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Heat and Mass Transfer in Desiccant Wheels

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1. Introduction

1.1 Background

Nowadays the interest in heating, ventilation, air-conditioning and refrigerating systems (HVAC&R) based on desiccant wheels is increasing due to the possibility of using renewable energy sources, making them an attractive alternative or complement to conventional systems. The thermally driven desiccant systems can potentially reduce the peak electricity demand and associated electricity infrastructure costs. They generally incur in higher initial cost compared with equivalent conventional systems, but cost reduction can be achieved at the design stage through careful cycle selection, flow optimisation and size reduction.

The performance of these systems can be evaluated by experimental or numerical approaches. To date there still exists a lack of data of real manufactured wheels enabling to perform a dynamic energy analysis of such alternative systems with reasonable accuracy at design stage.

The data given by the manufacturers of desiccant wheels are usually restricted to particular sets of operating conditions. Besides, the available software for sizing is usually appropriate to run only stationary operating conditions. For these reasons, it is recognized the importance of the use of a simple predicting method to perform the dynamic simulation of air handling units equipped with desiccant wheels.

In this chapter, the results of a detailed numerical model are used to determine the effectiveness parameters for the coupled heat and mass transfer processes in desiccant wheels, allowing the use of the effectiveness method as an easy prediction tool for designers.

1.2 General characterization and modelling aspects

Desiccant wheels are air-to-air heat and mass exchangers used to promote the dehumidification of the process airflow. The rotor matrix, as illustrated in Fig. 1, is compact and mechanically resistant, and consists of a high number of channels with porous desiccant walls. The rotation speed of the wheel is relatively low. The hygroscopic matrix is submitted to a cyclic sequence of adsorption and desorption of water molecules. The regeneration process of the matrix (desorption) is imposed by a hot airflow. In each channel of the matrix, a set of physical phenomena occurs: heat and mass convection on the gas side as well as heat and mass diffusion and water sorption in the desiccant wall. The regeneration airflow should be heated by recovering energy from the system and using renewable energy sources whenever possible.

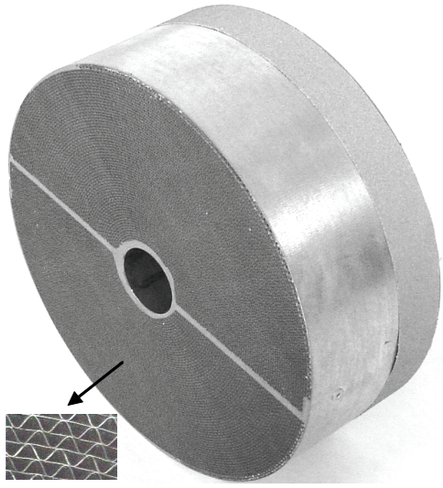


Fig. 1. Desiccant wheel and detail of the porous structure of the matrix

In the schematic representation of a desiccant wheel in Fig. 2, airflow 1 (process air) and airflow 2 (regeneration air) cross the matrix in a counter-current configuration, with equal or different mass flow rates. The desorption zone is generally equal or smaller than the adsorption zone.

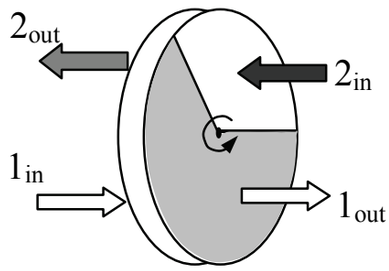


Fig. 2. Desiccant wheel (- Adsorption zone; - Desorption zone)

The approaching airflows in each zone can present instabilities and heterogeneities and are generally turbulent. However, the relatively low values of hydraulic diameter of the channels (frequently less than 5 mm) together with moderate values of the frontal velocity (usually between 1 and 3 m s^{-1}) impose laminar airflows. Besides, in very short matrixes, the entrance effects can be relevant, particularly for larger hydraulic diameters of the channels.

During the adsorption/desorption cycle, the matrix exhibits non uniform distributions of adsorbed water content and temperature, and the angular gradients depend on the constitution of the wall matrix and also on the rotation speed.

The desiccant wheels are mainly used in dehumidification systems to control the humidity of airflows or the indoor air conditions in process rooms of some industries. Fig. 3.a schematically represents a system with a heating coil, operating by Joule effect, or actuating as a heat exchanger, to heat the regeneration airflow. In Fig. 3.b, a desiccant hybrid system with two stages of air dehumidification is shown. The first stage occurs in a cooling coil of the compression vapour system and the second corresponds to the adsorption in the desiccant wheel. The heat released by the condenser is recovered to heat the regeneration airflow, improving the global efficiency of the system.

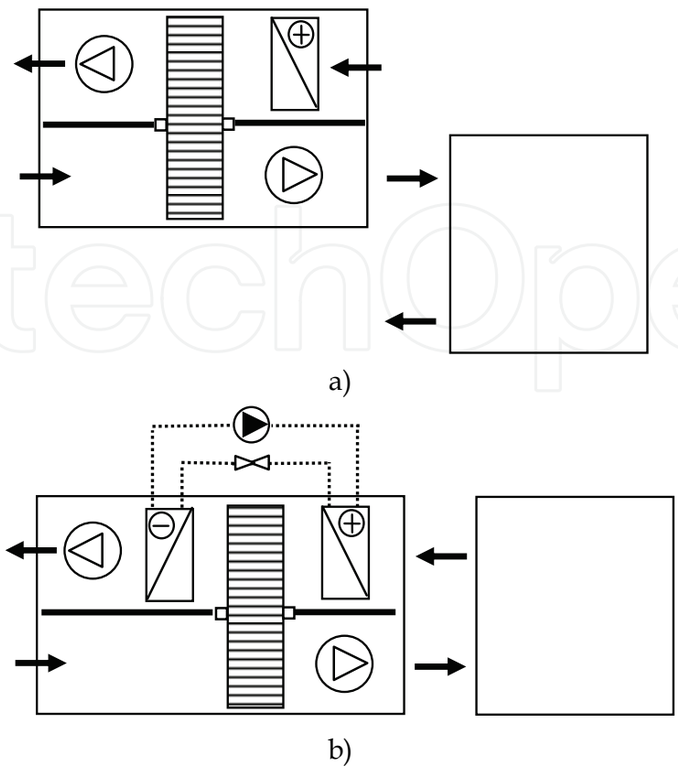


Fig. 3. Dehumidification systems based on desiccant wheels: a) simple dehumidification system and b) hybrid dehumidification system

Another possible interesting application, although less common, is for air cooling operations, combining the evaporative cooling with the solid adsorption dehumidification, as schematically represented in Fig. 4.

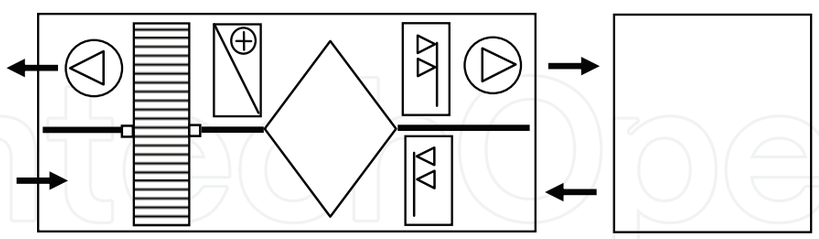


Fig. 4. Desiccant evaporative cooling system

The moisture removal capacity of the desiccant wheel can exhibit significant time variations according to the load profile and weather conditions, a fact that must be taken into account at design stage. On the other hand, the operational costs depend on the control strategy chosen for the system. The capacity control alternatives can be based on: *a)* fan modulation, *b)* by-pass of the process airflow or of the regeneration airflow, *c)* modulation of the heating device for regeneration or *d)* modulation of the rotation speed of the wheel. The strategies based on variable airflow by fan modulation are generally more efficient, presenting higher potential to reduce the running costs.

Different numerical modelling methods of solution supported by different simplified treatments of the flow and the solid domains have been used. Several numerical difficulties are related with the coupling between the different phenomena and the computational time consumption, mainly in detailed numerical models. One crucial aspect is the characterization of the matrix material of the desiccant wheel, namely the knowledge of its thermal properties, diffusion coefficients, phase equilibrium laws, hysteresis effects, etc. In Pesaran (1983), the study of water adsorption in silica gel particles is focussed on the importance of the internal resistances to mass transfer. The investigation of Kodama (1996) deals with the experimental characterization of the matrix of a desiccant rotor made of a composite desiccant medium, a fibrous material impregnated with silica gel.
It is recognized the importance of validating the numerical models by comparison with experimental data, necessarily covering a wide range of conditions, but the published data on this matter are scarce. In some cases, the degree of accuracy of the measured results is not indicated and, in other works, a poor degree of accuracy is reported. Moreover, some examples of exhaustive experimental research on the behaviour of a desiccant wheel (Cejudo et al., 2006) show significant mass and energy imbalances between the regeneration and the process air streams.

1.3 Real and ideal psychrometric evolutions

An example of the psychrometric evolutions in both air flows is schematically represented in Fig. 5. A decrease of the water vapour content and a temperature increase of the process air are observed and opposite changes are observed in the regeneration air.

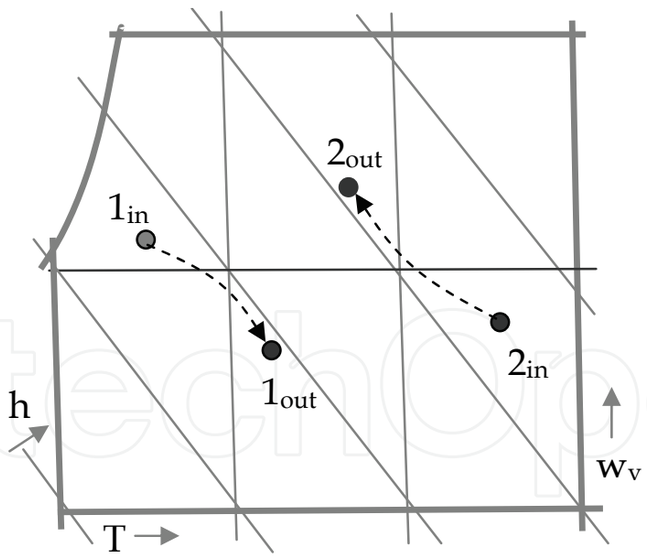


Fig. 5. Psychrometric evolutions of the airflows in a desiccant wheel

The outlet states of both airflows are influenced by the rotation speed, the airflow rates, the transfer area in the adsorption and the desorption zones of the wheel, the thickness of channel wall and its properties. The expected influence of the channel length and of the adsorption/desorption cycle duration on the outlet states of both airflows is schematically represented in Fig. 6, for the particular case of equal mass flow rates. The outlet state of each

airflow is defined by the interception of the isolines of the channel length L_c and of the cycle duration τ_{cyc}. The solid curves L_{c1}, L_{c2} and L_{c3} correspond to rotor matrix with short, medium-length and long channels, respectively. The solid curves τ_{cyc1}, τ_{cyc2} and τ_{cyc3} correspond to low, medium and high cycle durations, respectively. For each channel length an optimum value of the cycle duration exists, i.e. the optimum rotation speed that maximizes the dehumidification rate. This optimal rotation diminishes with the channel length.

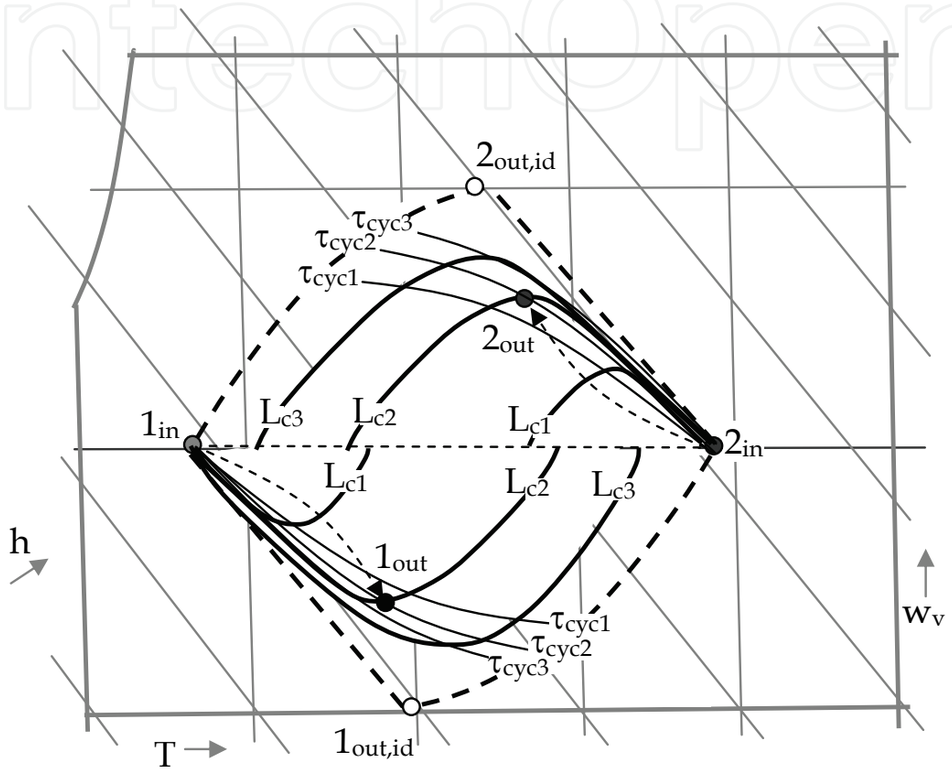


Fig. 6. Influence of the channel length and of the cycle duration on the psychrometric evolutions

The ideal behaviour of a desiccant wheel corresponds to cases with infinite transfer area of the channel. It is common to take the maximum ideal dehumidification rate as a reference, the corresponding outlet states being represented in Fig. 6 by $1_{out,id}$ and $2_{out,id}$. The identification of the ideal outlet states requires the knowledge of the equilibrium curves of the hygroscopic matrix, i.e. the sorption isotherms. Such information is schematically represented in Fig. 7 by the adsorbed water content X_ℓ as a function of the water vapour content w_v and of the temperature T.

The adsorbed water content in the hygroscopic matrix at the equilibrium condition imposed by the inlet state of the process airflow corresponds to the ideal maximum value. The minimum value of the adsorbed water content that can be achieved in ideal operating conditions is dictated by the inlet conditions of the regeneration airflow. The horizontal lines c′1out and c′2out in Fig. 7 represent those minimum and maximum values, respectively, and correspond to the dashed curves c′1out and c′2out in Fig. 8. In most hygroscopic

matrices, those curves correspond to constant or quite constant values of the ratio of the water vapour partial to saturation pressure (p_v/p_{vs}). This ratio corresponds strictly to the relative humidity concept of the moist air only in the cases where the temperature of the moisture air is lower than the water saturation temperature at local atmospheric pressure (ASHRAE, 1989).

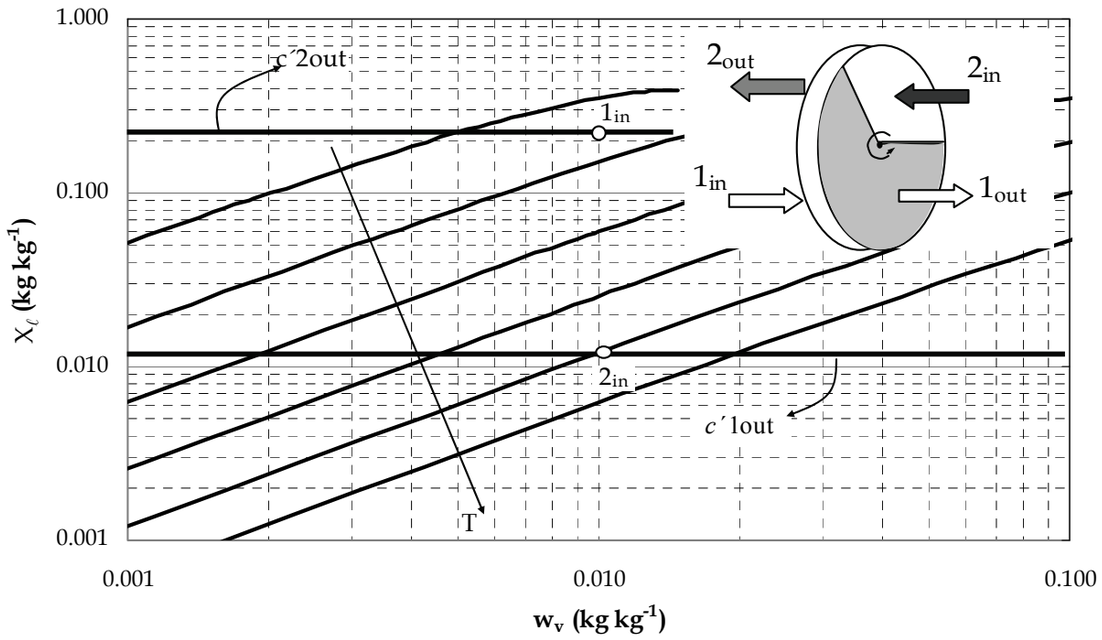


Fig. 7. Representation of the equilibrium curves between the desiccant and the moist air

The ideal outlet state of the process air ($1_{out,id'}$) is defined by the interception of the curve c′1out with the line of constant specific enthalpy h_{1in}. In a similar way, the ideal outlet state of the regeneration air ($2_{out,id'}$) is defined by the interception of the curve c′2out with the line of constant specific enthalpy h_{2in}. Consequently, the ideal (maximum) mass transfer rates are in a first step estimated as:

$$\dot{m}_{w1,id'} = \dot{m}_1 \left(w_{1in} - w_{1out,id'} \right) \tag{1.a}$$

and

$$\dot{m}_{w2,id'} = \dot{m}_2 \left(w_{2out,id'} - w_{2in} \right), \tag{1.b}$$

which can most probably present different values, the lower value indicating the limiting airflow (hereafter called *critical airflow*). The equality between the mass transfer rates in both airflows is imposed by the principle of mass conservation, which implies the redefinition of the outlet ideal sate of the non-critical airflow ($1_{out,id}$ or $2_{out,id}$). This rationale is illustrated in Fig. 8, a case where the critical airflow is the process air (airflow 1).

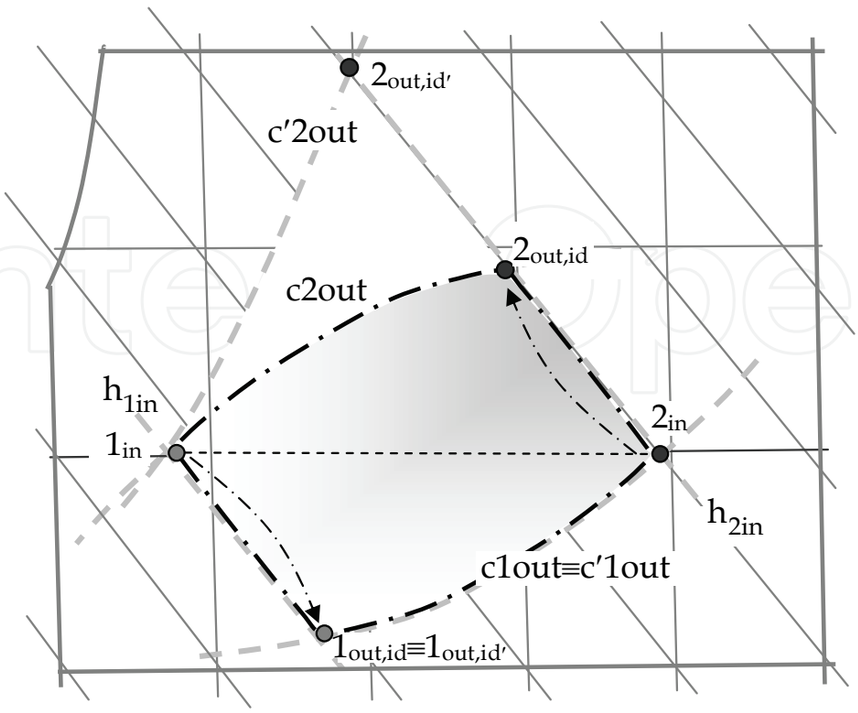


Fig. 8. Ideal air evolutions in a desiccant wheel, where the critical airflow is the process air

1.4 Pair of effectiveness parameters

Following the classical analysis of the behaviour of heat exchangers, the concept of effectiveness results from the comparison between a real heat exchanger and an ideal one adopted as a reference. The application of the so-called *effectiveness method* to a desiccant wheel requires the use of two effectiveness independent parameters due to the existence of the simultaneous and coupled processes of heat and mass transfer. Furthermore, those parameters should be quite independent of the inlet states of both airflows or, at least, easily correlated with them.

The use of the effectiveness method has practical interest, mainly to perform quick simulations of desiccant wheels, but it needs the prior knowledge of the ideal outlet conditions or of the ideal transfer rates, as described in the previous section.

The deviation of the outlet states of both airflows relatively to the ideal ones, as illustrated in Fig. 6, is an indicator of the effectiveness of the heat and mass transfer phenomena in the desiccant wheel. So, the state changes registered in both airflows in a real application should be compared with those of the ideal operation. Taking into account the analogy with the classical analysis of heat exchangers, the following generic definition for the effectiveness is purposed:

$$\eta_{\phi} = \frac{\phi_{1in} - \phi_{1out}}{\phi_{1in} - \phi_{1out,id}} = \frac{\phi_{2in} - \phi_{2out}}{\phi_{2in} - \phi_{2out,id}}, \tag{2}$$

where the generic variable ϕ can assume different meanings such as the adsorbed water content at equilibrium between the moist air and the desiccant.

According to preliminary investigation, the recommended independent parameters for a desiccant wheel are those based on the changes of adsorbed water content X_ℓ (kg of adsorbed water/kg of dry desiccant,) and of the specific enthalpy h (J/kg of dry air), respectively, $\eta_{X\ell}$ and η_h. Taking into account, for example, the changes occurring in the process airflow, $\eta_{X\ell}$ can be calculated by:

$$\eta_{X\ell} = \frac{X_{\ell,1in} - X_{\ell,1out}}{X_{\ell,1in} - X_{\ell,1out,id}}, \tag{3}$$

where $X_{\ell,1out,id} = X_{\ell,2in}$. Concerning the evaluation of η_h, it is not possible to consider that $h_{1out,id} = h_{1in}$. So the following definition is proposed, by convenience:

$$\eta_h = \frac{h_{1in} - h_{1out}}{h_{1in} - h_{2in}}. \tag{4}$$

At real conditions, it is expected that both effectiveness parameters exhibit a dependence on the airflow rates, channel length and rotation speed, as well on the inlet states of both airflows. In an optimized case, operating near the ideal conditions, the effectiveness parameter η_h should be low, near zero, while $\eta_{X\ell}$ should be as high as possible, near the unity, the dependence on the operating parameters and conditions being quite negligible. The application of the effectiveness method is highly helpful in perform quick energy dynamic simulations of HVAC&R systems integrating desiccant wheels at the design stage, thus promoting the use of more efficient systems that allow the incorporation of renewable energy or waste energy recovery.

2. Modelling of desiccant wheels

2.1 Objectives and outline

The aim of this chapter consists mainly of the use of a detailed numerical model to study the behaviour of desiccant wheels. Focused on a representative channel of a compact matrix, which is hypothetically treated as a parallel-plate channel, the detailed mathematical formulation takes into account the important changes of properties in both the porous solid and airflow domains that generally occur in transient sorption processes.

Although the detailed model is not an appropriate tool to perform the dynamic simulation of a real desiccant wheel, due to its complexity and the required computational effort, it is an interesting complementary tool to be used in the product optimization by the manufacturer, in the investigation of the validity of the assumptions supporting simplified models (e.g., the lumped capacitance method) and also to evaluate the dependence of the effectiveness parameters on the operating parameters and conditions.

2.2 Detailed numerical modelling of a representative channel

The physical domain of the hygroscopic wheel can be considered as a set of small angular slices, the channels in each slice having the same behaviour. The transient three-dimensional problem is too complex to be solved in a very detailed way and, therefore, it is necessary to adopt a set of simplifications. The most common simplification about the physical domain is the consideration of two-dimensional airflow between desiccant parallel plates. The

hypothesis of two-dimensionality, together with the consideration of cyclic inlet conditions, real wall thickness and ratio of airflow rate to wetted perimeter is frequently adopted when modelling the behaviour of desiccant wheels (Dai et. al, 2001 and Zhang et al., 2003).
The wall domain of a channel of the hygroscopic matrix is modelled in a detailed way, by taking into account the simultaneous heat and mass transfer together with the adsorption/desorption process. Fig. 9 illustrates the physical domain of the channel to be modelled. Two phases co-exist in equilibrium inside the desiccant porous medium, the equilibrium being characterized by sorption isotherms. The ordinary diffusion of vapour is neglected due to the small dimension of the pores (Pesaran, 1983). Therefore, only two mechanisms of mass transport are considered: surface diffusion of adsorbed water and Knudsen diffusion of water vapour. For simplification purposes, the wall is considered to be a homogeneous desiccant porous material. The upper boundary of the domain is considered impermeable and adiabatic. The treatment of the airflow as a bulk flow and the use of suitable convective heat and mass transfer coefficients are considered to evaluate the exchanges occurring at the interface between the airflow and the desiccant wall surface.

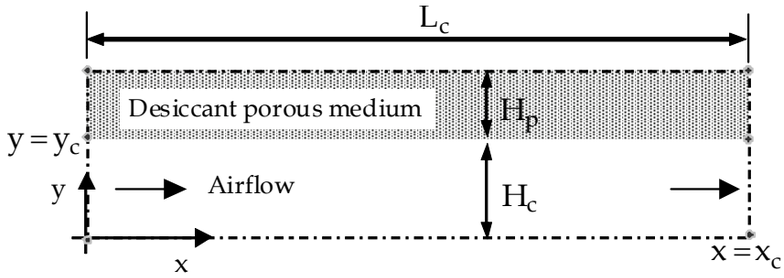


Fig. 9. Physical domain of the modelled channel

For the wall domain, the complete set of conservation equations to be solved by the model can be reduced to the general form:

$$\frac{\partial}{\partial t}\left(\rho_\phi \phi\right) + \frac{\partial}{\partial x_j}\left(-\Gamma_\phi \frac{\partial \phi}{\partial x_j}\right) - S_\phi = 0\,, \tag{4}$$

where the density ρ_ϕ, the diffusion coefficient Γ_ϕ and the source-term S_ϕ assume different meanings depending on the nature of the generic variable ϕ considered ($\phi = X_\ell$ - mass conservation equation of adsorbed water, $\phi = T$ - energy conservation equation, $\phi = \varphi_v$ - mass conservation equation of water vapour). According to the local equilibrium condition assumption, only one of the two differential mass conservation equations is solved, the mass conservation equation for water adsorbed water. The mass fraction of water vapour inside the porous medium φ_v is calculated through the knowledge of the sorption isotherm.
For the airflow domain, the simplified one-dimensional conservation equation is considered:

$$\frac{\partial}{\partial t}\left(\rho_f \phi\right) + \frac{\partial}{\partial x}\left(\rho_f u_f \phi\right) - S_\phi = 0 \tag{5}$$

where the source-term S_ϕ assumes also different meanings depending on the nature of the generic variable ϕ considered ($\phi = 1$ - global mass conservation equation, $\phi = \varphi_v$ - mass conservation equation of water vapour, $\phi = T$ - energy conservation equation, $\phi = u_f$ -

momentum conservation equation). At the interface ($y = y_c$), the mass and heat convection transfers are modelled assuming that the low mass transfer rate theory is valid (Bird, 1960 and Mills, 1994). The heat convection coefficient h_h is estimated after the Nusselt number Nu for developed laminar channel flow. As for the mass convection coefficient h_m, the Sherwood number Sh is related to Nu according to the Chilton-Colburn analogy. The convective fluxes at the interface are calculated as:

$$j_{v,gs} = h_m \rho_f \frac{\varphi_{v,f} - \varphi_{v,i}}{1 - \varphi_{v,i}} \tag{6}$$

$$j_{h,gs} = h_h \left(T_f - T_i \right) \tag{7}$$

where $\varphi_{v,i}$ and T_i are values at the interface, respectively, for the vapour mass fraction and the temperature.

The water vapour content in the airflow or inside the pores of the desiccant medium is related with the mass fraction of water vapour by $w_v = \varphi_v / (1 - \varphi_v)$.

The modelling of a channel requires the definition of the initial conditions and of the conditions of the airflow entering the channel. The initial conditions are imposed by specifying uniform distributions of T and X_ℓ in the desiccant wall. The airflow domain is assumed to be initially in thermodynamic equilibrium with the desiccant wall. The condition of the airflow entering the channel is imposed by specifying the inlet velocity of the airflow $u = u_{in}$ (or the corresponding mass inlet velocity, $F_m = F_{m,in}$), as well the inlet temperature T_{in} and the water vapour fraction $\varphi_{v,in}$. The total pressure is assumed to be constant and its value is imposed.

The numerical solution procedure is based on the solution of the discretized partial differential equations using the finite volume method. The values of the diffusion coefficients at the control-volume interfaces are estimated by the harmonic mean, thus allowing the conjugate and simultaneous solution in both gas and solid domains (Patankar, 1980). The energy and the vapour mass transport equations are solved in a conjugate procedure that covers simultaneously both sub-domains. Within the desiccant wall sub-domain, the equilibrium value of the vapour mass fraction is locally specified.

Additional data and the complete description of the formulation of different versions of the model can be found in previous works (Ruivo et al, 2006; Ruivo et al, 2007[a,b]; Ruivo et al, 2008[a,b] and Ruivo et al. 2009). The numerical model has been used in simulating the cyclic behaviour of a typical channel of desiccant wheels and also the behaviour of a wall element of the channel, namely to inspect the validity of some assumptions that support simplified numerical methods.

2.3 Prediction of the behaviour of desiccant wheels

The behaviour of the modelled channel enables the prediction of the global behaviour of the desiccant wheel crossed by two airflows at steady state conditions. The adsorption mode corresponds to the adsorption zone of the rotor matrix, where the dehumidification of the process airflow occurs, while the desorption mode corresponds to the desorption zone, where the rotor matrix is regenerated. The cyclic process with a duration τ_{cyc} is divided into the adsorption and the desorption modes, with durations τ_{ads} and τ_{des}. From the point of

view of the modelled channel, the desorption and the adsorption processes occur, respectively, when $0 < t \leq \tau_{des}$ and $\tau_{des} < t \leq \tau_{cyc}$. The modelled channel that is representative of the matrix is submitted to an initial transient process that must be started at a certain condition. The transition of mode, from desorption to adsorption, or vice-versa, is done by suddenly changing the inlet airflow conditions and reversing the airflow direction in the channel. After a certain number of desorption/adsorption cycles, the differences between two consecutive cycles are negligible, meaning that the stationary cyclic regime was achieved.

The initial condition for the sequence of the cycles corresponds to the beginning of one of the modes of the cycle (desorption or adsorption), imposing uniform distributions for temperature and adsorbed water content in the desiccant and assuming that the airflows are initially in thermodynamic equilibrium with the desiccant medium.

At steady state conditions, the mass transfer rate occurring in the desorption zone is equal to that occurring in the adsorption zone. Therefore, considering the desorption mode, the following expressions can be deduced, respectively, for the mass and heat transfer rates between both airflows, per unit of transfer area of the matrix:

$$\dot{J}_{v,gs} = \frac{1}{x_c} \int_0^{x_c} j_{v,gs} dx \tag{8}$$

$$\dot{J}_{h,gs} = \frac{1}{x_c} \int_0^{x_c} j_{h,gs} dx \tag{9}$$

The global mass and heat transfer rates in the desiccant wheel at steady state operating conditions, per unit of transfer area of the matrix, are:

$$\dot{J}_m = \int_0^{\tau_{des}} \frac{\dot{J}_{v,gs}}{\tau_{cyc}} dt \tag{10}$$

$$\dot{J}_h = \int_0^{\tau_{des}} \frac{\dot{J}_{h,gs}}{\tau_{cyc}} dt \tag{11}$$

At the outlet of each zone, the air state exhibits a non uniform angular distribution. The downstream average of temperatures and of water vapour contents at the outlet of the channel in each operation mode are evaluated, the achieved values representing the outlet states of the regeneration and process airflows crossing the desiccant wheel at steady state condition (Ruivo, 2007b).

2.4 Properties and coefficients

The numerical model takes into account the changes occurring in the airflow properties and in the convection and diffusion coefficients. The major part of the relations for the dry air, water vapour and liquid water was derived from thermodynamics tables (Çengel, 1998) in the form of polynomial expressions (Ruivo, 2005). The properties of the air-mixture such as the specific heat and the thermal conductivity are weighted averages based on the dry air and water vapour mass fractions. Similarly, the specific heat and the thermal conductivity of

the wet desiccant medium are weighted averages based on the mass fraction of each component (dry-air, water vapour, adsorbed water and dry desiccant).
The properties of silica gel RD, the relations for the equilibrium condition, the heat of wetting, the adsorbed water enthalpy and the adsorption heat are indicated in Ruivo et al. (2007[a]). The dependences of the mass diffusion coefficients on the temperature and on the adsorbed water content are also presented in Ruivo et al. (2007[a]), and were derived after the expressions in Pesaran (1983). The equilibrium curve for the pair silica gel-moist air is represented in Fig. 10.

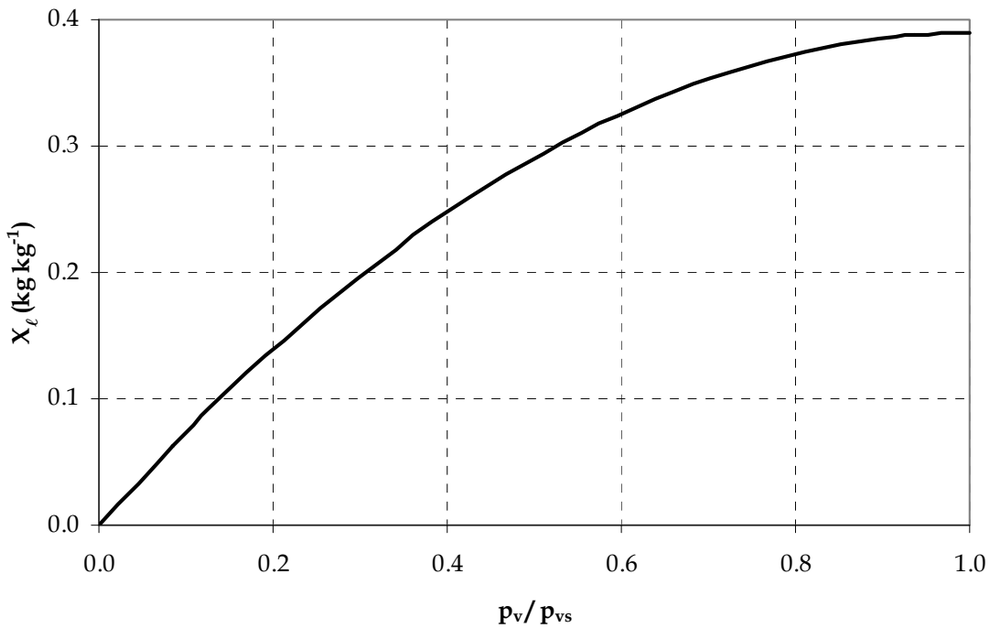


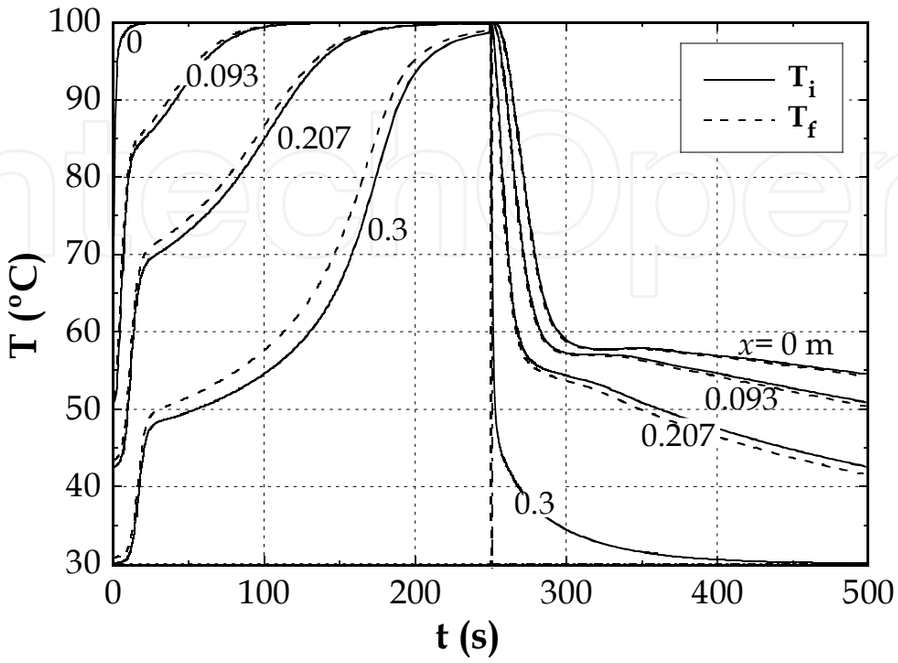
Fig. 10. Equilibrium curve for the pair silica gel-moist air

3. Study cases and results

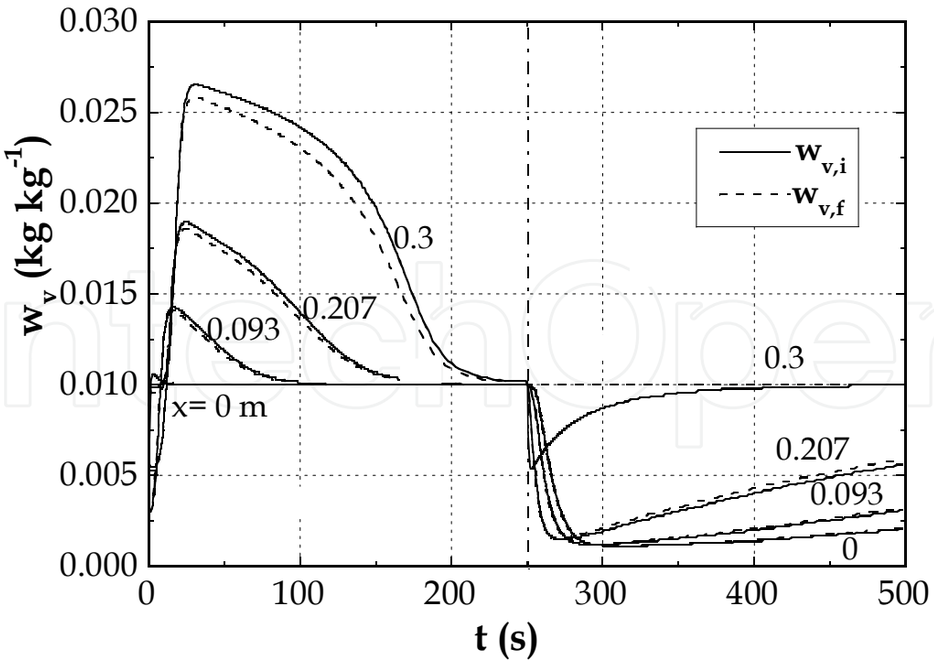
3.1 Prediction of the performance of desiccant wheels

One of the potentialities of the present numerical model is the calculation of the transient evolutions of the internal fields of temperature and of water vapour content, both in the airflow and in the channel wall domains. Different parametric studies have been conducted using the numerical model to investigate the influence of a set of parameters, namely the rotation speed, the cell dimensions, the wall thickness, as well as the inlet conditions of both airflows, on the behaviour of desiccant wheels (Ruivo, 2005 and Ruivo et al. 2007[b]). The research done by using such detailed numerical model gives to the manufacturers important guidelines to the optimization of the desiccant dehumidification equipments. Moreover after calibration by comparison with experimental data, the detailed numerical models are also an interesting tool to generate data of global performance of desiccant wheels, namely the outlet state of both airflows or the heat and mass transfer rates for a large set of operating conditions. The achieved global behaviour data can be displayed in a chart or in a table, represented by correlations or be used to test the validity of easy and quick predicting methods. This information is very helpful for a more accurate sizing of the dehumidification

and/or cooling installations and to analyse dynamically different solutions, namely to investigate the control strategies that lead to a better energy use.



a)



b)

Fig. 11. Cyclic evolutions of the interface and of the airflow states: (a) temperature and (b) water vapour content

The data plotted in Fig. 11 concern to the internal behaviour of a desiccant wheel composed by a compact corrugated matrix with sinusoidal cross section channels. The specific transfer area and the porosity of the matrix are 3198 $m^2 m^{-3}$ and 0.84, respectively. According to Ruivo et al. (2007b), the chosen matrix corresponds to cell B3 ($H_{cell} = 1.5$ mm, $P_{cell} = P_{sin} = 3$ mm, $E_p = 0.1$ mm, $H_{sin} = 1.27$ mm), the representative channel of the matrix being modelled with $H_p = 0.05$ mm and $H_c = 0.263$ mm. The channel length is $L_c = 0.3$ m. The rotor speed is 7.2 rotations per hour, that corresponds to $\tau_{cyc} = 500$ s. The desiccant wheel is divided into two equal parts, the adsorption and desorption zones being crossed by counter-current airflows. The desiccant is silica gel. The inlet temperatures of the process and regeneration airflows are 30 ºC and 100 ºC, respectively. Equal values of the inlet water vapour content (0.01 kg kg^{-1}) and of the mass inlet velocity (1.5 kg s^{-1} m^{-2}) are imposed to both airflows.

The illustrated time evolutions of the states of the interface and of the bulk airflow evidence the abrupt variations in the mode transition. From the temperature and the moisture content evolutions (Figs. 11.a and 11.b), it can be observed that the airflow and the wall are closely in thermodynamic equilibrium in most of the rotor domain, a condition that is sometimes taken as a simplifying hypothesis in the behaviour analysis of ideal desiccant wheels (v., e.g., Van den Bulk, (1985)). It can also be seen that only in the desorption mode the channel wall surface achieves equilibrium with the incoming air, an indication that the regeneration process is completed. This suggests that it is possible to optimise the dehumidification performance of the rotor through the changes of the rotation speed and of the adsorption and desorption zones.

Other cases with different cycle durations were simulated. The registered influence of τ_{cyc} on the global heat and mass transfer rates is shown in Fig. 12. The heat transfer rate exhibits a monotonic decreasing trend with the cycle duration while a maximum value of the mass transfer rate is observed.

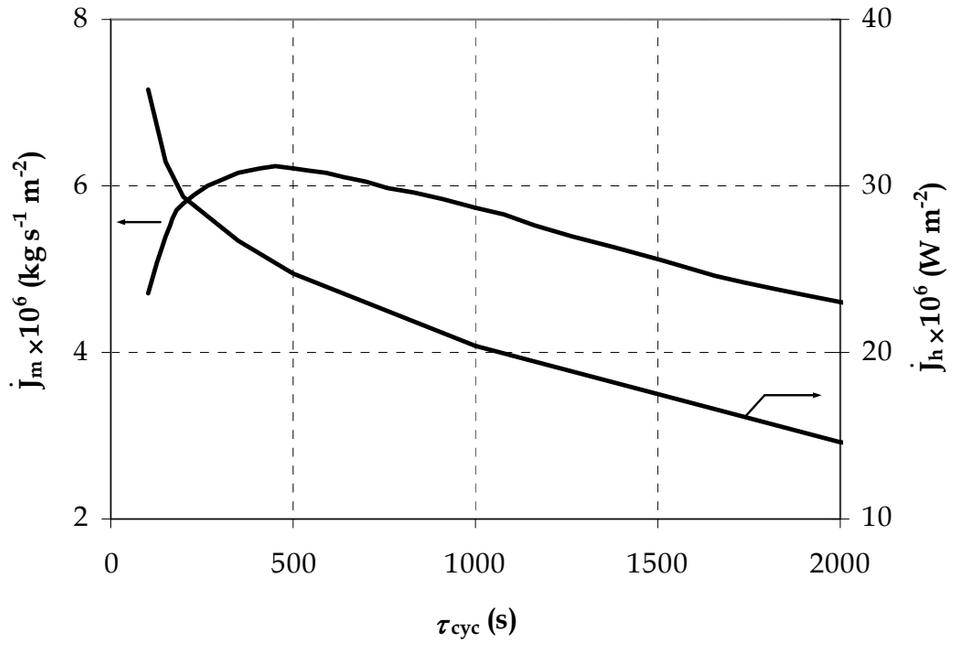


Fig. 12. Heat and mass transfer rates per unit of transfer area of the desiccant wheel

3.2 Test of simplifying assumptions for numerical modelling

Several studies have been carried out to predict the behaviour of desiccant wheels using simplified mathematical models (e.g. Zheng, 1993; Dai et al., 2001; Zhang et al. 2003 and Gao et al. 2005). In most of them, the heat and mass transfers inside the desiccant medium are not described in a detailed way, simplified approaches being adopted instead. The range of validity of such models can be investigated by using experimental techniques and by detailed numerical modelling. The air stream behaviour and its interaction with the desiccant medium are also often treated in a simplified way, namely by assuming a fictitious bulk flow pattern, as well as fictitious heat and mass convection coefficients for the gas side.
When advanced numerical methods are used, solving the complete set of differential transport equations, a number of critical issues still remain, such as the lack of suitable functions to describe the variation of the porous medium properties and the complexity of numerically solving the intrinsically coupled phenomena within the porous desiccant solid and the great time consumption of computational calculations.
In the present section, the numerical detailed model is used to simulate the physical behaviour of the desiccant layer of a wall element of the channel. It is also supposed that the desiccant layer belongs to the channel wall of a compact desiccant matrix, which is crossed by a moist air flow. The hypothesis of one-dimensionality assumed in this study is mainly intended to better identify the effects to be analysed, namely the importance of neglecting the internal heat and mass diffusive resistances. The physical model is schematically represented in Fig. 13.

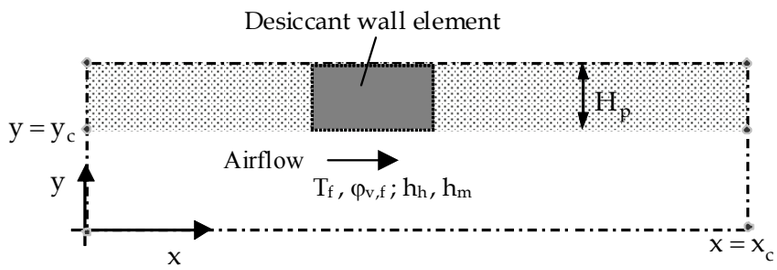
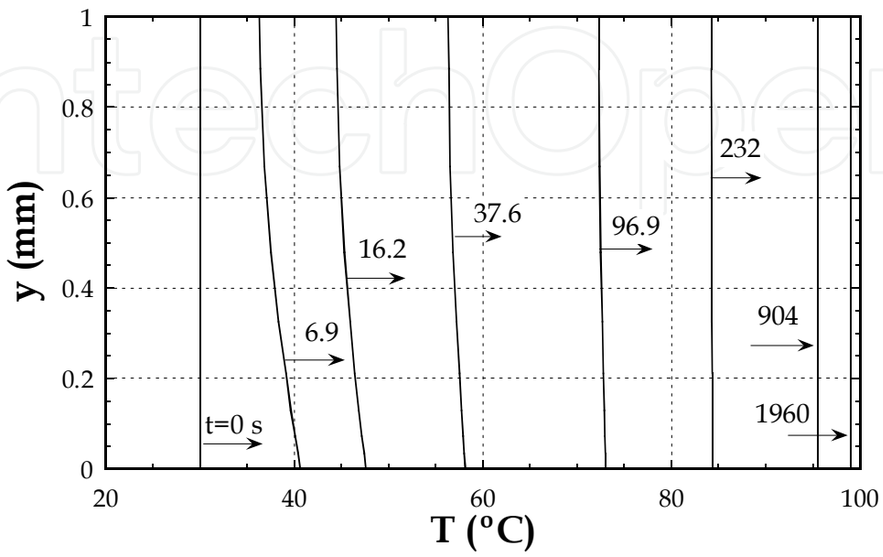


Fig. 13. Schematic representation of the channel wall element

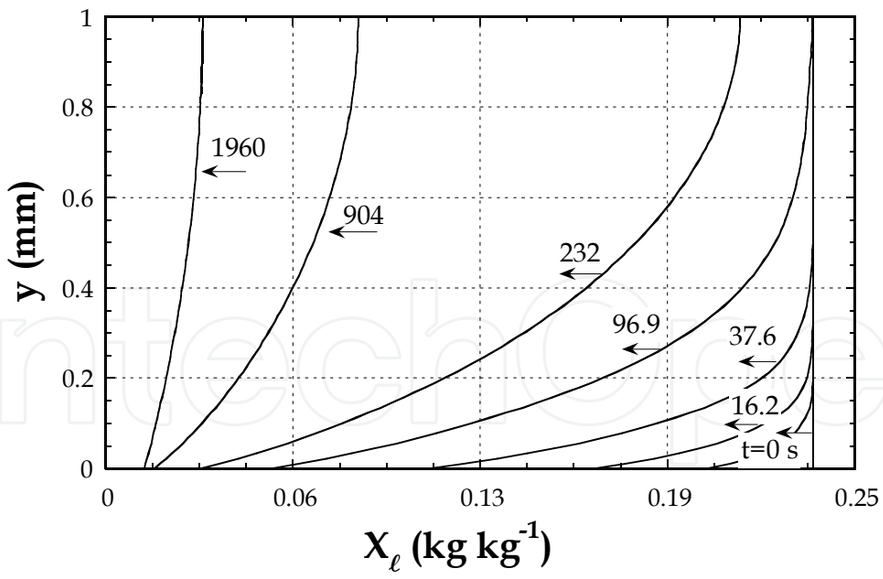
For the assessment of the internal resistances of the porous medium in the cross direction, there is no interest to consider the streamwise variation of the flow properties. Therefore the physical domain is reduced to an element of the channel wall, which is considered as a homogeneous desiccant medium, having the properties of silica-gel and an infinitesimal length in the flow direction. The heat and mass transfer phenomena inside the porous medium are considered only in the y direction.

The air stream in contact with the infinitesimal-length wall element is treated as a well mixed flow (bulk flow), characterised by constant and uniform properties (pressure, temperature and vapour content), thus dispensing the need of solving any conservation equation in the flow domain.
Results of the investigation about two simplifying approaches based on the lumped-capacitance method (Ruivo et al., 2008[b]) are here presented. The first approach corresponds to the theoretical analysis of the system with negligible internal resistances to the heat and mass diffusion, commonly known as the global lumped-capacitance method (approach A- "null resistances"). It is numerically simulated by specifying enough great values of the

diffusion coefficients (the thermal conductivity and the coefficients of Knudsen diffusion and of surface diffusion). The other approach corresponds only to the thermal lumped-capacitance method (approach B-"null thermal resistance"). It is numerically simulated by imposing an enough great value to the thermal conductivity of the desiccant medium.



a)



b)

Fig. 14. Time-varying profiles of the dependent variables along the desorption process in a desiccant layer of $H_p = 1$ mm: (a) temperature and (b) adsorbed water content X_ℓ

The numerical tests of both simplifying approaches consists of the analysis of the response of the desiccant wall to a step change of the airflow conditions, starting from a given initial

desiccant state and finishing when the desiccant wall achieves the equilibrium with the moist airflow.

The results here presented are for the simulation of the transient process of desorption, where the initial temperature and adsorbed water content in the desiccant were 30ºC and 0.2363 kg kg^{-1}, respectively. The airflow conditions were 100ºC and 0.01 kg kg^{-1}, respectively for the temperature and the water vapour content. The process pressure was assumed as 101325 Pa.

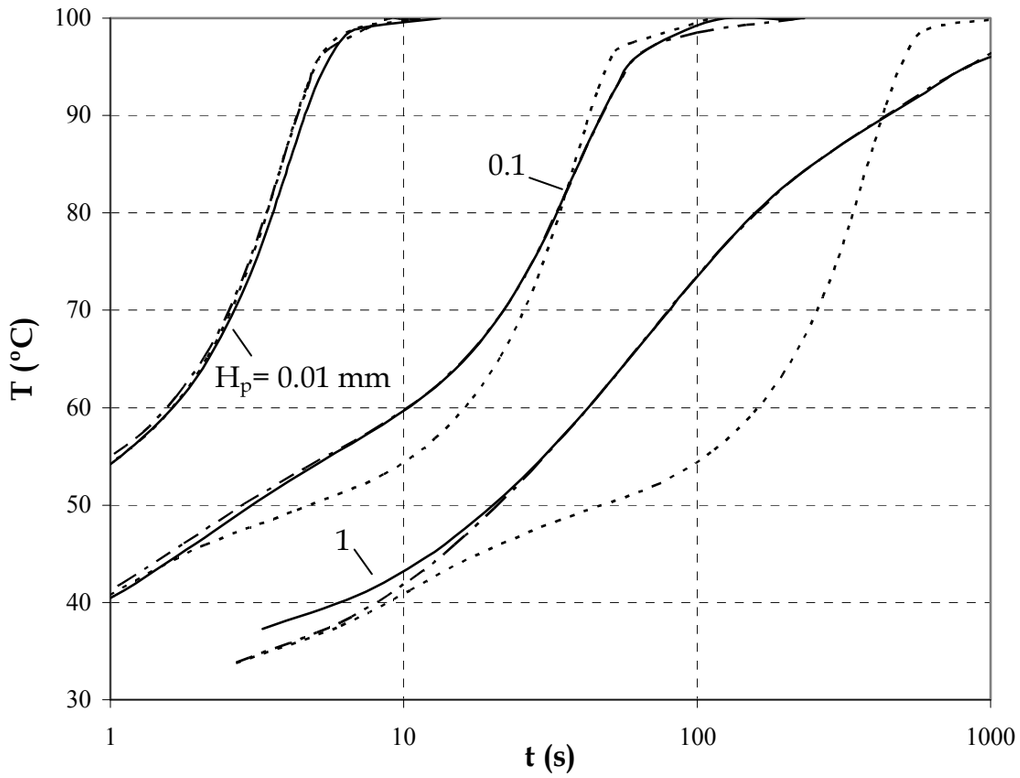


Fig. 15. Predicted temperature at the convective interface considering normal internal resistances (———), null thermal and mass resistances (- - - - - - approach A) and null thermal resistance (-·-·-·- approach B)

The value 2.45 was assigned to the Nusselt number corresponding to heat convection between a uniform temperature wall and a fully-developed laminar flow inside a corrugate sinusoidal-type channel of a compact exchanger (Zhang et al., 2003). The channel cross-section area was 4.5 mm^2, with an internal perimeter of 10.6 mm and a hydraulic diameter of 1.69 mm, approximately. The conducted runs covered a wide range of values of the layer thickness in order to study the validity of neglecting internal thermal and mass resistances and only the thermal resistance. The properties of the desiccant medium were referred also to silica gel RD (Pesaran, 1983). A particular case was selected for the analysis of the transient evolutions of the main variables inside a desiccant layer with 1 mm of thickness. Time-evolving profiles are shown in Figs. 14.a and 14.b as calculated with the "normal"

internal resistances. It is seen that the temperature field presents small gradients, meaning that the internal resistance to heat diffusion is almost insignificant, contrarily to those restricting the mass diffusion. The gradients of the adsorbed water content are significant during almost all the transient process, mainly near the convective surface.

The diagrams in Figs. 15 and 16 show the time evolutions of the temperature and of the adsorbed water content at the interface determined by the detailed model for the three different scenarios: with normal internal resistances, without internal resistances to the heat and mass and without internal resistance to heat conduction. It can be observed that the results of approach A (dashed lines) show an increasing deviation relatively to those of the detailed model (full lines) for desiccant layers with $H_p \geq 0.1$ mm. Moreover, the results of approach B agree reasonably well with the detailed model for all studied wall thicknesses, unlike those of approach A. This indicates that significant inaccuracies may result when the internal resistance to mass diffusion is neglected, leading to unrealistic estimation of the convection fluxes at the interface.

It can be concluded that the heat and mass lumped capacitance assumption supporting the pseudo gas-side model is acceptable for desiccant layers thinner than about 0.1 mm.

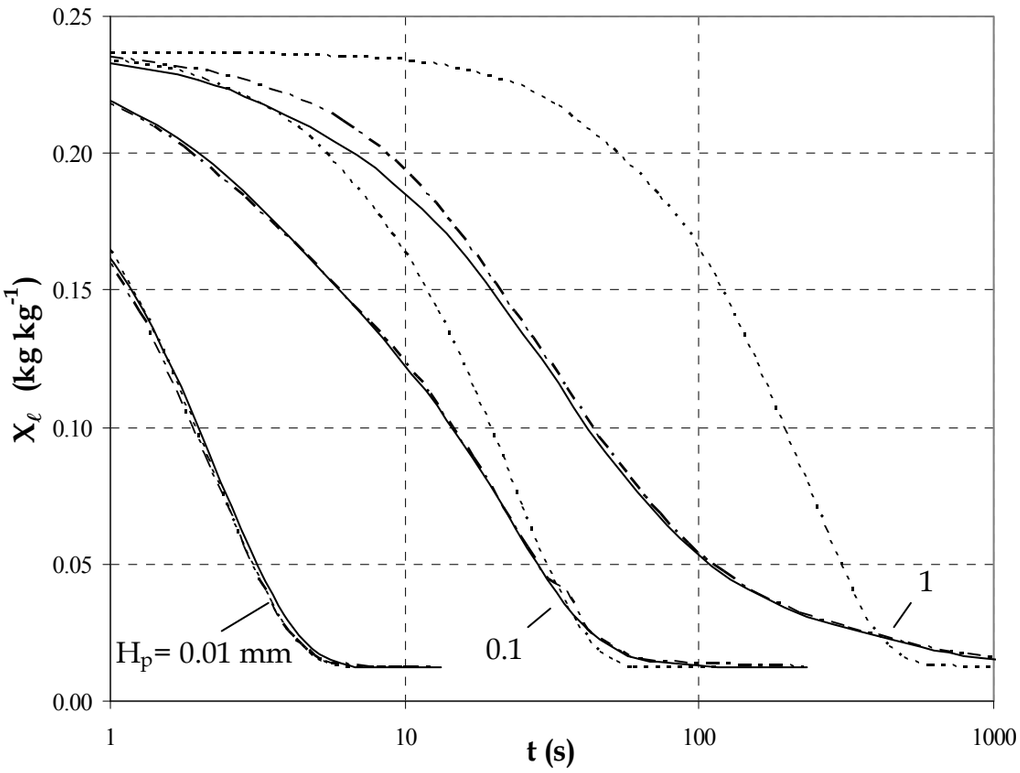


Fig. 16. Predicted adsorbed water content at the convective interface considering normal internal resistances (———), null thermal and mass resistances (- - - - - - approach A) and null thermal resistance (-·-·-·- approach B)

3.3 Assessment of effectiveness parameters

Several assessments of the desiccant wheel effectiveness parameters have been recently conducted based on experimental and numerical modelling data. The cases here presented were generated by the detailed numerical model to investigate the influence of the regeneration temperature on the effectiveness parameters. Different inlet states of the regeneration airflow were considered, corresponding to 80, 100 and 120ºC of temperature, all with the same value of the water vapour content 0.01 kg kg^{-1}. The value of 1.5 kg s^{-1} m^{-2} is considered for the mass inlet velocity of both airflows. The inlet state of the process airflow is defined by a temperature of 30ºC and water vapour content of 0.01 kg kg^{-1}. The desiccant wheel is symmetric. The desiccant is silica gel. The rotor matrix corresponds also to cell B3, i.e, the specific transfer area and porosity of the matrix are 3198 m^{2}m^{-3} and 0.84, respectively. According to Ruivo et al. (2007[b]), the representative channel of the matrix being modelled with H_p =0.05 mm, H_c=0.263 mm. The channel length is L_c=0.3 m.

The rotation speed corresponds to cycle duration of 500 s, close to the optimum value that maximises the dehumidification rate (see Fig. 12). The output results of the detailed numerical model for the different simulated cases are indicated in Table 1. The effectiveness parameters η_h and $\eta_{X\ell}$ presented in Table 2 were calculated, respectively, by the Eqs. 3 and 4.

Case	T_{1in} [ºC]	$w_{v,1in}$ [kg kg^{-1}]	T_{2in} [ºC]	$w_{v,2in}$ [kg kg^{-1}]	T_{1out} [ºC]	$w_{v,1out}$ [kg kg^{-1}]
1	30	0.01	80	0.01	54.89	0.003182
2	30	0.01	100	0.01	60.80	0.002035
3	30	0.01	120	0.01	65.01	0.001478

Table 1. Output results of the detailed numerical model

Case	η_h	$\eta_{X\ell}$
1	0.1519	1.000
2	0.1502	0.999
3	0.1471	0.995

Table 2. Calculated effectiveness parameters η_h and $\eta_{X\ell}$.

The registered inlet regeneration temperature dependence of η_h and $\eta_{X\ell}$ is small, being the constant value corresponding to the average of the values acceptable to use in the in the effectiveness method. It should be remarked that the set of analysed cases does not

represent an exhaustive study. Further research should be done based on additional numerical or experimental modelling data.

4. Conclusions

This Chapter gives an overview of the research towards the prediction of the behaviour of desiccant wheels. Ideal and real psychrometric evolutions of process and regeneration airflows were analysed, and the general trend of the influence of the channel length of the matrix and the cycle duration was presented, as well as the procedure to determine the ideal outlet states of both airflows. This procedure takes into account the curves of equilibrium between the moist-air and the desiccant medium as well as the relation between both airflow rates, and enables the identification of the airflow that limits the process of heat and mass transfer (critical airflow). A new pair of independent parameters for the effectiveness of the coupled heat and mass transfer in desiccant wheels is proposed, the values at ideal operating conditions being physically intuitive, i.e. $\eta_h = 0$ and $\eta_{X\ell} = 1$, and independent of the operating conditions.

A numerical model for simulating the cyclic adsorption/desorption process in a representative channel of the desiccant matrix was briefly referred. The model is based on the solution of the differential equations for the conservation of mass and energy. The airflow is treated as a bulk flow, the interaction with the wall being evaluated by using appropriated convective coefficients. The wall domain is treated in detail, considering the internal time-varying fields of variables and properties. To illustrate the potentialities of the model in predicting the internal behaviour of a desiccant wheel, data that are useful for the manufacturer to product optimization, the results of a particular case were presented. Results of a parametric study were also presented, showing the dependence of the global behaviour of the desiccant wheel on the rotation speed. An expected optimum point maximizing the dehumidification rate was determined. An adapted version of the model to simulate the detailed heat and mass transfer during the adsorption process in a wall element of the channel was used to investigate the validity of simplifying assumptions, namely those that neglect the internal heat and mass diffusive resistances. The results of the parametric study show that the internal resistance to mass diffusion is much more important that the internal thermal resistance. This justifies the use of a simplified method assuming no internal thermal gradients in the desiccant wall in the direction normal to the airflow. The use of a lumped capacitance method for the coupled heat and mass transfer is acceptable only for very thin desiccant wall layers.

Another parametric study of the global behaviour of a desiccant wheel at different regeneration temperatures was presented and its results were used to calculate the effectiveness values, a quite negligible dependence of η_h and $\eta_{X\ell}$ relatively to the regeneration temperature being observed. The adoption of the effectiveness method seems to be an interesting tool, at the same time easy and intuitive, for design purposes.

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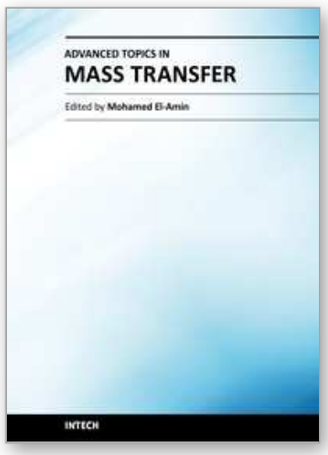
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