Performance Analysis of a Rotary Wheel Dehumidifier Applied to Air Conditioning

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Abstract: This study presents an analysis of the parameters that affect the performance of a rotary wheel desiccant dehumidifier, when used as a component of an evaporative-adsorptive system applied to air conditioning for comfort. The temperature and moisture of the process and reactivation airflows, the air velocity through the dehumidifier, the reactivation temperature and the Reactivation and Process airflow ratio (R/P) are analyzed. The analysis is made on a dehumidifier available in the market, by means of two softwares of adsorption dehumidifier equipment manufacturers. It is concluded, among other results, that lower reactivation temperatures and lower R/P relationship give the process air a better thermodynamic condition for the desirable application.

Key words: Desiccant dehumidification, evaporative cooling, desiccant cooling

INTRODUCTION

Adsorption is the phenomenon in which fluid molecules are concentrated spontaneously over a solid surface. This phenomenon is the result of non-balanced forces acting between the solid surface and the fluid that attract and keep the fluid's molecules together. The solid surface is called adsorbent, the chemical substance kept by the adsorbent is called adsorbate and the fluid in contact with the surface is called adsorptive.

Adsorbents are solid porous materials, with a large internal surface area by unit mass and, structurally, are like rigid sponges. The adsorbed water is kept by condensation inside the capillaries developed in the crystalline structure of the material. The capacity of an adsorbent to attract moisture depends on the size of its pores and the relation between the water amount on its surface and the air moisture content. This difference is reflected in the vapor pressure at the surface and at the air[1].

In theory it is admitted that on the solid substances surface there are non-balanced forces producing an attraction between liquid and gaseous molecules. Basically, these forces include dispersion ones (attractive), short range repulsive ones and electrostatic forces. The dispersion forces (also called Van der Walls forces) appear due to the fast fluctuation of the electron density inside each atom, leading to an electrical dipole moment at the neighborhood of the atom, resulting in a mutual attraction.

Cal[2] classifies the size of the pores as follow: micropore (less than 2 nm), mesopore (between 2 and 50 nm) and macropore (more than 50 nm). The reason for this classification is that each pore size corresponds to different adsorption effects. The potential interaction in micropores is much bigger than in macropores due to the proximity of the pore walls, resulting in the increase of adsorption potential. Adsorption forces developed around the ten atoms closest to the surface keep an adsorbed molecule inside a micropore. The forces at the adsorbate molecules are function of the distance between the adsorbate and adsorbent atoms and this atoms polarity. Inside mesopores a capillary condensation occurs and at the macropores zone, the adsorbate's Partial Pressure (P_v/P_{vs}) becomes very close to 1. Thus, the physical adsorption involves relatively weak intermolecular forces between the air moisture and the desiccant's surface, constituting a typical exothermal process[3]. The adsorption heat can measure the adherence force.

Moisture is usually removed by heating the desiccant up to temperatures between 50 and 320°C, by supplying a reactivating airflow. The reactivation temperature depends on the adsorbent material used and

the application. The calorific energy for reactivation may be obtained by electricity, water vapor, hot air or other heat source. Whenever available, the use of economic energy sources, as in cogeneration systems, should be considered.

There are many desiccant dehumidifier configurations, but this study analyses the performance of the rotary desiccant wheel type. Figure 1 shows this configuration, also called honeycomb. A rotary impregnated wheel with desiccant material is utilized. The outside air flow passes through a part of the wheel, been dehumidified, while the warm reactivation air flow goes around in counter-flow, removing the moisture[4].

Configuration of the evaporative-adsorptive system: In air conditioning systems, new technologies about the adsorption dehumidification process applied to cooling have been applied in recent years, such as those presented by Shen and Worek *et al.*,[5-11].

Camargo[12] proposed an evaporative cooling system coupled to an adsorptive dehumidifier. Figure 2 shows the configuration of such system, composed by a rotary desiccant dehumidifier coupled to two direct evaporative coolers and to an indirect evaporative cooler. In this configuration the outside air is first mixed with the return air and goes through the dehumidifier loosing latent heat (moisture) and receiving sensitive heat (temperature). After that, the air is first cooled in an Indirect Evaporative Cooler (IEC) unit and than in a Direct Evaporative Cooler (DEC), been introduced in the conditioned environment in satisfactory human thermal comfort temperature and moisture conditions. The adsorbent reactivation air is also composed by a mixture of outside and return air, that is initially cooled in a DEC and after in an IEC.

OPERATION PARAMETERS OF A DESICCANT DEHUMIDIFIER

The main parameters affecting performance of the desiccant dehumidifier are the R/P ratio (reactivation air flow/ process air), the process air moisture and temperature at the inlet, the process air velocity through the desiccant, the reactivation air temperature, the reactivation air moisture, the reactivation air velocity through the desiccant and the amount of desiccant in contact with the air stream.

For a better understanding o f the influence of these parameters, this study analyses a basic study of a dehumidifier type rotary wheel operating on pre-established conditions and compared to the same system operating in several conditions. Figure 3 shows the airflow on each side of the dehumidifier. In the basic
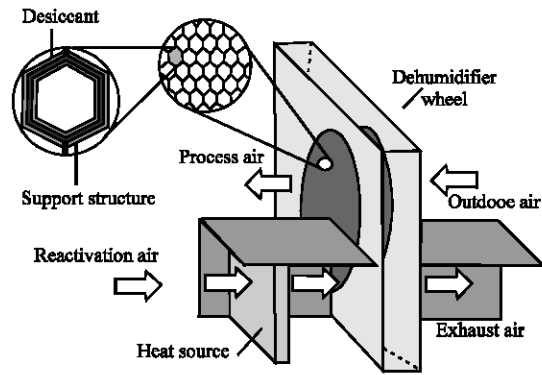

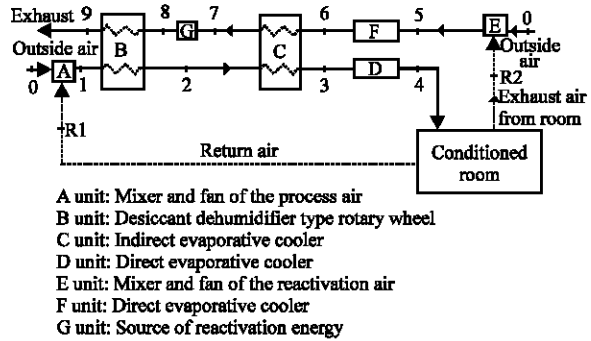Fig. 1: Rotary dehumidifier wheel

A unit: Mixer and fan of the process air
B unit: Desiccant dehumidifier type rotary wheel
C unit: Indirect evaporative cooler
D unit: Direct evaporative cooler
E unit: Mixer and fan of the reactivation air
F unit: Direct evaporative cooler
G unit: Source of reactivation energy

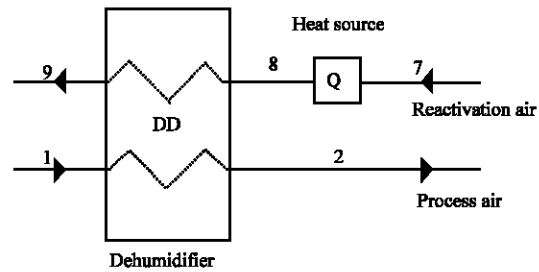Fig. 2: Diagram of the system proposed by Camargo[12]

Fig. 3: Process and reactivation air flows

study, the inlet data for point 1 of the Fig. 3 were: Dry Bulb Temperature (DBT) = 28.85°C; Wet Bulb Temperature (WBT) = 21.84°C and the absolute moisture of the air $w = 3.51$ g_w/kg_{air}, under the mixing conditions of 50% outside air and 50% return air from the conditioned environment (ARI condition) for city of São Paulo, Brazil. The dehumidifier outlet conditions were determined from inlet conditions using two softwares provided by the makers of adsorption dehumidifier equipments: *Novelaire Technologies-Desiccant Wheel Selection Program-Version 1.0.5* and *Munters Cargocaire DH Selection Program-Version 9.5a.*

Table 1: Thermodynamic conditions of the airflows

Point	1	2	7	8	9
DBT (°C)	28.85	48.22	49.00	115.50	65.20
w (g$_w$/kg$_{air}$)	13.51	7.78	18.47	18.47	33.34

Table 2: Influence of the process inlet air flow moisture

	In		Out		
Case	DBT (°C)	w (g$_w$/kg$_{air}$)	DBT (°C)	w (g$_w$/kg$_{air}$)	Δw
Basic	28.85	13.51	48.22	7.78	5.73
Lower moisture	28.85	10.0	47.44	5.24	4.76
Higher moisture	28.85	17.0	48.83	10.48	6.52

Silica gel was used as adsorbent material in this simulation. A low reactivation temperature characterizes this material.

To discuss the variables influencing the performance of the system, a dehumidifier operating in equilibrium is considered, that is, the total energy of the process air is balanced by the energy of the reactivation side. In the basic study the power needed to the reactivation is 51 kW. The thermodynamic conditions, at standard atmosphere pressure, are shown in Table 1.

Influence of R/P ratio (reactivation air/process air flow): Figure 4 shows the influence of the reactivation air mass flows and the process air at the dehumidifier process air outlet conditions. In this simulation the R/P ratio was variable and the reactivation temperature was kept constant at 115.5°C.

Figure 4a shows the influence of R/P ratio on the dehumidifier outlet inlet dry bulb air temperature DBT$_2$ (point 2 of Fig. 3) and Fig. 4b shows the influence of R/P ratio on the absolute moisture of the dehumidifier outlet air w$_2$.

It is seen that lower R/P ratio implies a lower dehumidifier outlet process air temperature, a desirable property whenever the dehumidifier is used in a comfort air conditioning system. Lower R/P ratio implies in lower power consumption for reactivation. For the conditions analyzed in this study a change of R/P from 0.385 to 0.670 produces a change in the reactivation power from 51 to 90 kW.

Influence of process inlet airflow moisture: Considering a change in the original moisture content of the process inlet air, the effect in the outlet moisture is show in Table 2.

Thus, the increase of the process air temperature is proportional to the amount of moisture removed from the process air.

Influence of the process inlet airflow temperature: In the basic study, the process inlet air temperature is 28.85°C,
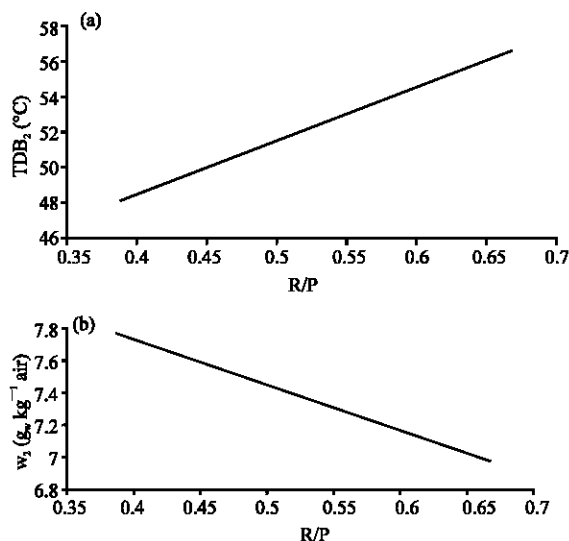

Fig. 4: Influence of the reactivation and process air flows ratio

as in Table 1. Reducing this temperature to 26°C the moisture at the dehumidifier outlet will be 7.44 g$_w$/kg$_{air}$ instead of 7.78 g$_w$/kg$_{air}$. In this study the moisture removed will be (13.51-7.44) = 6.06 g$_w$/kg$_{air}$. The performance in moisture decrease is better because the desiccant is cold and, due to that, there is a lower vapor pressure at the surface, attracting and keeping more moisture than in the basic study. On the other hand, if the inlet temperature is increased to 31°C, the process outlet air will not be so dry, with a moisture content equal to 8.03 g$_w$/kg$_{air}$. In this study, the moisture removed will be 5.48 g$_w$/kg$_{air}$. Thus, keeping constant all other variables, lower inlet temperatures improve the performance of the system. This way of operation has some implications such as: a) If high temperatures are expected, a higher capacity dehumidifier must be predicted or a lower temperature sensitive desiccant must be chosen and b) the benefit of a low inlet temperature is lower when the air has lower moisture content. For example, under 2.0 g$_w$/kg$_{air}$ the effect is very low and as a consequence pre-cooling the air from 18°C to 12°C will reduce the outlet moisture by only 0.01 g$_w$/kg$_{air}$, which probably is not enough to justify the investment in a cooler equipment.

Influence of air velocity through the process side: A change in the process airflow will change its velocity through the dehumidifier. The slower the air moves through the desiccant bed, the dryer the outlet moisture will be. In the basic study the air moves through the bed at a velocity of 3.08 m/s and leave at a moisture condition of 7.78 g$_w$/kg$_{air}$. If the velocity is reduced to 2.2 m/s the outlet moisture will be 7.47 g$_w$/kg$_{air}$ rather than 7.78 g$_w$/kg$_{air}$. If the velocity is increased the outlet air will be moister.
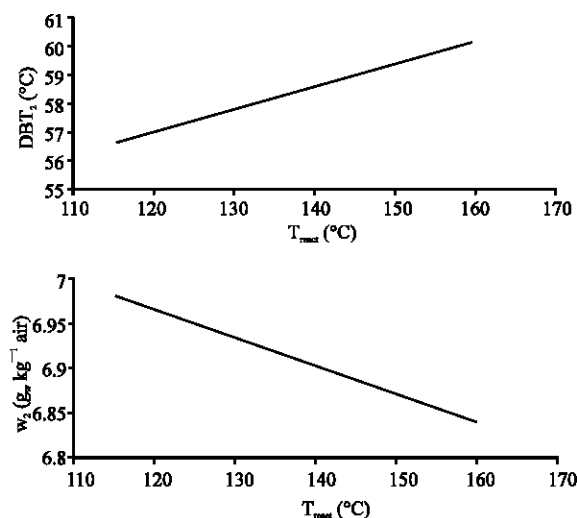
Fig. 5: Influence of the reactivation temperature

Table 3: Influence of the reactivation inlet air flow moisture

w_7 (g_w/kg$_{air}$)	1.0	5.0	10.0	16.0	20.0	30.0	40.0
DBT$_2$(°C)	48.33	48.27	48.27	48.22	48.22	48.17	48.11
w_2 (g_w/kg$_{air}$)	8.07	7.67	7.71	7.76	7.79	7.86	7.94

Some implications of changing the process air velocity are: a) if the outlet moisture must be very low, the process air velocity is quite critical and the designer may want to install an air flow monitoring device and control system to avoid unplanned velocity changes and b) if moisture removal rate is more important than delivered air dew point, then high velocities will result in smaller and less expensive equipment.

Influence of reactivation inlet airflow temperature: Reactivation air temperature has a strong effect over the performance of the system, because the warmer the desiccant, the easier the moisture will be eliminated. Essentially, a drier desiccant in the reactivation will be able to absorb more moisture from the process air stream.

In the basic study the reactivation temperature is assumed to be 115.5°C, producing an outlet moisture on the process side of 7.78 g_w/kg$_{air}$. If the reactivation temperature is increased to 140°C, the process air outlet becomes drier, leaving the unit at 7.37 g_w/kg$_{air}$.

Figure 5 shows the influence of the adsorbent reactivation temperature in the process air outlet conditions (air that will be injected in the environment). Figure 5a shows the influence of the reactivation temperature in the dehumidifier outlet process air temperature DBT$_2$ (point 2 of Fig. 3). In this situation the reactivation temperature was changed leading to a different R/P ratio. Figure 5b shows the influence of the reactivation temperature on the absolute moisture of the

dehumidifier outlet process air (w_2). Analyzing the resulting values it is seen that temperature-increasing gradient is higher than the dehumidification gradient. The variation in the moisture content is 2% and the temperature variation is 6%. Thus, for evaporative cooling applications, it is better to operate with the minimum reactivation temperature.

Therefore, the reactivation temperature effect shows that: a) if very dry conditions are necessary, plan to use high reactivation temperatures; b) desiccant dehumidifiers can make use of very low temperature reactivation heat sources. However, in this study, the dehumidifier will need to be larger than one using a high-temperature reactivation energy source to produce the same outlet conditions in the process air.

Influence of reactivation inlet airflow moisture: Table 3 shows the variation of the absolute moisture and process air temperature (point 2 at Fig. 3) as a function of the variation of the reactivation air moisture (point 7).

It is seen that when the reactivation air moisture changes from 1.0 g_w/kg$_{air}$ to 40.0 g_w/kg$_{air}$ the process air temperature changes very little (from 48.11 to 48.33°C), as well as its moisture (from 8.07 g_w/kg$_{air}$ to 7.94 g_w/kg$_{air}$), showing that the silica gel is a very low sensitive material to reactivation air moisture changes.

Influence of air velocity through reactivation side: In a dehumidifier type rotary wheel it is important to keep both reactivation airflow and its temperature proportional to the moisture load that is being removed by the desiccant. If the moisture load of the desiccant increases, more energy must be applied to the desiccant to insure complete reactivation and to keep the system in equilibrium.

The effect of lower reactivation air is similar to having a lower reactivation temperature, because the net heat available to the desiccant is a function of airflow multiplied by the temperature difference between the air and the desiccant. In other words, high temperatures and high reactivation air flows deliver more heat to the desiccant, which means it can absorb more moisture in process because the material has been more completely dried in reactivation. However, if the temperature entering reactivation remains constant and airflow is increased beyond the minimum necessary to carry the heat to the desiccant, the energy will simply be wasted, because the reactivation air leaves the dehumidifier warmer than necessary, carrying heat off to the outside (higher temperature on point 9 at Fig. 3). Thus, the reactivation airflow should be properly controlled to avoid higher than expected air velocities through the desiccant.

Influence of the amount of desiccant in contact with air flows: The amount of moisture removed from the air depends on how much desiccant the air encounters as it moves through the dehumidifier. More desiccant means more moisture removed. There are two ways to provide more desiccants to the air: a deeper or a faster wheel. Either strategy will have an additional energy cost. Increasing the depth of the wheel will increase the lost of load, increasing the wheel energy cost. Turning it faster, the unit capacity will increase, but also the energy consumption. For example, in the basic study the wheel rotation is 18 RPH for a process air velocity of 3.08 m/s. By increasing the air velocity to 3.96, the rotation will increase to 24 RPH while the reactivation temperature is kept constant.

CONCLUSION

This study analyses the influence of several operational variables in the performance of an adsorptive dehumidifier and it is concluded that: a) a lower R/P ratio leads to a lower process air outlet temperature and to a lower energy consumption to reactivation; b) an entering process air moisture higher than the expected leads to a higher dehumidifier outlet temperature; c) lower inlet temperatures improve the performance at the moisture removal because the desiccant will have lower vapor pressure on its surface, being able to attract and keep more moisture; d) increasing the air process velocity through the dehumidifier will leave lower dry by reducing its contact time with the adsorptive material; e) an increase of the reactivation temperature leads to an increase of the process air temperature. For applications in evaporative cooling it is better to operate at the minimum reactivation temperature; f) process air temperature changes very little with change of the reactivation air moisture when the adsorbent material is silica gel; g) the amount of removed moisture by de dehumidifier depends on the load of desiccant material contacts while moving through the dehumidifier; h) for each application the designer should analyze, among other properties, the characteristics of the desiccant material as well as its adsorption capacity as function of time.

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