Numerical Investigation of a Desiccant Packed Bed Performance

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Abstract

The main objective of the present work is to give the results of theoretical investigations of a desiccant packed bed. For this purpose, the finite difference scheme is proposed and investigated numerically by solving the equation describing mass diffusion in the desiccant bed. This results in a tridiagonal system, which is solved by using Thomas Algorithm. Also, the mass transfer of water vapor and the energy balance equations in both air stream and solid desiccant are solved using the fourth order Runge – Kutta method. The analysis is carried out for typical inlet conditions of 28^{o}C dry bulb temperature and 66% humidity ratio for desiccant masses (5, 10 and 15 kg) and air mass flow rates (7.4 and 10.2 kg/min) during dehumidification operation mode. The reactivation of the desiccant at different regeneration temperatures and air flow rates as well as desiccant masses is also investigated. For the same layer thickness the water content in the desiccant increases by 65% when the desiccant mass increased from 5 to 10 kg while it's increased by 170% when the desiccant mass increased from 5 to 15 kg.

Key words: Desiccant packed bed, finite difference, Thomas Algorithm, Runge – Kutta.

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Nomenclature

Symbol	Meaning	Unit
Ac	column free flow area	m^2
As	column total heat or mass transfer area	m^2
cp.e	specific heat at constant pressure	kJ/kg.K
C	mass ratio	(---)
D	nondimensional surface mass diffusion	(---)
f	Fluid fraction coefficient	(---)
Ga	air mass flux, m•G/A	kg m^2/s
L	column length	m
Le	overall Lewis number, hc/KG cp.e	(---)
m1	mass fraction of water vapor in humid air	Kg_w/kg_{air}
m•G	mass flow rate of humid air	Kg/s
Ntu	number of mass transfer units,KG pL/ m•G	
P	Pressure	mmHg
p	parameter of column, As/L	m
r	radial coordinate	m
R	particle radius	m
Re	Reynolds number, 2RV/ν	(---)
t	Time	s
T	Temperature	^{o}C or K
U	Moisture content	Kg_w/kg_{da}
Y	humidity ratio or humidity removal	Kg_w/kg_{da}
Z	Axial coordinate	m
γ	ratio of air mass flow rate	
ε	Porosity	(---)
ν	kinematic viscosity	m^2/s
ρ	Density	Kg/m^3
τ	half –cycle period	min
φ	Relative humidity	%

Subscripts

0	Initial value
1	Water vapor
a	Air
ad	Dry air
ads	Adsorption
b	Packed bed
e	humid air in the stream
p	Particle
s	Surface

Introduction

In the area of high humidity, the ambient air brings in lot of unwanted moisture, which presents the major problem for human comfort and air conditioning systems. Both desiccant and mechanical refrigeration systems can remove the moisture from the air. Electric vapor compression air conditioning systems are typically used, where latent cooling is achieved by cooling air to temperature below its dew point to condense the water vapor and achieve the desired degree of dehumidification. In most of the situations, over cooling of air is done, thereby reheating it to a temperature suitable for maintaining comfort and control is needed. This process makes the system inefficient and uneconomical **fatouh et al, [2009]**. Solid desiccant based on air conditioning systems are quite different from mechanical refrigeration systems which attract moisture from the air by creating an area of low vapor pressure at the surface of the desiccant materials. The pressure exerted by the water vapor in the air is high, so that water vapor molecules move from the air to the desiccant and the air is dehumidified **fatouh et al, [2010]**. The effect of design and operating parameters on the performance of multilayer desiccant packed bed was theoretically and experimentally studied by **Kabeel, [2009]** where the transient value of the mass of adsorbed water and desorbed water was measured for different values of the bed length. **Surajitr and Exella [2006]** investigated the regeneration of silica gel desiccant by a solar air heater for use in an air conditioning system. The hot air is produced by a compound parabolic concentrator collector (CPC). The couple non-equilibrium heat transfer and moisture transfer were investigated experimentally and numerically by **Jin Sun, Robert W. Besant, [2005],** where the modified model gives transient response results that agree with the experimental data within the uncertainty bounds. **Subramanyam et al., [2004]** investigated a desiccant wheel integrated air-conditioner for low humidity air-conditioning. The desiccant wheel integrated with a vapor compression air conditioning system was tested at various supply air flow rates. **Chang et al., [2004]** evaluated the commercial silica gel and the modified silica gel with improved transport properties used in the adsorption dehumidification process. Effects of the regeneration temperature and the regeneration time on the specific moisture uptake in the adsorption dehumidification process using the commercial and the modified silica gels were observed. The performance of air dehumidifiers using triethylene glycol (TEG) as a desiccant under hot and humid conditions was investigated by **Abdul-Wahab et al., [2004]**. Structured packing with different densities was used to study the impact of a number of design variables on the performance of dehumidification process. The performance of the dehumidifier was evaluated and expressed in terms of the moisture removal rate and the dehumidifier effectiveness. A transient mathematical model has been analyzed of a 4-bed adsorption chiller using CO2 as the refrigerant and Maxsorb III as the adsorbent by **Skander Jribi et al., [2014]**.

Ramy H. Mohammed et al., [2017]. Darcy-Brinkman equation is solved, by using transient three-dimensional local thermal non-equilibrium model (LTNE), in both the vapor passage and the porous layers. Silica-gel/water is selected as a working pair. Heat and mass diffusion time are calculated from analysis of the governing equations.

From the previous studies in this field there is a lack of data on the mathematical studies of a desiccant packed bed under different design conditions.

Thus, the objective of the present work is to predict the performance of a desiccant system mathematically using finite difference method.

System Description

A packed-bed system usually consists of two columns which are filled with an adsorbent (Fig. 1). The two columns are arranged in a periodic-switched operation. While one is for adsorption, the other is for desorption. In order to proceed a cyclic operation, an input heat is required for the regeneration of the adsorbent in the desorption process. The amount of the input heat is usually indicated by the temperature of the air for regeneration. Thus the regeneration temperature is a factor affecting the system performance. Besides the regeneration temperature, type of desiccant material, air mass flow rates, cyclic switching period, column length and cross-sectional area, inlet air temperature and humidity ratio are the other factors governing the performance of a packed bed.

Mathematical Model

The transient response of the heat and mass transfer in many thin packed beds was analyzed by using the Pseudo-gas-side controlled model (PGC) in the model the overall mass transfer from the air stream to the adsorbent is represented by a gas-side coefficient which is reduced to account for solid-side resistance.

Recently, Pesaran and Mills proposed a solid-side resistance model (SSR) for predicting the transient response of the heat and mass transfer in thin silica gel packed beds. The model includes both solid and gas-side resistances in the analysis of the diffusion of water vapor. Thus it is more delicate and accurate than the PGC model. In this work the solid-side resistance model is modified by adding a fluid friction effect. The fluid friction effect may play an important role in a long column packed bed or in the operation with a high air mass flow rate.

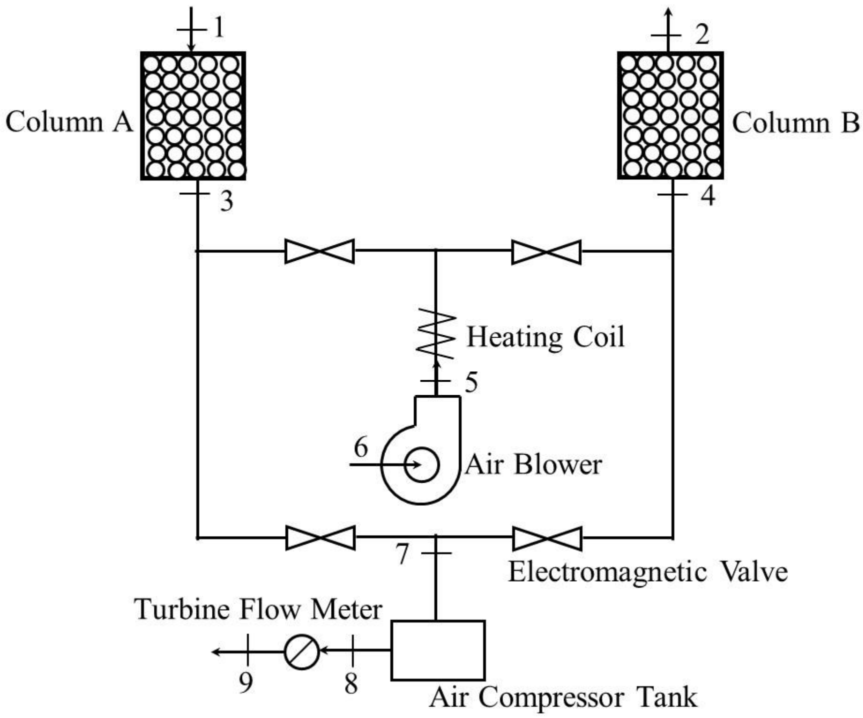

Fig. (1) Schematic diagram of desiccant packed bed system.

In the solid-side resistance model the equilibrium condition on the surface of the silica gel particle is initially evaluated. The result then the information in the analysis of the heat and mass transfer in the pseudo-channels of the column (Fig. 2). In this work, a published isotherm equation for a regular density silica gel is used and a corresponding and expression of the heat of adsorption is adopted. Based on the above assumptions and using several defined nondimensional variables and parameters, the governing equations can be rearranged in the following forms.

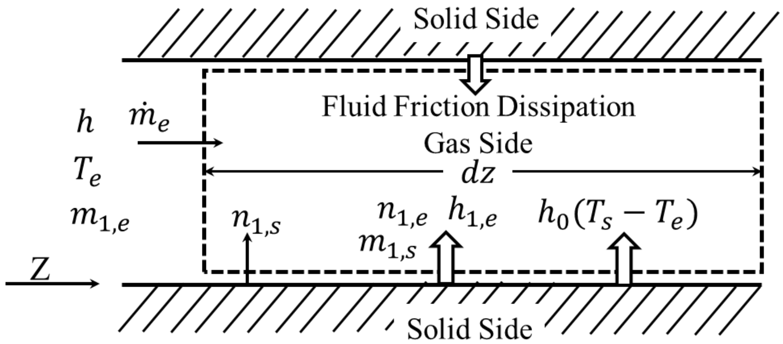

Fig. (2) Heat and mass transfer in a pseudo channel.

(i) Mass diffusion in the particle:

$$\frac{\partial U}{\partial \mathrm{t}} = \frac{1}{r^2}\ \frac{\partial}{\partial \mathrm{r}}\left[r^2\, D\,\frac{\partial U}{\partial \mathrm{r}}\right] \qquad (A)$$

Initial condition: U(r, z, t = 0) = 0

(ii) Equilibrium relationship:

$$m_{1,s} = \frac{0.622\emptyset_s \cdot P_{sat}(T_s)}{P_{total} - 0.378\emptyset_s \cdot P_{sat}(T_s)} \qquad (B)$$

Where

$$\emptyset_s = 0.0078 - 0.05759U + 24.1655U^2 - 124.478U^3 + 204.22U^4$$

(iii) Mass transfer of water vapor in the air stream:

$$\frac{\partial m_{1,e}}{\partial Z} = Ntu(m_{1,s} - m_{1,e})(1 - m_{1,e}) \qquad (C)$$

(iv) Energy balance in the stream:

$$\frac{\partial T_e}{\partial Z} = Ntu[Le(T_s - T_e) + \gamma_1(T_s - T_e)(m_{1,s} - m_{1,e})] + \left(\frac{1}{2C_{p,e}T_{in}}\right)\left(\frac{G_a}{\rho_m \varepsilon_b}\right)^2 \cdot \mathcal{F} \cdot \left(\frac{A_s}{A_c}\right) \qquad (D)$$

Where

$$\mathcal{F} = \begin{cases} 19.336Re^{-o.616}, & 0 \le Re < 200 \\ 4.064Re^{-o.313}, & 200 \le Re < 500 \\ 1.478Re^{-o.15}, & Re > 500 \end{cases}$$

$$\left(\frac{1}{2C_{p,e}T_{in}}\right)\left(\frac{G_a}{\rho_m \varepsilon_b}\right)^2 \cdot \mathcal{F} \cdot \left(\frac{A_s}{A_c}\right) = \left[\frac{3\nu^2 \cdot L(1 - \varepsilon_b)}{8C_{p,e}T_{in}R^3{\varepsilon_b}^3}\right](\mathcal{F}Re^2) \equiv \sigma(\mathcal{F}Re^2)$$

(v) Energy balance in the solid

$$\frac{\partial T_s}{\partial t} = \frac{Ntu}{C}\left[Le \cdot \gamma_2(T_e - T_s) + \gamma_3(m_{1,s} - m_{1,e})\right] \qquad (E)$$

Solving equation (A)

$$\frac{\partial U}{\partial \mathrm{t}} = \frac{1}{r^2}\frac{\partial}{\partial \mathrm{r}}\left[r^2 D \frac{\partial U}{\partial \mathrm{r}}\right]$$

$$\frac{\partial U}{\partial \mathrm{t}} = D\frac{\partial^2 U}{\partial r^2} + \frac{2D}{r}\frac{\partial U}{\partial r} \qquad (1)$$

To transfer from (r, t) to (z, t)

Put

$r = 2\,Z^{\frac{1}{2}}$ $\qquad Z = \frac{1}{4}r^2,$ $\qquad \frac{\partial Z}{\partial r} = \frac{1}{2}r$ & $\qquad \frac{\partial^2 Z}{\partial r^2} = \frac{1}{2}$

$$\frac{\partial U}{\partial \mathrm{t}} = Z \cdot D \cdot \frac{\partial^2 U}{\partial Z^2} + \frac{3}{2}D\frac{\partial \mathrm{U}}{\partial \mathrm{Z}} \qquad (2)$$

The last equation will be solved numerically by finite difference scheme, while equations C, D and E will be solving by fourth order Ronge-kutta method, using MATLAB program.

Results and Desiccation

This section reports the results of a mathematical investigation on a desiccant packed bed. The influences of desiccant mass (5, 10 and 15 kg), desiccant layer thickness (4, 8, 12 and 15 cm) and the air flow rate (7.4 and 10.2 kg/min) on the transient performance of a desiccant bed.

Figure (3) illustrate that the variation of the water content with time for the same layer thickness at different masses. It is seen that the water content in desiccant for the layer thickness 2.5 cm at desiccant mass 10 kg is greater than that of water content in desiccant for the layer thickness 2.5 cm at desiccant mass 5 kg by (65%), while at desiccant mass 15 kg is greater than that of water content in desiccant for the layer thickness 2.5 cm at desiccant mass 5 kg by (170%).

Figure (4) shows that the variation of desiccant water content with time at different layer thickness (hight) and different desiccant masses. It is clear that the water content in desiccant increases with time at layer thickness for all masses, due to the continuous transferring of water vapor from humid air to the desiccant materials. Also it is increases with layer thickness increases at same time and desiccant mass.

Figure (5) shows that the effect of desiccant height on temperature in humid in the stream with time at different desiccant masses. It is clear that the temperature in humid air in the stream increases with time for all masses, due to the continuous transferring of water vapor from humid air to the desiccant materials. Where the temperature in humid air in the stream increases with increase the desiccant mass at the same time.

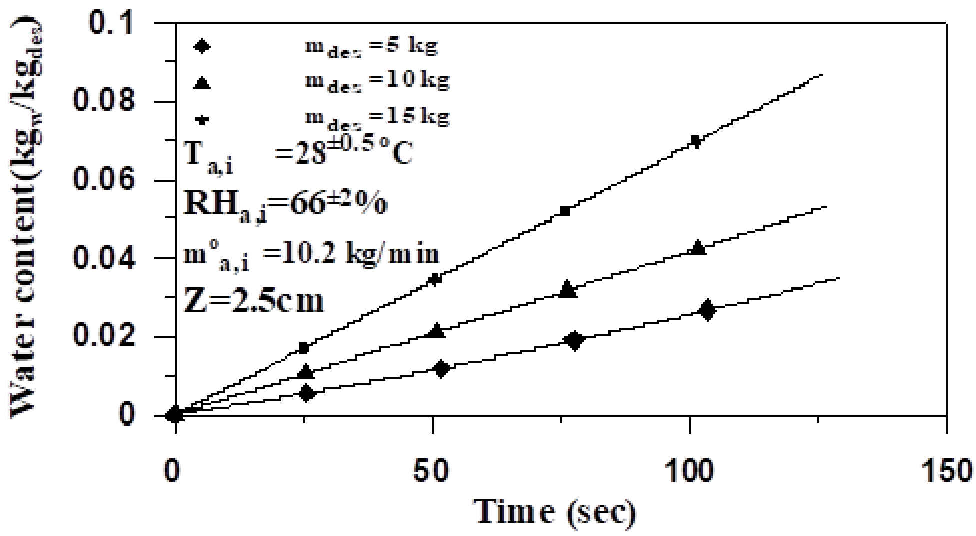

Fig. (3) Effect of desiccant mass on desiccant water content in the same layer

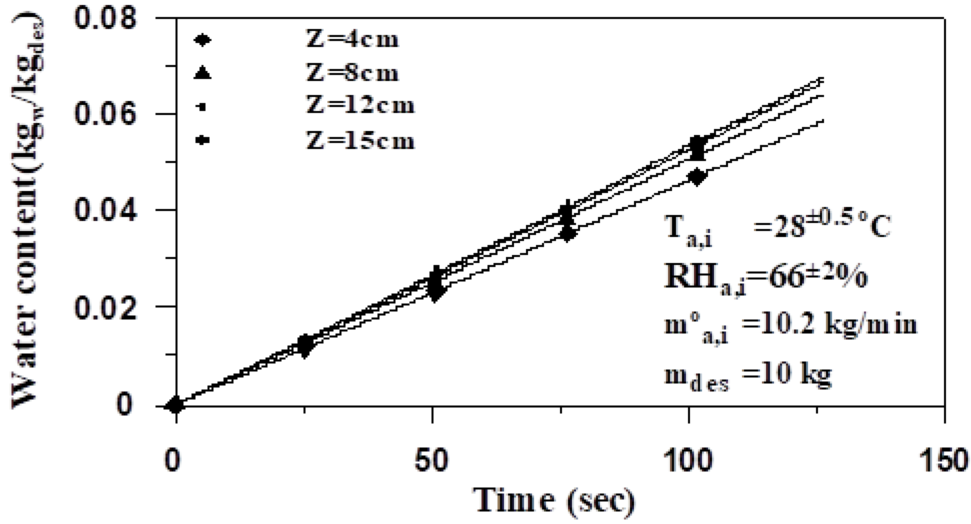

Fig. (4) Effect of desiccant layer thickness on desiccant water content

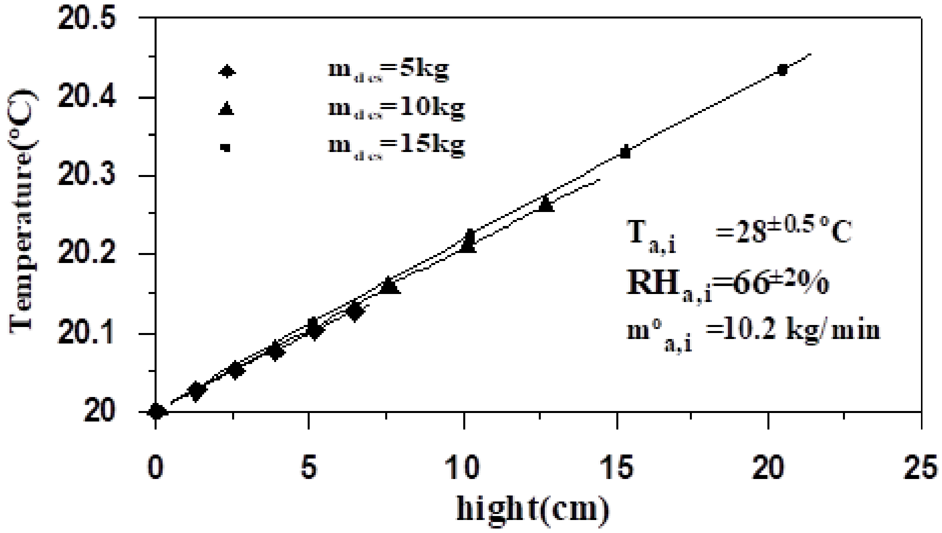

Fig. (5) Effect of desiccant layer thickness on Temperature in humid air in the stream

Figure (6) shows that the effect of temperature in humid air in the stream on surface temperature. We can see that the surface temperature increases when the temperature in humid air in the stream increase for the same height and desiccant mass.

Figure (7) illustrate that the variation of the water content with time for the same layer thickness at different air flow rates. It is seen that the water content in desiccant for the layer thickness 2.5 cm at air flow rate 7.4kg/min is greater than that of water content in desiccant for the layer thickness 2.5 cm at flow rate 10.2 kg/min by (19%).

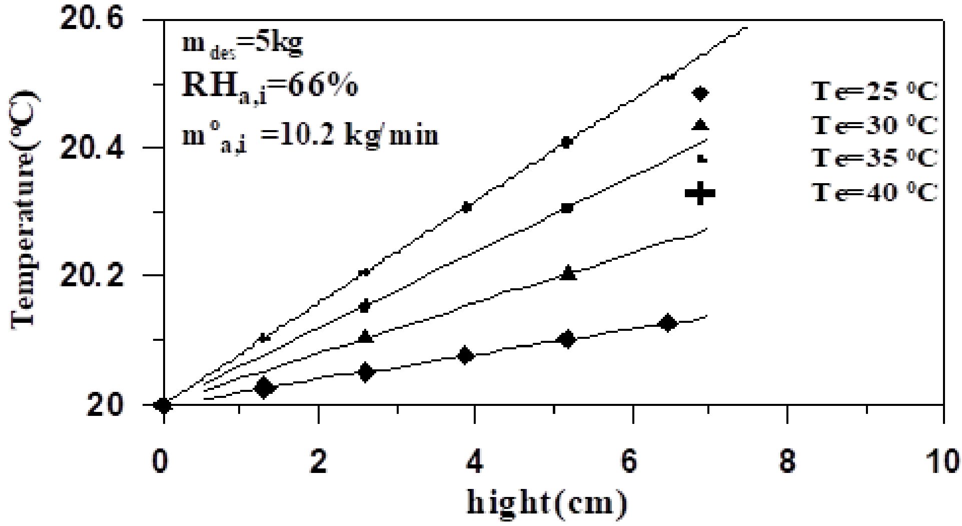

Fig. (6) Effect of Temperature in humid air in the stream on surface temperature

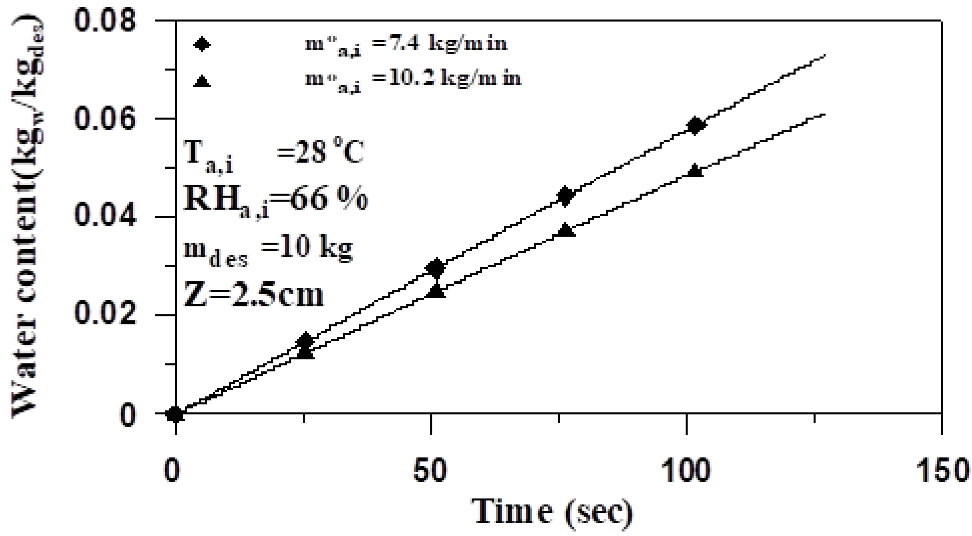

Fig. (7) variation of water content with time at different air flow rate

Figure (8) shows that the effect of layer thickness (height) on mass fraction in humid air in the stream at different air flow rate. It is clear that the mass fraction in humid air in the stream decreases with height for all flow rates, due to the continuous transferring of water vapor from humid air to the desiccant materials. Where the mass fraction in humid air in the stream decreases with increasing the air flow rate at the same height.

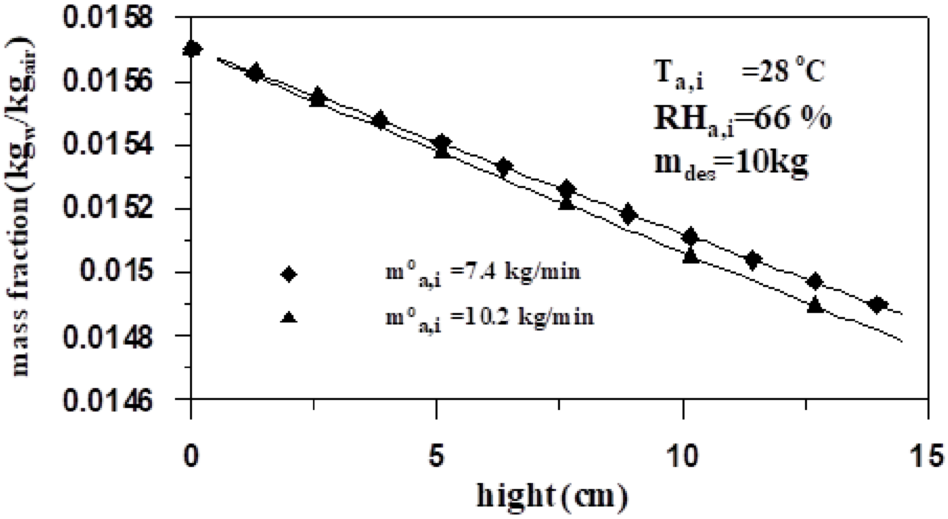

Fig. (8) Effect of air flow rate on mass fraction in humid air stream

Regeneration mode

The results of a mathematical studies on a desiccant packed bed in regeneration mode. The influences of desiccant mass (5, 10 and 15 kg), desiccant layer thickness (4, 8, 12 and 15 cm) and the air flow rate (7.4 and 10.2 kg/min) on the transient performance of a desiccant bed are reported in this section.

Figure (9) shows that the variation of desiccant water content with time at different layer thickness and different during the regeneration mode. It is clear that the water content in desiccant decreases with time for all layer thickness and all, due to the continuous transferring of water vapor from desiccant materials to the humid air. Also it is decreases with layer thickness increases at same time.

Figure (10) illustrate that the variation of the water content with time during the regeneration mode for the same layer thickness at different masses. It is seen that the water content in desiccant for the layer thickness 2.5 cm at desiccant mass 10 kg is greater than that of water content in desiccant for the layer thickness 2.5 cm at desiccant mass 5 kg by (1.6%), while at desiccant mass 15 kg is greater than that of water content in desiccant for the layer thickness 2.5 cm at desiccant mass 5 kg by (4%).

Figure (11) illustrate that the variation of the water content with time for the same layer thickness at different air flow rates. It is seen that the water content in desiccant for the layer thickness 2.5 cm at air flow rate 7.4kg/min is less than that of water content in desiccant for the layer thickness 2.5 cm at flow rate 10.2 kg/min by (4%).

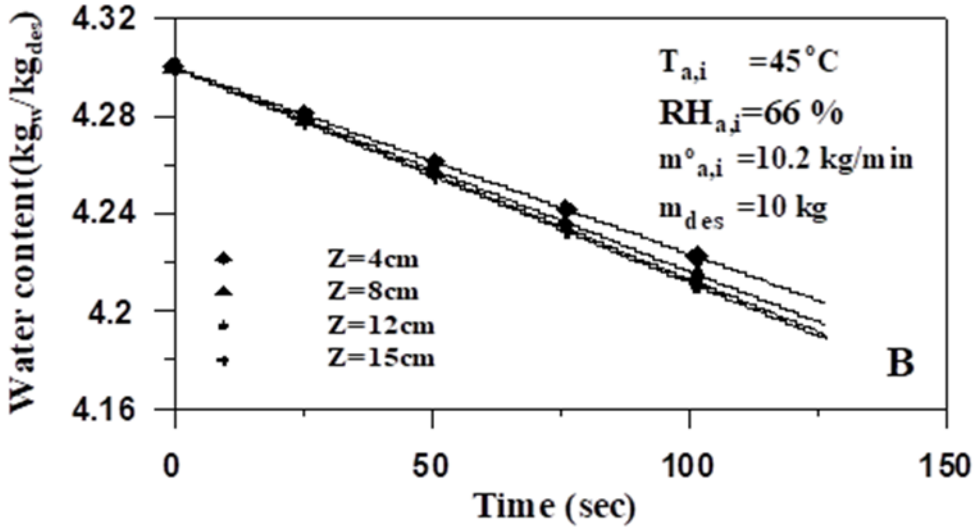

Fig. (9) Variation of water content with time at different layer thickness

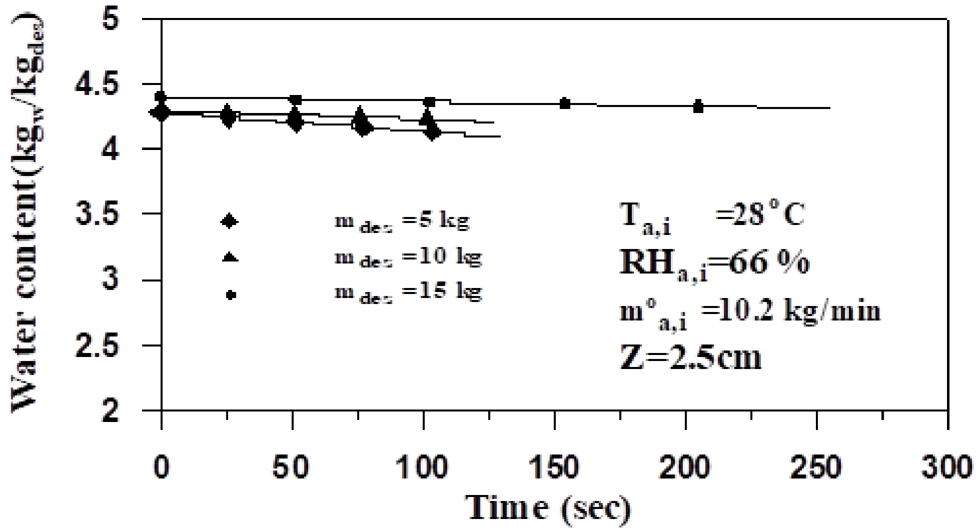

Fig. (10) Effect of mass of desiccant on desiccant water content with time

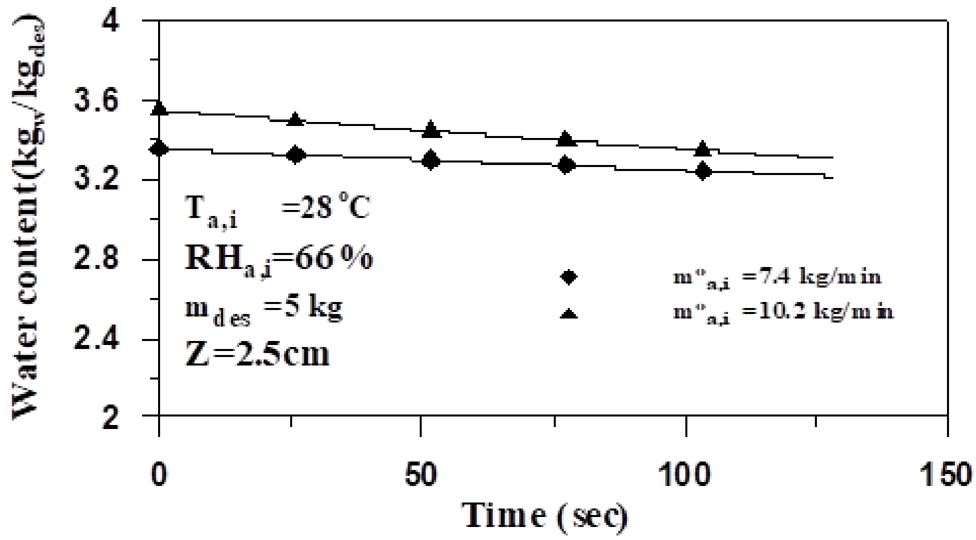

Fig. (11) Effect of air flow rate on desiccant water content with time

Conclusions

Based on the reported results the following conclusions can be drawn:

- For the same layer thickness, when the desiccant mass was changed from 5kg to 10kg the water content increasing by 65%.
- For the same desiccant mass, when the layer thickness was changed from 2.5 to 5cm the water content increasing by 13.9%.
- For the same desiccant mass and same layer thickness, when the air flow rate was changed from 7.4 to 10.2 kg/min the water content increasing by 19%.
- The water content in desiccant for the same layer thickness at desiccant mass 10 kg is greater than that of water content in desiccant at desiccant mass 5 kg by 1.6%.
- The water content in desiccant for the same desiccant mass at layer thickness 2.5 cm is greater than that of water content in desiccant for the layer thickness 5cm by 0.3%.
- The water content in desiccant for the same layer thickness and same desiccant mass at air flow rate 7.4kg/min is less than that of water content in desiccant for the air flow rate 10.2 kg/min by 4%.

REFERENCES

Abdul-Wahab, S, A., Zurigat, Y. H., Abu-Arabi, M. K., (2004) “Prediction of moisture removal rate and dehumidification effectiveness for structured liquid desiccant air dehumidifier”, Energy Vol. 29, pp. 19-34.

Chang, K. S., Wang, H. C., Chung, T. W., (2004), effect of regeneration conditions on the adsorption dehumidification process in packed silica gel beds” Applied Thermal Engineering, Vol. 24, pp. 735-742.

Jin Sun, Robert W. Besant, (2005), “Heat and mass transfer during silica gel–moisture interactions”, International Journal of Heat and Mass Transfer vol. 48, pp. 4953-4962.

Kabeel A. E., (2009), “Adsorption-desorption operationsof multilayer desiccant packed bed for dehumidification applications”, Renewable energy vol. 34, pp. 255-265.

M. Fatouh, Talaat A. Ibrahim, A. Mostafa, (2009) “Experimental investigation on a solid desiccant system integrated with a R407C compression air conditioner”, Energy Conversion and Management Vol. 50, pp. 2670–2679

M. Fatouh, Talaat A. Ibrahim, A. Mostafa, (2010) “Performance assessment of a direct expansion air conditioner working with R407C as an R22 alternative”, Applied Thermal Engineering Vol. 30, pp. 127–133

Pesaran A. A., Mills A. F., (1987), “Moisture transport in silica gel packed beds. Theoretical study”, Int. J. Heat Mass Transfer Vol. 30, pp. 1037-1049.

Ramy H. Mohammed, Osama Mesalhy, Mohamed L. Elsayed, Louis C. Chow, (2017) “Novel compact bed design for adsorption cooling systems: parametric numerical study”, International Journal of Refrigeration Vol. 80, pp. 238-251.

Skander Jribi, Bidyut Baran Saha, Shigeru Koyama, Hatem Bentaher, (2014) “Modeling and simulation of an activated carbon–CO2 four bed based adsorption cooling system” Energy Conversion and Management Vol. 78, pp. 985-991.

Subramanyam N., Maiya, M. P., Srinivasa Murthy S., (2004), “Application of a desiccant wheel to control humidity in air-conditioning systems”, Applied Thermal Engineering, Vol. 24, pp. 2777-2788.

Surajitr Pramuang*, R. H. B. Exella, (2006), “The generation of the silica gel desiccant by air from solar heater with a compound parabolic concentrator”, Renewable energy vol. 31, pp.