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Experimental and numerical analysis of desiccant wheels activated at low temperatures

F. Comino*, M. Ruiz de Adana

Departamento de Química-Física y Termodinámica Aplicada, Escuela Politécnica Superior, Universidad de Córdoba, Campus de Rabanales, Antigua Carretera Nacional IV, km 396, 14072 Córdoba, Spain

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ABSTRACT

Desiccant wheels, DW, can be used to control the indoor air conditions in buildings and industrials environments. The control of the outlet process air conditions of a DW can be obtained by controlling the moisture removal capacity, MRC, and sensible heat ratio, SHR. The objective of this work is to obtain MRC and SHR of a DW activated at low temperatures when the process airflow rate and air regeneration temperature are varied. Two secondary objectives are to obtain the influence of the variation of the process airflow rate and air regeneration temperature on the outlet process air conditions and the relationship between MRC and SHR. Three empirical and simulated case studies are carried out.

The results show that a decoupling of the outlet air temperature and humidity ratio can be obtained when the process airflow rate and air regeneration temperature are varied. This decoupling allows several MRC values for a constant SHR value, and vice versa, to be obtained, achieving ranges of 7 kg h^{-1} and 0.25, respectively. These results suggest that a control strategy for DW activated at low temperatures, would allow MRC and SHR to be controlled by setting the process airflow rate and air regeneration temperature.

1. Introduction

Desiccant systems present an alternative solution to refrigeration vapour compression systems, commonly used for dehumidification and humidity control in rooms with high latent loads. Refrigeration vapour compression systems reduce the air temperature to condense its moisture, although these systems present some problems in the combined treatment of sensible and latent loads in rooms [1]. Furthermore, refrigeration vapour compression systems working under partial load conditions, presented a reduced latent capacity compared to nominal latent capacity [2]. Desiccant dehumidifier systems differ from refrigeration vapour compression systems in the way moisture is removed from the air. Desiccant dehumidifier systems adsorb water vapour from the air reaching an area of low vapour pressure at the surface of the desiccant [1]. These systems combined with refrigeration vapour compression systems, called hybrid HVAC systems, proved to be especially useful in the decoupling of sensible and latent loads in buildings [3,4].

In HVAC systems, control strategies are required to achieve the independent control of temperature and humidity. The aim of a control strategy is to improve the performance of the system, while satisfying user's thermal comfort [5]. Many HVAC systems based on DW using two-stage dehumidification achieved a fine tuning of humidity ratio [6–8]. However, this control would not guarantee independent control of temperature and humidity. Other HVAC systems with DW combined with a enthalpy wheel were studied to control indoor conditions [9]. This system did not have capacity to control indoor humidity during some critical periods.

Previous research studies on DW control strategies were carried out with the aim of saving energy by setting the regeneration section with a purge sector [10]. Another control strategy approach is based on the rotation speed of a DW [11,12]. The control system would be much more energy efficient using the variable airflow rate [13]. The rotation speed and the regeneration temperature were also used as a control strategy [14]. Nevertheless, these works have not satisfactorily clarified the capacity to decouple the outlet process air conditions, temperature and humidity ratio, especially as regards the quantitative effect of both variables.

Manufacturers often provide controls inside the system to modulate the reactivation energy of the DW in response to changes in the moisture load. There are three common methods of controlling dehumidification capacity [15]: (i) on-off reactivation control; (ii) reactivation energy modulation; and (iii) variable air bypass. Each of these methods is effective, depending on the degree of precision needed for the humidity control level in the building [15].

A schematic of a DW system with an air bypass is shown in Fig. 1. It requires a bypass air duct and variable-position dampers for the face of the DW and for the bypass duct. The DW would oper-

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* Corresponding author.
E-mail address: francisco.comino@uco.es (F. Comino).

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Nomenclature

A	Area [°C g kg^{-1}]
AR	Area ratio
b	Estimated parameter
CC	Cooling coil
DOE	Design of experiments
DW	Desiccant wheel
EA	Exhaust air
F	Centrifugal fan
FC	Flow conditioner
EH	Electric heater
HC	Heating coil
HR	Relative humidity [%]
K	Number of parameters
MA	Mixed air
MB	Mixing box
MRC	Moisture removal capacity [kg h^{-1}]
N	Number of experimental tests
OA	Outdoor air
P	Pressure [Pa]
PT	Pitot tube
$\dot{Q}$	Heat transfer [kW]
RA	Recirculated air
SH	Steam humidifier
SHR	Sensible heat ratio
T	Temperature [°C]
t	Time [s]
$\dot{V}$	Volumetric airflow rate [m^3 h^{-1}]
X	Input variable
$\hat{Y}$	Estimated output value

Greek letters

Δ	Increase
ρ	Density [kg m^{-3}]
ω	Humidity ratio [g kg^{-1}]
Ω	Specific mass airflow rate [kg s^{-1} m^{-3}]

Subscripts

d	Dew point
i	Inlet
L	Latent
o	Outlet
p	Process
r	Regeneration
S	Sensible

Superscripts

’	Mixed outlet process air conditions

ate with unbalanced airflow rates to achieve the outlet process air conditions. This method is preferred for industrial process applications, where control within ±1 or 2% relative humidity is essential [15]. Previous results also showed that if the outlet moisture must be very low, the process airflow rate is quite critical and therefore this must be controlled [1].

Different experimental works have been carried out in order to study the influence of unbalanced airflow rates in DW [16,17]. Other authors developed mathematical models of DW which allowed its behaviour with unbalanced airflow rates to be analysed [18,19]. However, the methodology used to fit these models requires a high number of experimental tests. Some physical characteristics of the DW required by these models are not usually available.

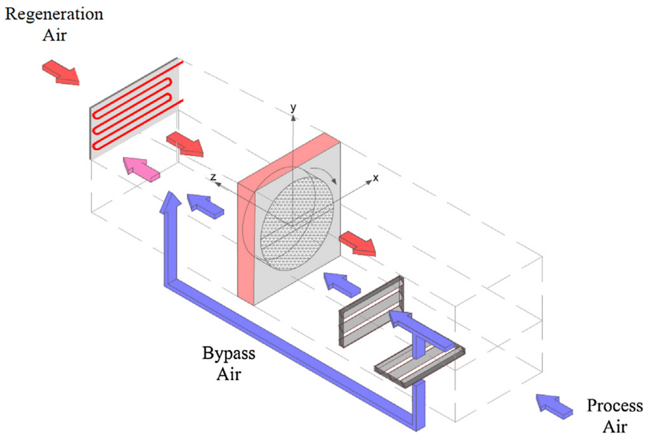

Fig. 1. Schematic of a DW system with bypass air.

It has been shown that the variation of process airflow rate allowed the psychrometric trend of the process air stream and moisture removal capacity, MRC, to be modified [20]. The psychrometric trend of the process air stream can be studied by sensible heat ratio, SHR, [21]. Several studies on HVAC systems with DW analysed SHR [22,23]. Nevertheless, to modify MRC the air regeneration temperature was more influential than the airflow rates [24].

MRC was considered to be the most appropriate parameter to analyse the performance of a DW with unbalanced airflow rates [25]. The higher the temperature of the desiccant material, the higher the MRC, and the easier it is to remove moisture. Thus, the regeneration air temperature has a strong effect on MRC [26,27]. Therefore, a significant energy consumption is required to regenerate the DW to obtain high MRC values. Energy savings are usually obtained when the DW is regenerated using waste heat from other processes [28]. However, in some cases waste heat energy is not available or the corresponding temperature level is not adequate. On the other hand, previous studies on DW operated at low regeneration temperatures and reached acceptable MRC values [29,30]. A DW activated at low temperatures could be integrated in refrigeration vapour compression systems in a building or industrial environment [31,32]. In this paper, values below 60 °C were considered as low regeneration temperatures. The regeneration temperatures usually used range from 60 °C to 120 °C [33,34].

The performance and the outlet process air conditions of a DW strongly depend on its control strategy. Therefore, it would be interesting to know the behaviour of a DW activated at low temperatures by setting the process airflow rate and air regeneration temperature, in order to control MRC and SHR.

The objective of this work was to obtain empirically MRC and SHR of a DW activated at low temperatures when the process airflow rate and air regeneration temperature were varied. To obtain this, two secondary objectives were carried out: first, to study the influence of the variation of the process airflow rate and air regeneration temperature on the outlet process air conditions, and then to obtain the relationship between MRC and SHR.

2. Methodology

2.1. Experimental setup

An experimental test rig was built to analyse the performance of DW under different working conditions. A schematic representation of the experimental setup is shown in Fig. 2. The process and regeneration air streams were configured in a countercurrent flow. The facility is also designed to bypass up to 40% of the process air