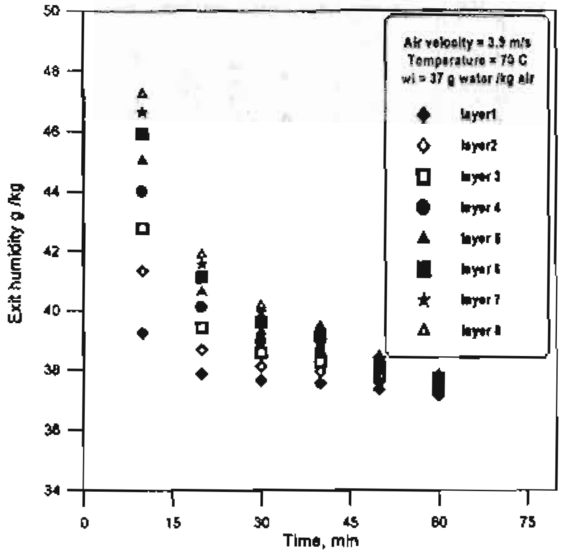


Fig. (11-d)

Fig. 11: Variation of the exit humidity for different layers of the packed bed during the desorption process.

In the adsorption process the dry bulb temperature of the exit air increases with time. Figure 12 shows the variation of the dry bulb temperature of the exit air from the packed bed versus time at different flow velocities. It can be seen that the air exit temperature increases with time. The value of it increases with flow velocity increasing. The increasing value depends on inlet parameters (air velocity and humidity). After 45 minutes, it reached 2 C at velocity 0.97 m/s, reached 3 C at velocity 1.67 m/s, reached 5 C at velocity 3.8 m/s and reached 7 C at velocity 9.6 m/s. These results show that the temperature increases with the flow velocity increases which need amount of energy to return to the initial temperature. On the hand the amount of adsorbed water increases with flow velocity increases. The designer must obtain the optimum between these two conditions.

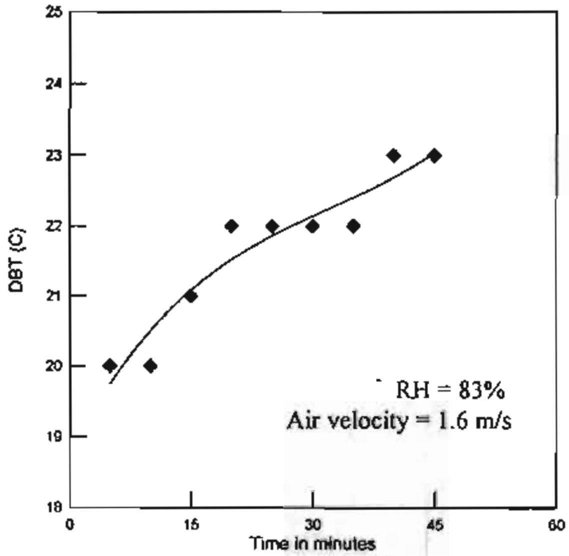


Fig. (12-a)

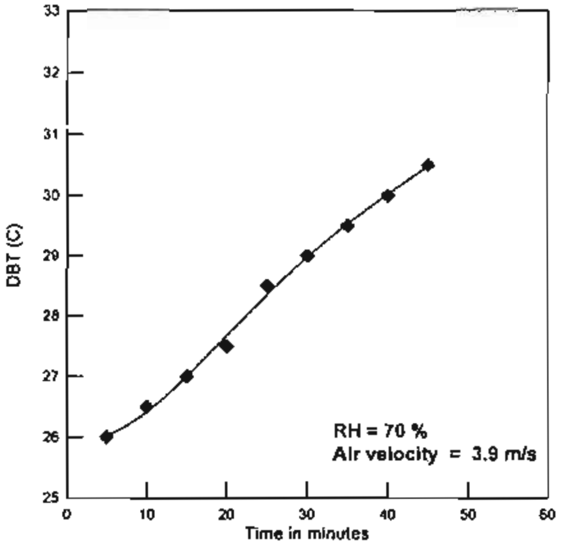


Fig. (12-c)

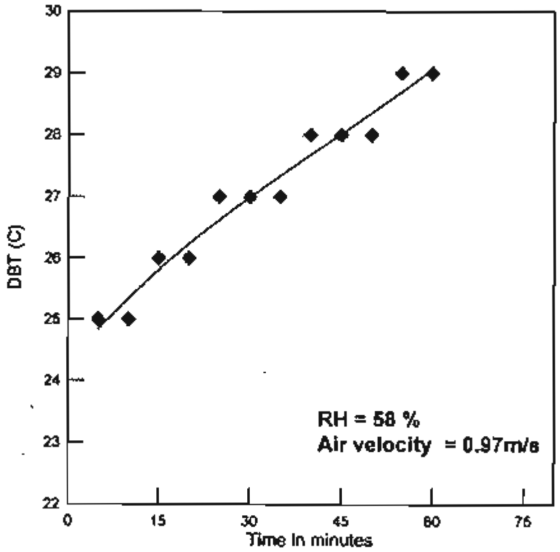


Fig. (12-b)

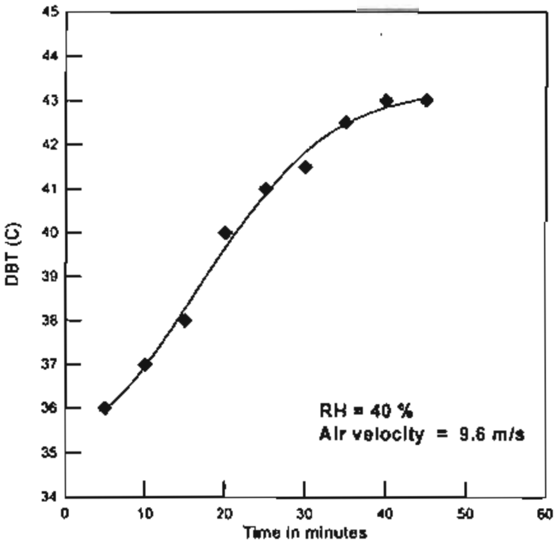


Fig. (12-d)

Fig 12: Variation of dry bulb temperature with time at different air velocity

Figure 13 shows the variation of relative humidity of the exit air from the packed bed with time during the adsorption process. The value depends on the time and the flow rate as seen from the figure. The difference between the relative humidity of exit and inlet air reached 27 at velocity 0.97 m/s and reached 30 at velocity 1.67 m/s. This means that the difference depends on the flow rate.

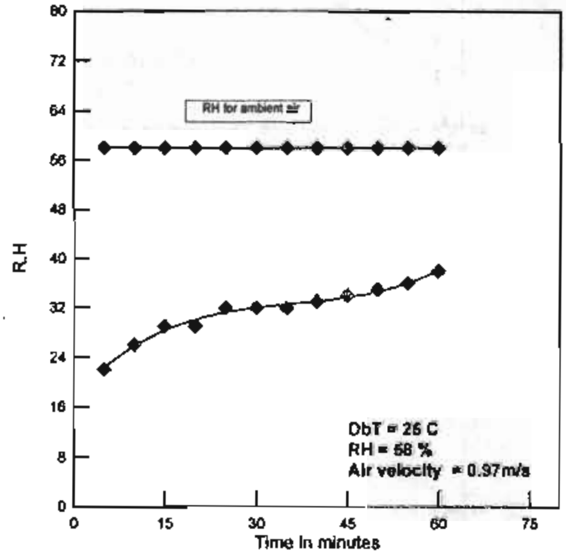


Fig. (13-a)

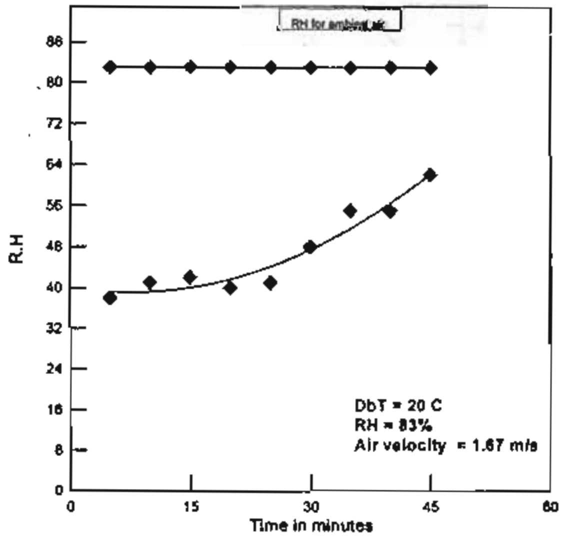


Fig. (13-b)

Fig. 13: Variation of relative humidity with time

The mass transfer potential is expressed in terms of vapour pressure difference or vapour pressure density between the flowing air and the desiccant bed. The value of vapour pressure is used to evaluate the vapour density which is used as the mass transfer potential to evaluate the mass transfer coefficient. The variation of vapour pressure of the flowing air at bed inlet and exit for one velocity as example is illustrated in Figure 14. It can be seen the value increases with time.

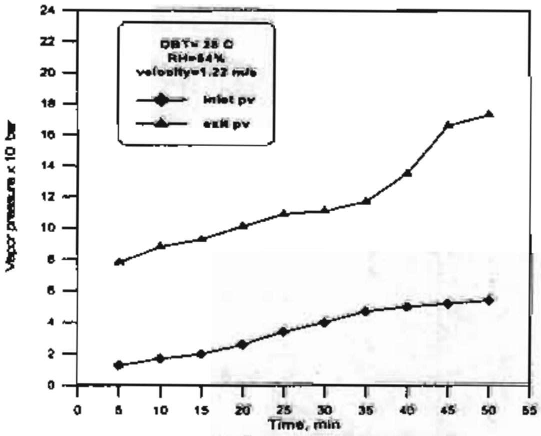
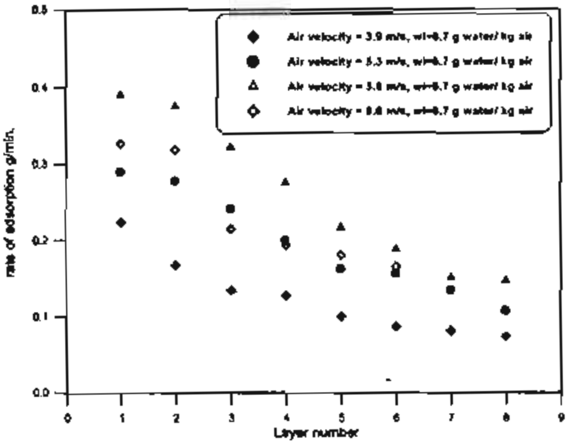
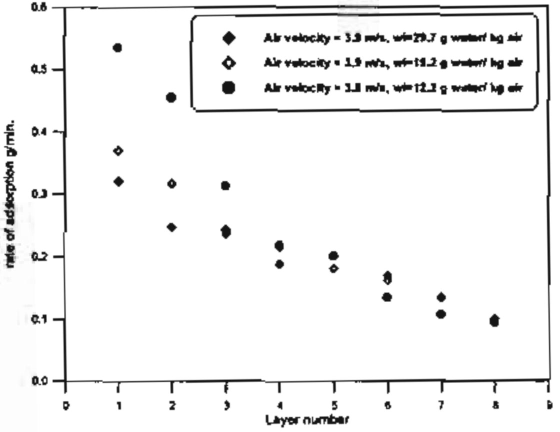


Fig.14: Variation of water vapour pressure on desiccant surface with time at different air velocity

In desiccant air conditioning applications, the time interval used is small. To study the performance of the different layers in the packed bed, it will take the small time interval 15 minutes (the smallest time used in the present experimental work). Fig. 15 shows the variation of the adsorption rate after 15 minutes from the experimental beginning for the eight layers used in this work at different inlet conditions. It can be seen that the rate is small for the last layers 7 and layer 8.



(15-a) constant inlet humidity



(15-b) constant velocity

Fig.15: Variation of rate of adsorption water after 15 minutes from experimental beginning for adsorption process

The variation of rate of desorbed water after 10 minutes from experimental beginning for adsorption process at different inlet condition is shown in Figure 16. It can be observed that the rate of desorption at desorption temperature 42 C approximately equals the rate at desorption temperature 60 C from the second layer. Also, it can be observed that the rate of desorption decreases sharply from the first layer to the eight. The rate of desorption for all layers at 70 C is higher that the rate at 42 C for all layers.

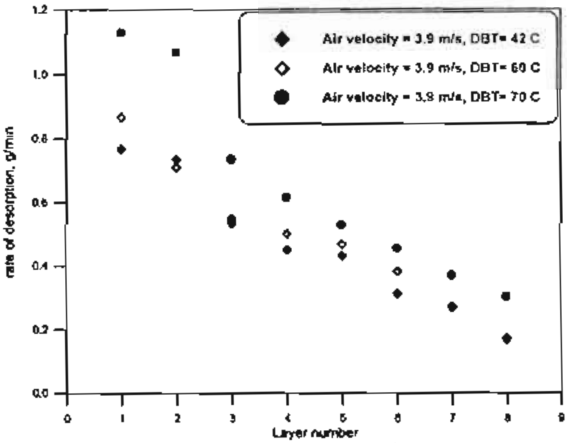


Fig.16: Variation of rate of desorption water after 10 minutes from experimental beginning for adsorption process

The mass transfer coefficient for the adsorption from the packed bed for one experimental as example is presented in Figure 17. It can be seen that the mass transfer coefficient is higher values at the beginning of adsorption and decreases with time. The change in the mass transfer coefficient during the process can be explained in the light of the bed operating characteristics

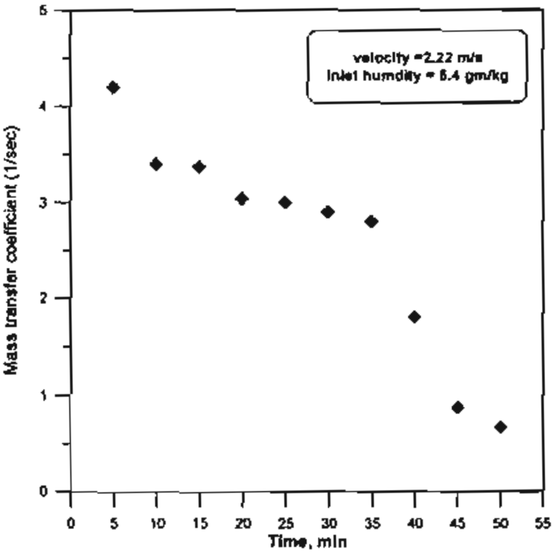


Figure 17: Variation of the mass transfer coefficient with time

Figure 18 shows the comparison between and experimental results and the analytical results of the dimensionless humidity ratio $\frac{(W_i^*-W)}{(W_i^*-W_o)}$ against dimensionless time (Equation 11) at different flow velocity. Good agreement can be observed between the theoretical and experimental results. The difference increases between the model and the experimental results as the adsorption time increase. This is due to the assumption of the isothermal equilibrium. It is true at the beginning of the adsorption but at higher time values the bed temperature increases. The empirical equation can be obtained from the experimental results as follows:

$$\frac{(W_i^*-W)}{(W_i^*-W_o)} = Exp(-0.00105\frac{u_o t}{L})$$

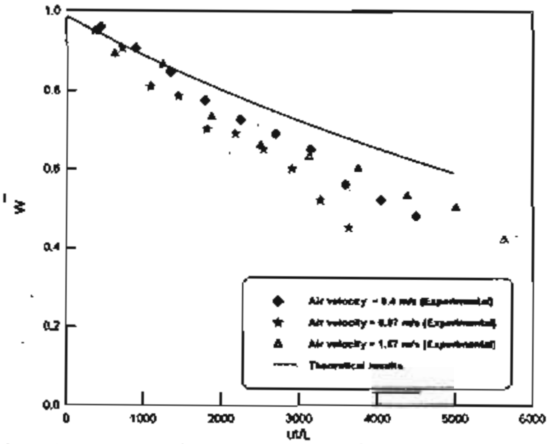


Fig 18: Comparison between the experimental results and theoretical analysis

Figure 19 shows the variation of the temperature ratio $\frac{T_{gi}-T_p}{T_{gi}-T_{po}}$ with dimensionless time $\bar{T}$ (defined by Equation 14) for both of present theoretical results (Equation 18), experimental results and previous theoretical results [15]. It can be seen that good agreement exists between the present theoretical; and experimental results. Figure 19 presents also the good agreement of the present theoretical equations with the previous theoretical results of Walaa [15] especially for the small values of $\bar{T}$ ($\bar{T}$<2000). For values of $\bar{T}$>2000 the difference increases until it reaches about 10% of the value $\bar{T}$= 6000. This difference may be due to neglecting the energy of adsorbed water in the theoretical model of [15].

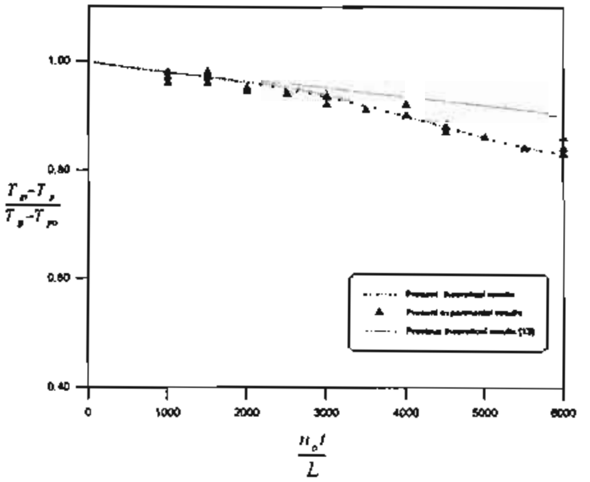


Fig. 19: Variation of the temperature ratio $\frac{T_{gi}-T_p}{T_{gi}-T_{po}}$ with dimensionless $\frac{u_o t}{L}$

A plot the optimum bed length versus the air velocity is shown in Figure 20. Calculations are carried out at different adsorption periods (5, 10 and 20 min.). Also, the specific conditions of the dehumidification air is defined by $\dot{W}_i = 0.4, W_O = 0.05$. As shown in Figure, the optimum length increases with air velocity and desorption period.. Also, the value depends on the air velocity. From the figure the optimum length at any condition can be obtained.

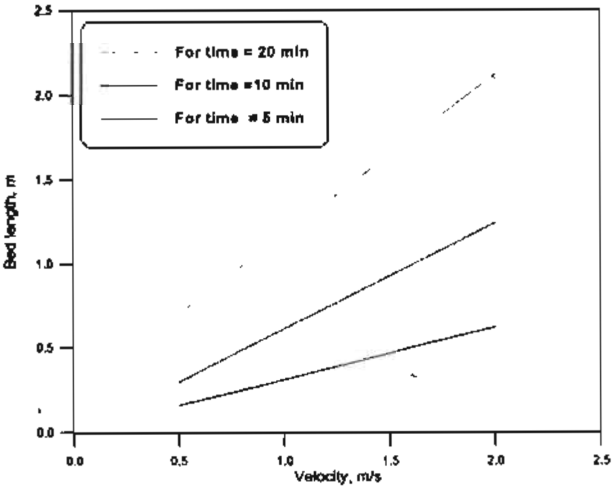


Fig. 20: optimization of the bed length at different times

Conclusions

Transient adsorption and desorption characteristics of multi-layer silica packed bed was studied experimentally and theoretically. The dimensionless equations for both of water content ratio and temperature ratio as a function of dimensionless time are obtained in the theoretical model. The theoretical model also introduces an equation which can be used to predict the optimum bed length at different operating conditions. Comparisons between the mathematical model results with experimental results show good agreement and validate the theoretical model. Results show that the desorption rates depends on the inlet temperature. It reached a maximum value after one hour at a flow rate of 3.9 m^3/s and 60 C. Also, results show that accumulated adsorbed water depends mainly on the inlet air velocity and humidity. The variation of the accumulated water between the first bed layer and the last layer is about 200-400% (after one hour) depending on the inlet conditions. Results show also, that humidity difference between ambient and exit air from each layer decreases from first layer to last layer depending on the inlet conditions. The experimental results show also the variation of adsorbed and desorbed water at different conditions for each packed bed layer which gave an indication of the effect of length. For small time interval (15 minutes in adsorption and 10 minutes in desorption), results show that the adsorption and the desorption rate decreases sharply from the first layer to the last layer.

Nomenclature

A	the tube cross section area, m^2
C_{ps}	the specific heat of silica gel , kJ/kg.
C_{pg}	the specific heat of air at constant pressure, kJ/kg. K
C_{pw}	the specific heat of water content in the bed, kJ/kg. K
d	the effective diameter of the particles, m
E_w	the latent energy removed from the dehumidified system, kW
f	the frication factor
G	is the mass velocity of air stream.kg/s m^2
K_1, K_2	the regression constants
L	the bed length, m
Le	the latent heat of evaporation for water at the bed temperature, kW/kg
m_{vi}	the mass flow rate of vapor inlet to the bed, kg/s
m_{ve}	the mass of vapor exit from the bed, kg/s
m_s	the weight of dry silica gel bed
m_g	the air mass flow rate, kg/s
m_w	the adsorbed water, kg
K	mass transfer coefficient 1/s
P_m	the power consumed due to the pressure drop in the bed, kW
P_v	the Vapor pressure, bar
Q	the volume flow rate, m^3/s
Re	Reynolds number.
u_o	the superficial air velocity flowing in the bed, **m/s**
V	the bed volume, m^3
W	the water content of Silica gel
w_i	the moisture fraction in air at inlet condition, kg water/kg dray air
w_e	the moisture fraction in air at exit condition, kg water/kg dray air
W^*	the water content of air which is equilibrium with silica, kg/kg
W	the moisture fraction, kg/kg

w_o	the initial value of weight fraction of adsorbed water on the silica on a dry basis, kg $_{water}$/ kg $_{dry}$ silica
t	Time, s
T_{gi}	the air temperature at the bed inlet, K
T_{ge}	the air temperature at the bed exit, K
T_p	the bed temperature, K
$\bar{T}$	the dimensionless time,

Greek symbols

ρ_g	the air density, kg/m^3
ρ_s	the dry silica gel density , kg/m^3
ε	the void fraction of silica gel particle
β	a dimensionless value
ΔP	the Pressure drop, Pa
$\Delta\rho$	the mean density difference, kg/m^3

Superscript

*	At equilibrium condition
o	initial value

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