Quantification of the influence of RD silica gel bed porosity and process air inlet temperature on heat and mass transfer

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***Abstract*— This work is on the studies carried out to evaluate the heat and mass transfer performance of a regular density (RD) silica gel packed bed during adsorption mode. A quite precise quantification of the influence of both bed porosity and process air inlet temperature on the magnitude of heat and mass transfer in a silica gel packed bed is carried out. Accurate tendency curves for the transferred humidity and enthalpy data are, then, identified and interpreted. Correlations, permitting to calculate, in function of bed porosity or process air inlet temperature, both the maximum quantity of removed humidity from air and the maximum enthalpy released by the silica gel medium during an adsorption process, are provided. All numerical simulations are carried out using Finite Volume method.**

***Keywords*— Air conditioning, Adsorption, Heat and mass transfer, Porosity, Silica gel.**

I. INTRODUCTION

During adsorption phenomena, it is well known that the variation of operating conditions, such as adsorbent bed porosity and the inlet temperature of process air affect considerably the mass and heat transfer rates, between adsorbent particles and humid air. Precisely quantifying the influence of these two operating conditions helps to ensure a good choice of bed porosity and inlet air temperature, when aiming to design an efficient adsorption bed.

Examining the literature talking about the effect of bed porosity and the inlet air temperature on heat and mass transfer in a porous medium, some interesting works can be mentioned.

Hasan Demir *et al.* [1] performed an interesting study concerning the effect of porosity on heat and mass transfer in a granular adsorbent bed. The evolutions of adsorbent temperatures, adsorptive pressure and moisture content were studied for 3 values of bed porosity (0.1, 0.2 and 0.3). It was shown that the period of adsorption augments when bed porosity increases. All simulations illustrate that both pressure adsorptive and moisture content of adsorbent are affected by the bed porosity just at the beginning of the adsorption cycle, and they approach the equilibrium value after a relatively short time.

Kuei-Sen Shang *et al.* [2] performed an experimental work to evaluate the effect of inlet air temperature and the regeneration cycle duration on the mass transfer within a silica gel packed bed. A comparison between commercial and improved properties silica gel is done when evaluating the moisture uptake of silica gel. It was shown that the silica gel with improved properties (modified silica gel) does not require a high regeneration air temperature to attain a specific moisture uptake, as it is the case for commercial silica gel. This fact was explained by the low mass transfer resistance of modified silica gel compared to the commercial one. A considerable energy saving, when regenerating the improved properties silica gel, is then allowed.

The aim of this work is to quantify the influence of bed porosity and inlet air temperature on some characteristic variables of heat and mass transfer which are the maximum enthalpy released by desiccant material and the maximum removed quantity of humidity from the process air.

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In section 2, the silica gel packed bed characteristics and the conditioned space dimensions are presented in order to determine an adequate air velocity based on the desired air flow rate. In section 3, differential equations governing the heat and mass transfer problem in silica gel packed bed are expressed. Numerical simulations results are presented and interpreted. In section 4, the work is concluded.

II. STATEMENT PROBLEM

As described in Fig.1, the desiccant unit is one component among several others forming the whole air conditioning system. Solar energy is used to regenerate the desiccant material.

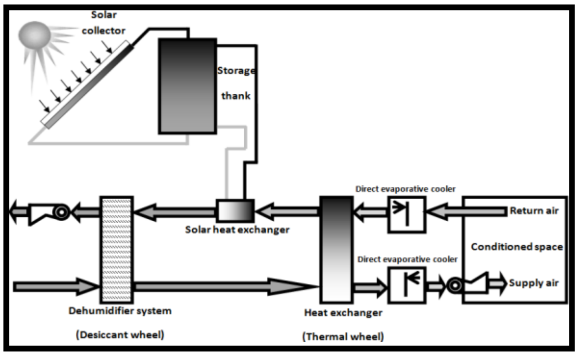

Fig. 1. Desiccant air conditioning system.

A. Silica gel packed bed

The silica gel packed bed has a squared cross section $S_b=2.5\times10^{-3}m^2$ and a height $H_b=0.2m$. The used desiccant is a regular density silica (RD) gel silica gel. The bed, under investigation, is one sample among 8 identical beds forming the whole desiccant unit, and working with a suitable synchronization.

B. Conditioned space

The conditioned space has a square area $S=6.25m^2$ and a height $H=2.88m$. Thus, the space contains an air volume equal to $18m^3$. The whole air volume of the conditioned space is changed every 15 minutes. Taking into consideration the general working order of beds forming the desiccant unit and their number, the mass flow rate in each bed must be $0.3\ m^3/min$ which corresponds to an air velocity $V=2m/s$.

The studied heat and mass transfer problem is governed by the following equations,

C. Drying kinetic equation

The drying kinetic equation is widely used in literature[3,4],

$$\frac{\partial q}{\partial t} = \frac{15D_e}{r_p^2}(q_\infty - q) \qquad (1)$$

where,

q : Silica gel moisture content (*Kg (H2O)*/Kg (*dry silica gel*)

q_∞: Equilibrium moisture content (*Kg (H2O)*/Kg (*dry silica gel*)

D_e: Effective diffusivity (m^2/s)

r_p: Silica gel radius particle (*mm*).

The effective diffusivity coefficient is given by the formula [5,6]

$$D_e = \frac{D_0}{\tau_s}\exp\left(-0.947.\frac{H_{ads}.10^{-3}}{T}\right) \qquad (2)$$

where,

D_0: Surface diffusion coefficient (m^2/s)

τ_s: Tortuosity factor for intraparticle surface diffusion

H_{ads}: Heat of adsorption (*KJ/Kg*(*water*))

T: Air temperature (K)

D. Mass conservation equation

$$\varepsilon\rho_a\frac{\partial\omega}{\partial t} + \rho_a V\frac{\partial\omega}{\partial x} = \rho_a D_e\left(\frac{\partial^2\omega}{\partial x^2}\right) - (1-\varepsilon)\rho_s\frac{\partial q}{\partial t} \qquad (3)$$

where,

ω: Air humidity ratio (*Kg (H2O)*/Kg (*dry* air)

ρ_a: Air density (Kg/m^3)

ρ_s : Silica gel density (Kg/m^3)

ε: Medium porosity

E. Energy conservation equation

$$\left(\varepsilon\rho_a(C_{pa}+\omega C_{pv}) + (1-\varepsilon)\rho_s(C_{ps}+qC_{pw})\right)\frac{\partial T}{\partial t} + \rho_a(C_{pa}+\omega C_{pv})V\frac{\partial T}{\partial x} = \rho_s H_{ads}(1-\varepsilon)\frac{\partial q}{\partial t} + (\varepsilon\lambda_a + (1-\varepsilon)\lambda_s)\frac{\partial^2 T}{\partial x^2} \qquad (4)$$

where,

C_{pa}: Air specific heat (*KJ/KgK*)

C_{pv}: Water vapor specific heat (*KJ/KgK*)

C_{ps}: Silica gel specific heat (*KJ/KgK*)

C_{pw}: Water specific heat (*KJ/KgK*);

λ_a: Air thermal conductivity (*W/mK*)

λ_s: Silica gel thermal conductivity (*W/mK*).

III. RESULTS AND INTERPRETATIONS

It is to note that all numerical simulations are carried out in the outlet of the bed (x=0.2 m).

A. Influence of bed porosity

To quantify the influence of bed porosity on both the humidity remove and enthalpy release, we set particle radius r_p=1.8mm, air velocity V=2m/s, process air inlet temperature

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$T_{inlet\ air}$ =35°C and we vary the bed porosity ε over the range [0.4, 0.7].

Figs. 2 show the evolution of the maximum enthalpy (dashed line) released by the desiccant and the maximum quantity of humidity (solid line) removed from process air, in function of bed porosity, during the adsorption cycle.

The evolutions of released enthalpy and removed humidity in function of bed porosity have both polynomial tendencies. Correlations governing these evolutions are,

For heat transfer,

$$H_{released} = H_{\max} - H_{initial} = -1771\times\varepsilon^2 - 20725\times\varepsilon + 22203 \quad (5)$$

For mass transfer,

$$\omega_{removed} = \omega_{initial} - \omega_{\min} = = -3\times10^{-5}\times\varepsilon^2 - 0{,}008\times\varepsilon + 0{,}008 \quad (6)$$

The decreasing tendency for both heat and mass transfer in adsorption mode, when bed porosity augments, is expected. In fact, the quantity of adsorbent decresases when bed porosity increases. This diminishes, obviously, the total adsorbent surface of silica gel particles. The amount of Van Der Waals bonds, formed on the silica gel surfaces during adsorption phenomena, is, so, reduced. This coresponds to a decrease in mass transfer.

The creation of Van Der Waals bond is an exothermic reaction. Evidently, the quantity of heat relased is proportional to the amount of formed Van Der Waals bonds. This explains the decrease of heat transfer when bed porosity augments.

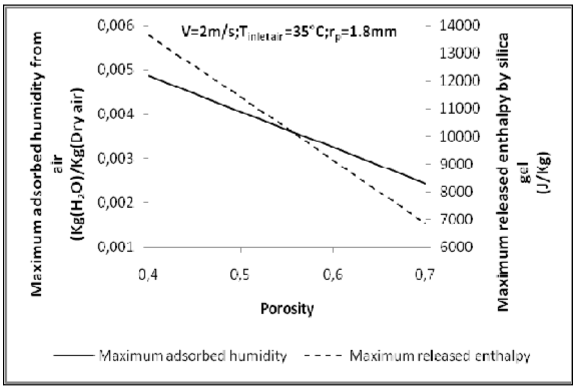

Fig. 2. Evolution of heat and mass transfer in function of bed porosity during adsorption cycle.

B. Influence of process air inlet temperature

To quantify the influence of process air inlet temperature on both humidity remove and enthalpy release, we set we set particle radius r_p=1.8mm, air velocity V=2m/s, bed porosity ε=0.55 and we vary the process air inlet air temperature $T_{inlet\ air}$ over the range [25°C, 45°C]

Fig. 3 show the evolution of the maximum enthalpy (dashed line) released by the desiccant and the maximum quantity of humidity (solid line) removed from process air, in function of process air inlet temperature, during the adsorption cycle.

The evolutions of released enthalpy and the maximum quantity of humidity removed form process air in function of process air inlet temperature have both a polynomial tendencies. Correlations governing these phenomena are,

For heat transfer,

$$H_{released} = H_{\max} - H_{initial} = 3{,}353\times T_{inlet}^{\ 2} + 66{,}89\times T_{inlet} + 3821 \quad (7)$$

For mass transfer,

$$\omega_{removed} = \omega_{initial} - \omega_{mix} = 10^{-6}\times T_{inlet}^{\ 2} + 2\times10^{-5}\times T_{inlet} + 0{,}001 \quad (8)$$

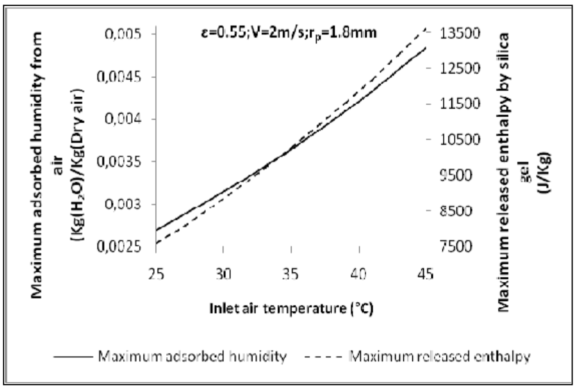

Fig. 3. Evolution of heat and mass transfer in function of process air inlet temperature during adsorption cycle.

The trend for both heat and mass transfer in adsorption mode is growin when the inlet temperature of the process air increases. This is predicted since the mass diffusivity of adsorbent particles augments as the process air inlet temperature increases. So, the mass transfer is enhanced: the quantity of Van Der Waals bonds, formed on the silica gel surfaces during adsorption phenomena, is, augmented. Consequently, the quantity of heat released is, also, augmented when the process air inlet temperature increases.

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Using the aforementioned correlations, it is easy to predict quite precisely the maximum quantity of removed humidity from the process air and the released enthalpy by the desiccant medium, given the silica gel bed porosity or the process air inlet temperature.

IV. Conclusion

A rigorous quantification of the influence of silica gel bed porosity and process air inlet temperature on heat and mass transfer within a packed bed was carried out. Evolution tendencies of heat and mass transfer was studied and interpreted. It was shown that the heat and mass transfer evolutions have polynomial tendencies in function of both bed porosity and process air inlet temperature.

Correlations, giving the exact quantity of heat and mass transfer in function of bed porosity and process air inlet temperature, were established, based on data describing the maximum removed humidity from the process air and the maximum enthalpy released by the desiccant medium. This can be useful for ensuring proper choice of bed porosity and process air inlet temperature when adsorption phenomena have to be carried out.

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