

STUDY ON AIR CONDITIONING THROUGH DESICCANT TECHNOLOGY

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Rezumat. Lucrarea propune un model matematic pentru studiul proceselor de transfer ce au loc în particula adsorbantă ce intră în componența adsorberelor rotative în strat compact. Rezultatele numerice obținute au permis evidențierea distribuției încărcării solidului adsorbant pe direcție radială precum și a variației parametrilor medii ai acestuia (temperatură și conținut de umiditate).

Cuvinte cheie: condiționarea aerului, transfer de căldură și masă, adsorbție, modelare.

Abstract. In the present paper, a behavioural model of the transfer processes within the desiccant pellet was proposed. The numerical simulation allowed to obtain the water content distribution on radial direction and the evolution of the average solid desiccant parameters (water content, temperature) during adsorption and desorption stages.

Keywords: air conditioning, heat and mass transfer, desiccant systems, modelling.

1. INTRODUCTION

Due to increasing outdoor temperatures in the last decades, the higher living and working standards and the relatively low prices of air conditioning units, the demand for air conditioning in buildings has sharply risen. This can also be noticed in the annual energy use of room air conditioners which increased from 6 TJ in 1990 to 160 TJ in 2010 [1].

The fast growing demand for air conditioning lead to a significant increase for electricity consumption and thus for primary energy. Electric appliances are used at maximum capacity in the hot summer days, but often fail to meet the demand. The resulting CO₂ emissions in the EU increased twenty times from 1990 to 2010 [1].

Desiccant Evaporative Cooling Systems represent an alternative for the classical methods with mechanical vapor compression [2]. This type of systems can handle sensible and latent heat loads independently without using CFCs or a large amount of electricity. This leads to a high level of comfort, environment protection and less energy used, expanding and promoting desiccant industry from niche applications to a broader market, such as hospitals, supermarkets, restaurants, theatres, schools and office buildings [3]. For small scale systems, there is no market available technology but for development of these systems special

research efforts are made.

Desiccant Evaporative Cooling Systems contains three basic components: a rotary adsorber (the dehumidifier) RA, an evaporative cooler EC and a sensible heat exchanger HE.

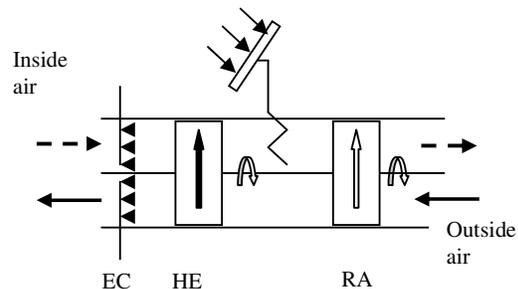


Fig. 1. Basic Desiccant Evaporative Cooling System

The adsorber, of rotary wheel type, is partitioned in two sections that allow flow in opposite directions (Fig. 1). In the process air (outside air) section, the moisture of the air is partially adsorbed by the solid desiccant. The released adsorption heat increases the temperature of the solid and of the air. Therefore, the air exits the process side of the wheel hot and dry. Passing through the sensible heat exchanger of Lungstrom type, most of the added adsorption heat is rejected on the regeneration side where the adsorbent is reactivated.

Nomenclature

c	vapor concentration in air, kg/m ³	x	water content of solid desiccant, kg/kg
c_p	specific heat, J/kgK	x^*	equilibrium water content on the vapor-solid interface, kg/kg
D_M	overall diffusion coefficients, m ² /s	\bar{x}	average water content, kg/kg
D_K	Knudsen diffusion coefficient, m ² /s	y	air humidity ratio, kg/kg
D_{12}	gas free diffusion coefficients, m ² /s		
d_p	pore diameter, m		
h	specific enthalpy, J/kg		
h_B	formation enthalpy, J/kg		
h_c	convection heat transfer coeff., W/m ² K		
h_m	mass transfer coefficient, m/s		
h_{lg}	latent heat of vaporization, J/kg		
h_{lg0}	latent heat of vaporization at 0°C, J/kg		
m	mass, kg		
R	radial coordinate, m		
R_p	pellet radius, m		
T	temperature, K		
w_b	air velocity, m/s		

Greek symbols

ε	porosity of particle
μ_p	tortuosity factor
ρ_s	adsorbent particle density, kg/m ³
τ	time, sec

Subscript

b	bulk flow
g	vapor
i	initial
s	solid desiccant

The evaporative process from evaporative cooler reduces substantially the air temperature, while the air humidity is maintained at a proper level.

The improvement of the adsorber performance is the most important step with a view to optimize the whole system. This is the reason why, in the present paper, a theoretical approach started with the heat and mass transfer processes within the desiccant pellet, which is the basic constitutive unit of desiccant wheel, is proposed. Thus, the main elements of some of the actual models were accepted [4] and corrections regarding as the definition and calculus of the adsorption heat and how this involves in the energy balance equation (through formation enthalpy and latent heat of vaporization) were made. Supplementary assumptions were used, such as uniform temperature within the desiccant pellet [5] and the energy storage in both adsorbent and adsorbate phases [6].

2. MATHEMATICAL MODEL

The mathematical model of the heat and mass transfer processes is based on the following main assumptions [4], [6]:

- the desiccant pellet is spherical and its physical properties are uniform;
- the circular macropores are disposed on radial direction, from the surface of the pellet to the central point;
- one adsorption component system is considered (water vapor);
- the heat transfer resistance is concentrated in the external film, thus the internal temperature

gradients are low and can be neglected [5];

- the heat of adsorption depends on water content and temperature of the solid;
- the free gas diffusion and the Knudsen diffusion characterize the mass transfer transport in macropores;
- the vapor diffusion in micropores is insignificantly;
- the equilibrium between gas phase and solid phase is manifested everywhere in the desiccant pellet; the relation between vapor concentration of air and the water content of the solid is expressed by the specific adsorption isotherm $x=x^*=f(c,T)$;
- the heat storage is made in both adsorbent and adsorbate phases.

2.1. Mass balance equation

The mass balance is applied on a control volume that is delimited by two concentrically spherical surfaces of R , respectively $R+dR$ radius (Fig.2).

The control volume contains a fraction of solid desiccant material and a fraction of pores (voids). The macropores are occupied by the adsorbate (water fixed on the internal gas-solid interface) and air with an actual water vapor concentration.

For an elementary period $d\tau$, the mass balance is expressed by the following equations [4], [6]:

$$(\dot{m}_{g,R+dR} - \dot{m}_{g,R})d\tau = dm_g + dm_a \quad (1)$$

$$\dot{m}_{g,R+dR} = \dot{m}_{g,R} + \frac{\partial \dot{m}_{g,R}}{\partial R} dR \quad (2)$$

The relevant masses for the transport process

are calculated with the following relations:

$$m_g = 4\pi R^2 \cdot dR \cdot \varepsilon \cdot c \quad (3)$$

$$m_g = 4\pi R^2 \cdot dR \cdot \rho_s \cdot x \quad (4)$$

$$\dot{m}_{gR} = \frac{D_M}{\mu_p} 4\pi \cdot R^2 \cdot \varepsilon \cdot \frac{\partial c}{\partial R}, \quad (5)$$

where
$$D_M = \frac{1}{1/D_{12} + 1/D_K}. \quad (6)$$

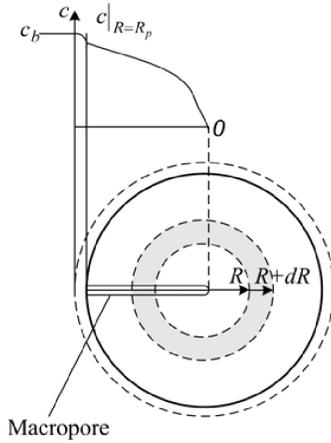


Fig. 2. Control volume for mass balance

Through successive mathematical processing, for the assumptions mentioned above, the final form of the mass balance equation is:

$$\frac{\partial c}{\partial \tau} \left(1 + \frac{\rho_s}{\varepsilon} \frac{\partial x}{\partial c} \right) + \frac{\rho_s}{\varepsilon} \frac{\partial x}{\partial T} \frac{\partial T}{\partial \tau} = \frac{D_M}{\mu_p} \left(\frac{\partial^2 c}{\partial R^2} + \frac{2}{R} \frac{\partial c}{\partial R} \right) \quad (7)$$

Energy balance equation

To deduce the energy balance equation, the differential spherical control volume is abandoned. Based on the assumption that the internal temperature gradients are insignificantly, for this analysis stage the entire pellet is considered. The energy stored within the pellet in the elementary period $d\tau$ is estimated with the relation:

$$\delta Q_{st} = (\dot{Q}_g - \dot{Q}_{cv}) \cdot d\tau + \dot{Q}_B \cdot d\tau. \quad (8)$$

The following relations were used for the calculus of diffusion heat rate \dot{Q}_g , convection heat rate \dot{Q}_{cv} and heat rate corresponding to the

formation enthalpy \dot{Q}_B :

$$\dot{Q}_g = \frac{D_M}{\mu_p} 4\pi R_p^2 \varepsilon \frac{\partial c}{\partial R} \Big|_{R=R_p} [h_{g0} + c_{pg} (T_b - 273,15)] \quad (9)$$

$$\dot{Q}_{cv} = h_c 4\pi R_p^2 (T - T_b) \quad (10)$$

$$\dot{Q}_B = \frac{\partial \bar{m}_a}{\partial \tau} \cdot h_B = \dot{m}_g \Big|_{R=R_p} \cdot h_B. \quad (11)$$

The amount of adsorbate, \bar{m}_a , which is the average value for the entire pellet, may be expressed as follows:

$$\bar{m}_a = \frac{4}{3} \pi R_p^3 \bar{x} = \int_0^{R_p} 4\pi R^2 \cdot \rho_s \cdot x \cdot dR. \quad (12)$$

Using the assumption that the intraparticle heat storage is made in both adsorbent and adsorbate phases, for the calculation of the term δQ_{st} the following equations were used:

$$\begin{aligned} \delta Q_{st} &= \dot{Q}_{st} d\tau = \frac{\partial}{\partial \tau} (\bar{m}_a h_a) + \frac{\partial}{\partial \tau} (m_s h_s) = \\ &= \frac{\partial \bar{m}_a}{\partial \tau} h_a + \bar{m}_a \frac{\partial h_a}{\partial \tau} + m_s \frac{\partial h_s}{\partial \tau} = \\ &= \frac{D_M}{\mu_p} 4\pi R_p^2 \varepsilon \frac{\partial c}{\partial R} \Big|_{R=R_p} [c_{pa} (T - 273,15)] + \\ &+ \frac{4}{3} \pi R_p^3 \bar{x} c_{pa} \frac{\partial T}{\partial \tau} + \frac{4}{3} \pi R_p^3 \rho_s c_{ps} \frac{\partial T}{\partial \tau} \end{aligned} \quad (13)$$

The final form of the energy balance equation is:

$$\begin{aligned} &\frac{4}{3} \pi R_p^3 \rho_s (c_{ps} + \bar{x} c_{pa}) \frac{\partial T}{\partial \tau} = \\ &= \frac{D_M}{\mu_p} 4\pi R_p^2 \varepsilon \frac{\partial c}{\partial R} \Big|_{R=R_p} [h_{gl} + h_B - c_{pg} (T - T_b)] - \\ &- 4\pi R_p^2 h_c (T - T_b) \end{aligned} \quad (14)$$

The initial and boundary conditions are:

$$\tau = 0, 0 \leq R \leq R_p : x = x_i, T = T_i$$

$$\tau > 0,$$

$$R = 0 : \frac{\partial c}{\partial R} \Big|_{R=0} = 0 \quad (15)$$

$$R = R_p : 4\pi R_p^2 h_m (c_b - c|_{R=R_p}) = \frac{D_M}{\mu_p} 4\pi R_p^2 \varepsilon \frac{\partial c}{\partial R} \Big|_{R=R_p}$$

For a greater accuracy of the results, the

components of the heat of adsorption, respectively latent heat of vaporization and formation enthalpy, are used through actual values ($h_{lg} = f(T)$ and $h_B = f(\bar{x})$). Also, the convection heat transfer coefficient h_c and the mass transfer coefficient h_m on the external surface of the pellet were calculated step by step using the Gnielinski's relations corresponding to the actual parameters.

To solve the balance equations, Crank Nicholson scheme coupled with Gauss elimination algorithm and Euler-Heun finite difference scheme were applied.

3. NUMERICAL RESULTS

For couple silica gel – humid air, characterized by decisive macropore diffusion, adsorption and desorption operations for the following process parameters were studied:

- adsorption $T_b=27$ °C; $y_b=12$ g/kg; $T_i=80$ °C; $x_i=22,1$ g/kg;
- desorption $T_b=127$ °C; $y_b=6$ g/kg; $T_i=27$ °C; $x_i=200$ g/kg;
- $w_b=0,2$ m/s; $R_p=3$ mm; $d_p=88 \cdot 10^{-9}$ m.

The numerical results allowed to obtain the evolution of average pellet parameters (Fig. 4, Fig. 6) - water content and temperature – and the water content distribution on radial direction at different times, during adsorption and desorption stages (Fig. 3, Fig. 5).

3.1. Adsorption stage

For the selected conditions the process begins with an extended desorption in the entire pellet (fig. 3); as the contact time between the two phases (air and desiccant solid) increases, desorption is restricted to the center of the pellet; the desiccant solid cools and recovers its adsorptive properties (Fig. 3, Fig. 4 a); initial desorption is not highlighted in the evolution of \bar{x} , apparently the whole pellet being in adsorption phase (differential layers involve with different weights in average water content calculation because of the different volume included);

The average water content of the solid desiccant increases in time, but the process dynamics decreases in time (fig.4 b). The temperature of the pellet decreases quickly in the first minutes because of the intense heat exchange through convection mode on the exterior surface of the pellet and the endothermic effect of the initial desorption in the superficial layers (Fig. 4 a).

Later it can be noticed a linear variation of

temperature and uniformity of the gradient $\frac{\partial x}{\partial R}$ within the pellet.

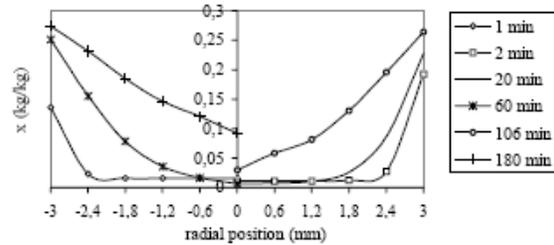
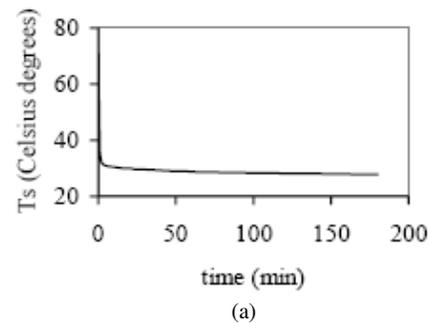
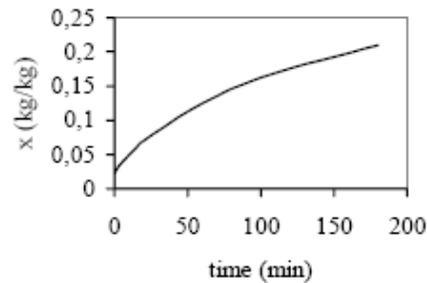


Fig. 3. The water content distribution within the pellet - adsorption operation



(a)



(b)

Fig. 4. The evolution of the average pellet parameters – adsorption operation

3.2. Desorption stage

In desorption stage, the phenomenon are complementary to those presented previously. In figure 5 and 6 b is highlighted the initial adsorption (the average water content raises over the initial level). In the same time the desiccant temperature increases quickly because of the intense convective heat exchange with the warm fluid and due to the released heat of adsorption.

Then, the average water content decreases fast, the successive layers being regenerated. The superficial layers are regenerated relatively quickly but, in the profoundness of the pellet the desorbed vapor move with difficulty because of the small diffusion coefficient D_M (Fig. 5).

The last phase corresponds to the evolution towards the equilibrium state. In fact, the regeneration is made until a residual load about 20 g/kg. Finally, can be noticed that the desorption is faster than adsorption (at least in terms of selected regenerations conditions)

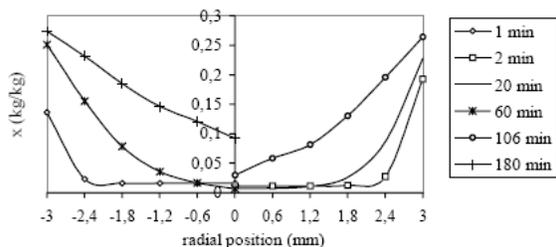


Fig. 5. The water content distribution within the pellet – desorption operation

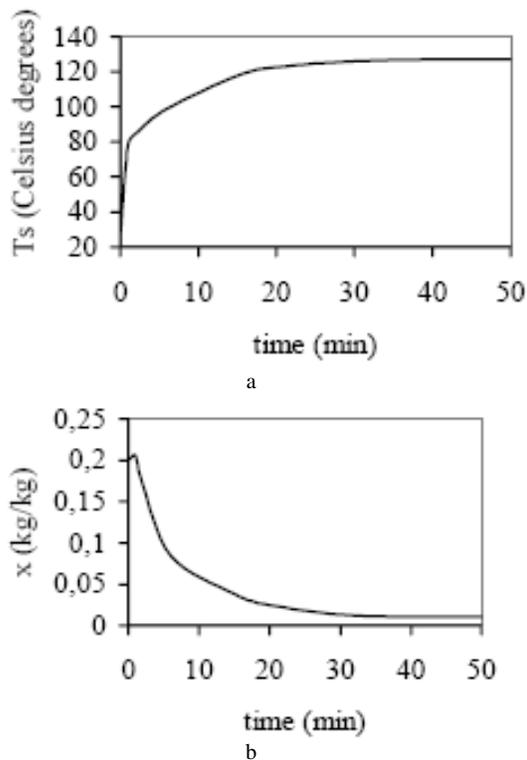


Fig. 6. The evolution of the average pellet parameters- desorption operation

4. CONCLUSIONS

The evolutions of the local and average parameters of the adsorbent pellet reveal the dynamics of the transfer processes and offer valuable information concerning the optimization possibilities of sorption operation. Thus, the model can be used to study the role of the particle size and of the desiccant material type. The work presented in this paper represents the second stage of a theoretical approach of the heat and mass transfer processes which occur within the packed bed adsorbers in fixed or rotary alternatives. In the first stage, a method for numerical simulation of the adsorber operation, based on the assumption of homogeneous pellet parameters, was proposed [7].

The authors plan to develop an integrated model for evaluation the adsorber performances beginning with the transfer processes at the particle level. Thus, the profoundness of the theoretical analysis and the accuracy of the numerical results will increase significantly.

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