A THERMAL MODEL OF A DESSICANT FAÇADE

Francisco Fernández Hernández, José M. Cejudo López, Fernando Domínguez Muñoz, Antonio Carrillo Andrés

Energy Research Group, University of Málaga, Spain

Corresponding author: jmcejudo@uma.es

SUMMARY

In this paper, a novel concept of desiccant unit is investigated. In conventional solid desiccant systems, the desiccant material is mounted on the surface of a rotating wheel that rotates between the process and regeneration streams. In the proposed system, the desiccant material is arranged inside a rectangular channel installed on the building façade. The process stream is the ventilation air for the building. The regeneration stream is hot air coming from an air solar collector integrated in the same channel, underneath the desiccant material. Process and regeneration streams flow alternatively through the desiccant section. The system works as a latent load reducer for the air handling unit.

In a previous work [1], the authors investigated a particular configuration of desiccant façade, in which the desiccant material was coated on the surfaces of the channel. In this paper, the desiccant material is formed into a block that is placed inside the channel. The performance of this new system is analysed by simulation in a Mediterranean climate. The desiccant domain is discretized into five control volumes, in which mass and energy balances are set up in order to calculate the outlet air conditions and the thermal behaviour of the desiccant. The simulations show the capacity of the system for a typical summer day and illustrate the operation of the desiccant channel.

INTRODUCTION

The ventilation load represents an important fraction of the total energy consumption of HVAC systems. Conventional vapour compression refrigeration systems commonly control only the sensible ventilation load, with dehumidification becoming an uncontrolled by-product of the process of reducing air temperature. This can be a problem, for example when the outside air has high water content but its temperature is similar to the set point temperature of the zone. In such a context, a ventilation system able to control both sensible and latent load becomes very interesting when looking for thermal comfort, especially in buildings with high internal gains.

In this paper a new ventilation system is proposed. Air ventilation is circulated through a ventilated façade that incorporates a desiccant section. Outside air is dried and heated before the required psychrometric treatment in the air handling unit. To regenerate the desiccant section, a solar thermal collector is used, which is incorporated into the façade too. A damper system diverts alternatively outside air or preheated air to the desiccant section, to be dried or regenerated, respectively.

The proposed system fits into the current building practices and standards [2] that search for buildings that generate its own energy. The façade becomes an active element of the building, thus contributing to what is called "zero energy balance".

There are many mathematical models for desiccant air flow systems in the literature. Pesaran [3] studied the water adsorption in silica gel particles. Ruivo [4] developed a numerical model of the behaviour of a channel of a hygroscopic compact matrix. In our case, the mathematical model of the desiccant façade is based in the same equations than those of desiccant wheel, modelling the heat and mass transfer between the humid air in the channel and the desiccant wall, but with a different geometry and adapted to a façade.

A thermal analysis of the system is performed by means of dynamic simulations with Trnsys [5]. The desiccant channel operation for a typical summer day and the latent load removed by the system are good indicators to measure the system efficiency.

THE SYSTEM DESCRIPTION

The desiccant façade is a new air ventilation system in which a desiccant section is incorporated into the building façade. The system is described as follows; firstly a ventilated façade is installed in the building. It consists of a double skin façade comprising two layers (insulation and finishing) and an intermediate channel that lets the outside air flow through it. Afterwards, a desiccant section is placed into the channel as seen in Fig. 1.

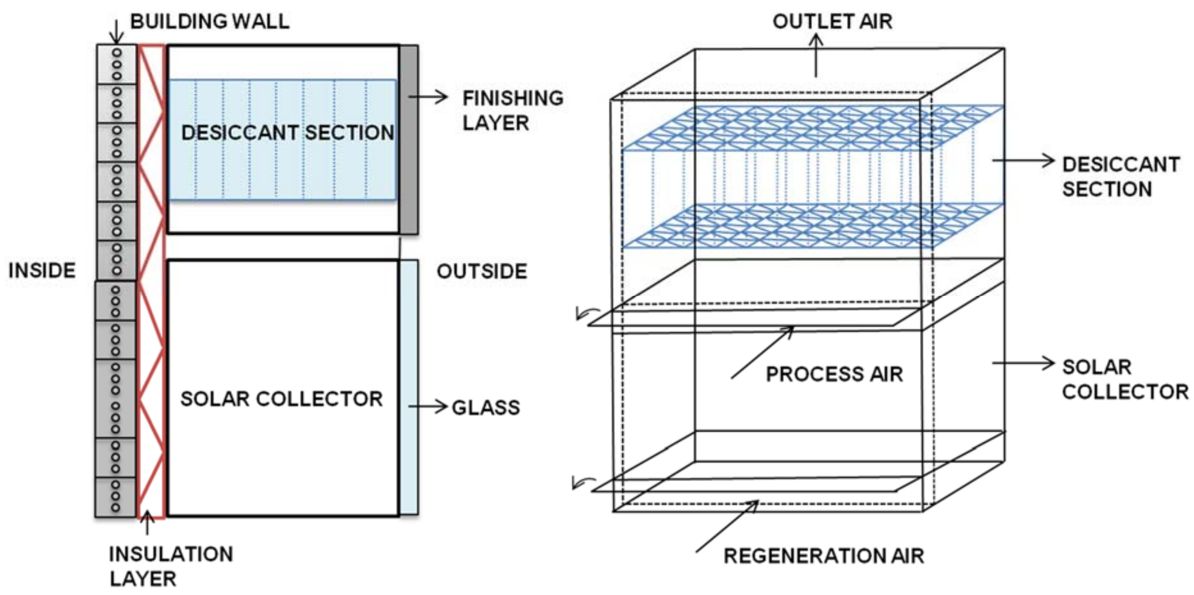

Figure 1. Schemes of the desiccant façade. a) Layers from inside to outside. b) Operation modes

When the adsorption mode is active, a fan forces the outside air through the desiccant section, where it is dehumidified and heated. This mode remains active until the desiccant becomes saturated with water, and thus must be regenerated. During the desorption cycle, outside air is drawn into the collector, where it is heated. Hot air is then passed through the desiccant module, forcing water to flow from the desiccant to the surrounding air.

A control system, based in opening and closing some dampers, makes it possible to alternate the operation modes. The system provides periodic output because it needs to switch the air flow periodically. A continuous service can be provided by operating two identical desiccant façade columns in tandem.

MATHEMATICAL MODELLING OF A DESICCANT FAÇADE

Modeling the flow of humid air through a desiccant channel is a complex, transient, 3D heat and mass transfer problem. Solving such a problem is very intensive in terms of computer time. The main purpose of the present study is to develop a simplified numerical model of the desiccant façade with reduced computational cost.

The balance equations of the model are similar to those proposed in [1], but adapted to the new desiccant configuration. The analysis is based on the following assumptions:

1. Diffusion, and not advection, causes the transport of water inside the porous media.
2. Mass transport is due to Knudsen diffusion (water vapor) and surface diffusion (water adsorbed).
3. Local thermal equilibrium between the air inside the pores and the solid desiccant is considered. Adsorption or desorption are the only phase change process considered.
4. The physical domain of the problem is a set of desiccant parallel channels that are integrated into a desiccant block. All channels are considered identical, with constant heat and mass transfer surface areas.
5. Mass and heat transfer flows between adjacent channels are considered negligible, so that the thermal behavior of the matrix is characterized by an equivalent channel.
6. The interior side of the channel is adiabatic.
7. Heat transfer in the outer side of the façade is steady due to the low thermal inertia of the finishing (usually a metal sheet).
8. The water vapor content in the airflow or inside the pores of the desiccant is related with the mass fraction, in $kg_{water}/kg_{humid\ air}$.

Based on the previous assumptions, a vertical discretization of the desiccant domain is proposed (See Fig. 2).

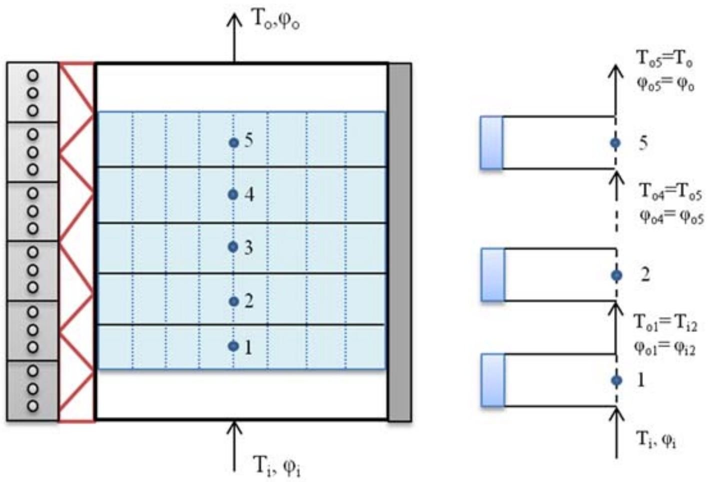

Figure 2. Vertical discretization of the desiccant domain.

The desiccant domain is divided into five control volumes, associated with five airflow nodes. The leaving air temperature and humidity (T_o and φ_o) for each control volume are the entering conditions (T_i and φ_i) for the next control volume.

For each control volume, we formulate a heat and mass balance at the desiccant-air interface, and a heat and mass balance for the air flowing inside the channel. Fig. 3 shows the heat and mass flows for a control volume.

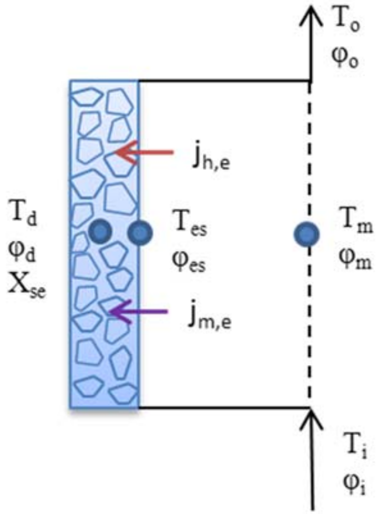

Figure 3. Heat and mass flows in a control volume.

In the figure 3, three different nodes are represented: air node (m), desiccant-air interface node (es) and desiccant node (d). The variables T and φ are the temperature (ºC) and specific humidity ($kg_{water}/kg_{humid\ air}$), respectively. X_{se} is the amount of water adsorbed by the desiccant ($kg_{adsorbed\ water}/kg_{dry\ desiccant}$). $J_{h,e}$ and $J_{m,e}$ are the heat and mass flows in the channel, and are calculated as follows:

$$j_{he} = h_h \cdot (T_m - T_{es}), \qquad (1)$$

$$j_{m,e} = h_m \cdot \rho_f \cdot (\varphi_m - \varphi_{es}), \qquad (2)$$

where ρ_f is the air density ($kg_{wet\ air}/m^3$), h_h is the heat transfer coefficient (W/m^2K) and h_m is the mass transfer coefficient (m/s). Both coefficients are calculated using the Chilton-Colburn analogy, which calculates the Sherwood number (S_h) from the Nusselt (N_u) and Lewis (L_e) numbers:

$$S_h = N_u \cdot {L_e}^{1/3} = \frac{h_m \cdot D_h}{D_f}, \qquad (3)$$

where D_h is the hydraulic diameter (m) and D_f is the diffusion coefficient of water vapor in the air of the channel (m^2/s). The Nusselt number is calculated depending on the regime (laminar or turbulent) and the degree of the development of the flow using the correlations of Kays and Crawford [6], Gnielinski [7] and Sieder and Tate [8].

Inside the desiccant, mass transport is due to vapor transport (Knudsen diffusion) and liquid transport (surface diffusion). Mass balance in the desiccant-air interface is obtained from the gradient of the water content in the air and in the solid at the interface:

$$h_m \cdot \rho_f \cdot (\varphi_m - \varphi_{es}) = \left[-\frac{D_{k,eff}}{\varepsilon_w}\frac{\partial}{\partial x}({\rho^*}_v \varphi_v)\right]_{x=0} + \left[-{\rho^*}_d D_{s,eff}\frac{\partial X_{se}}{\partial x}\right]_{x=0}, \qquad (4)$$

where $D_{k,eff}$ and $D_{s,eff}$ are the Knudsen and surface effective diffusion coefficients (m^2/s) respectively, which are obtained from temperature and adsorbed water content in the desiccant domain, ε_w is the porosity in the humid desiccant, $\rho^*_v\varphi_v$ is the water content concentration in the desiccant ($kg_{vapor}/m^3_{desiccant}$) and ρ^*_d is the apparent density of dry desiccant ($kg_{dry\ desiccant}/m^3_{desiccant}$). Taylor rule is used to transform differential equations into algebraic ones.

The other mass balance equation is based on the air flowing inside the channel:

$$L_D \cdot h_m \cdot \rho_f \cdot \left(\varphi_{es} - \varphi_{v,m}\right) = \dot{m} \cdot (\varphi_o - \varphi_i), \qquad (5)$$

where L_D is the length of the volume control (m) and $\dot{m}$ is the air mass flow per meter of façade ($kg_{wet\ air}/sm$).

Analogously, the heat balance equations are proposed. Due to the seventh assumption, a global thermal resistance between the air in the channel and the ambient is defined in the energy balance at the air-desiccant interface:

$$h_e \cdot (T_{es} - T_m) + h_m \cdot \rho_f \cdot \left(\varphi_{es} - \varphi_{v,m}\right) \cdot h_{fg} = \frac{T_{sol-air} - T_{es}}{\frac{1}{h_{c-r}} + \frac{e_p}{k_p} + \frac{e_d}{k_d}}, \qquad (6)$$

where h_{fg} is the latent heat (J/kg_{water}), h_{c-r} is the convective-radiant coefficient outside the façade (W/m^2K), e_p and k_d are the width (m) and thermal conductivity of the finishing layer (W/mK), e_d and k_d are the width (m) and the thermal conductivity (W/mK) of the desiccant wall, and $T_{sol-air}$ is the sol-air temperature (ºC), that is an equivalent outside temperature which takes into account: the incident solar radiation and the absorption capacity of the building envelope.

The energy balance in the channel can be written as:

$$L_D \cdot h_e \cdot (T_{es} - T_m) = \dot{m} \cdot Cp_f \cdot (T_o - T_i), \qquad (7)$$

where C_{pf} is the specific heat of humid air (J/kgK).

Finally, the equilibrium isotherm of the desiccant is used to close the system. It represents the equilibrium states between the humid air and the desiccant material:

$$X_{se} = f(T, \varphi) \qquad (8)$$

Regarding the solar thermal collector, a very simple model based on a global efficiency (η_{solar}) is used. This efficiency is obtained from the traditional Hottel-Whillier model [9], in which the heat losses parameter (F_RU_L) and the optical parameter ($F_R(\tau\alpha)$) are required. The regeneration temperature is calculated from the heat balance to the collector:

$$\dot{m} \cdot Cp_f \cdot \left(T_{reg} - T_o\right) = \eta_{solar} \cdot I_T \cdot A_c, \qquad (9)$$

where I_T is the solar radiation on the façade (W/m^2) and A_c is the solar collector surface per unit length of façade (m^2/m).

RESULTS

The model was implemented in FORTRAN and integrated into TRNSYS. Simulations were undertaken to analyze the performance of the desiccant façade on a typical summer day. The latent load removed by the system (Q_{lat}) is calculated as follows:

$$Q_{lat} = \dot{m} \cdot h_{fg} \cdot (w_i - w_o), \qquad (10)$$

As the system operation is alternative, the latent load is an integrated value over each adsorption-desorption cycle.

The most important simulation parameters are now commented. The desiccant façade and the solar collector are installed in a south-oriented vertical wall located in a Mediterranean climate (Málaga, Spain). The climatic file from the EnergyPlus database is used. The desiccant employed is a silica-gel RD, whose properties and adsorption isotherm curve are reported in Pesaran [3]. The width of the air channel is 0.01m. The inlet air velocity is 1 m/s. The length and width of the desiccant section are 0.4 m and 1 m, respectively. The exterior panel is a metal sheet with a thermal conductivity of 0.1352 W/mK. The solar collector has a length of 2 m and its characteristic parameters are $F_R U_L$=18.1 W/m^{2}K and $F_R(\tau\alpha)$=0.8121. The time step is 30 seconds, which is short enough to represent accurately the drying and regeneration processes, but large enough to enable us to consider that the stationary regime is reached.

Figs. 4 and 5 describe the desiccant channel operation for a sample hour (12:00 to 13:00), the 23rd of July in Málaga.

Fig. 4 shows the evolution of the inlet and outlet water content of the air during the considered hour.

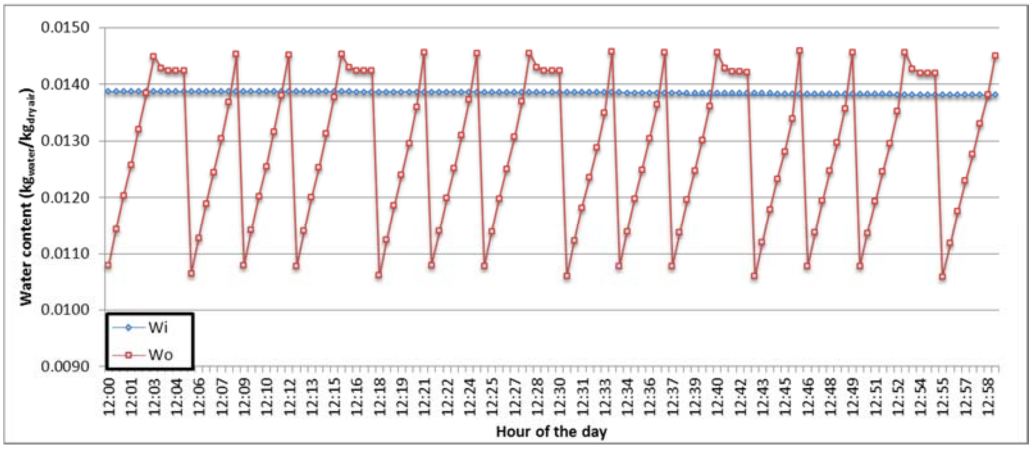

Figure 4. Air humidity variations in the desiccant channel.

The length of the adsorption and desorption cycles are 3 and 0.5-2.5 minutes, respectively. In the adsorption cycle, the inlet air humidity is about 13.7 $g_{water}/kg_{dry\ air}$ and, in the first time step, the ventilation air is dehumidified approximately 3.1 $g_{water}/kg_{dry\ air}$. Later, the humidity of the air is increased until equilibrium is reached and the regeneration mode is activated. At this point, hot air from the solar collector removes a high amount of adsorbed water, increasing the humidity content in the air and decreasing that of the desiccant. A new cycle starts.

Fig. 5 shows the evolution of the temperature of the air flow in the desiccant channel and the regeneration temperature.

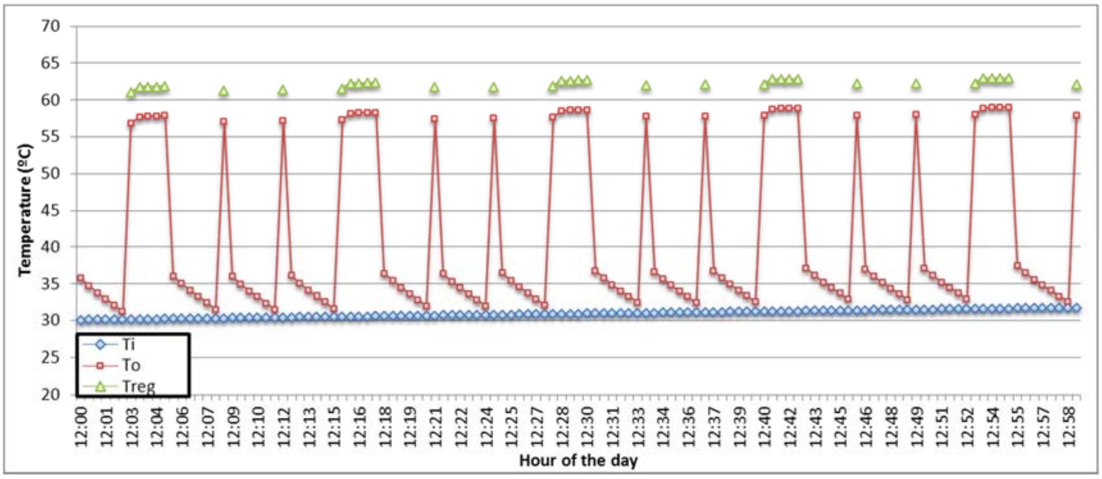

Figure 5. Temperature variations in the desiccant channel.

Regarding the air temperatures, the inlet air temperature is 30ºC and the air is heated in the desiccant channel until 36ºC during the adsorption process. When the desorption mode is activated, the solar collector heats up the air temperature to 62ºC. The regeneration temperature must be high enough to cause the vaporization of the adsorbed water in the desiccant and produce an effective regeneration of the desiccant section.

Fig. 6 shows the latent load removed by the system and the incident solar radiation during the considered day.

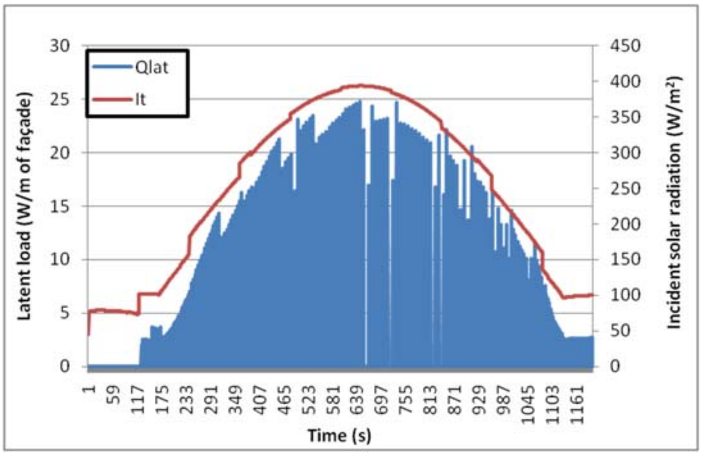

Figure 6. Incident solar radiation and latent load removed by the façade.

Firstly, the relationship between the latent load removed by the façade and the solar radiation it receives is very interesting. This relationship demonstrates that the capacity of the system largely depends on the solar radiation. In fact, the maximum capacity (25 W/m of façade) is achieved when the radiation level is maximum. This latent heat removal rate is similar to the rate of latent heat gain from one occupant performing light work. However, in the first or last hours of the day, when the radiation level is low, the capacity of the system is less than 10 W/m of façade and the drying and regeneration cycles are very short, so the system operation is not interesting.

SUMMARY AND CONCLUSIONS

This paper presents a new ventilation system in which a desiccant section is placed inside a ventilated façade. The air is dehumidified in the desiccant channel and introduced in a conventional dedicated outdoor air system before it is supplied to the zone. A solar collector is incorporated with the purpose of regenerating the desiccant.

A simplified mathematical model of the system is presented and used in a dynamic simulation. The results show that the ventilation air is dehumidified by approximately 3.1 $g_{water}/kg_{dry\ air}$ and heated by 6ºC for a regeneration temperature of 62ºC. The maximum latent load removed is about 25 W/m of façade, when a high solar radiation is impinging over the façade.

Currently, an experimental prototype is being tested (see Fig.7). The experimental results will allow the validation of the model.

Figure 7. Images of experimental façade prototype.

ACKNOWLEDGEMENT

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