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Experimental study of the moisture removal capacity of a desiccant wheel activated at low and high temperature

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Abstract
Desiccant dehumidifiers can be combined with refrigeration vapour compression systems to reduce and control the humidity ratio in buildings and certain industrial processes. These combined systems are referred to as hybrid systems.
Many studies about hybrid systems with desiccant wheels, DW, have been carried out. In these hybrid systems, a significant energy consumption is required for thermally activate the DW.

The objectives of this piece of work are to determine empirically the main variables which influence the moisture removal capacity, MRC, of a DW activated at low and high temperature, and analyse the variability of these on MRC. In order to compare the results obtained for a DW activated at low and high temperature, a secondary objective is to obtain the theoretical cooling energy needed to achieve the supply air set conditions. In this paper, values below 60°C were considered as low regeneration temperatures for a DW and values above 60ºC were considered as high regeneration temperatures. The methodology used was based on the statistical technique of design of experiments, DOE, which allows to study the behaviour of DW with a reduced number of experimental tests.

The results showed a significant influence of the inlet humidity ratio of the air process and the air regeneration on MRC. Using high regeneration temperatures, the MRC values were found 61% higher than using low regeneration temperatures. However, high regeneration temperatures led to higher process air temperatures and thus more cooling energy was required to achieve the supply air set conditions.

Keywords - desiccant wheel; low temperature activated systems; dehumidification

1. Introduction

Controlling the humidity ratio content in the air is necessary to maintain the required indoor air conditions in buildings and certain industrial processes. Desiccant dehumidifiers can be combined with refrigeration vapour compression systems to reduce and control the humidity ratio in buildings. These combined systems are referred to as hybrid systems.

Many studies about hybrid systems with desiccant wheels, DW, have been carried out [1,2]. Desiccant wheels are usually activated thermally at temperatures above 60ºC. In a DW the desiccant material is heated by the regeneration air stream. The higher the temperature of the desiccant material, the easier moisture is removed, so the regeneration air temperature has a strong effect on performance [3]. Therefore, a significant energy consumption is required to regenerate the DW, and energy savings are usually obtained when the DW is regenerated using waste heat from other processes [4]. However, in some cases waste heat energy is not available or the corresponding temperature level is not adequate. Other studies have analysed the use of solar energy to regenerate a DW [5], but the solar thermal system involves a significant increase in the overall cost of the system.

Several studies integrated DW into hybrid systems operated at low regeneration temperatures reaching acceptable desiccant capacities [6,7]. A DW activated at low temperature could be integrated in refrigeration vapour compression systems in a building or industrial environment. In this paper, values below 60°C were considered as low regeneration temperatures and values above 60ºC were considered as high regeneration temperatures.

ASHRAE defines Moisture Removal Capacity (MRC) as a primary figure of merit for desiccant wheel performance, as reported in [8]. In previous studies the desiccant capacity was analysed through the MRC [9–11].

The objectives of this work are to determine empirically the main variables which influence the moisture removal capacity, MRC, of a DW activated at low and high temperature, and analyse the variability of these on MRC. In order to compare the results obtained for a DW activated at low and high temperature, a secondary objective is to obtain the theoretical cooling energy needed to achieve the supply air set conditions. To achieve these objectives an experimental hybrid system was built and several tests were carried out using the statistical technique of design of experiments, DOE.

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. 1. Process and regeneration air streams were configured in a countercurrent flow. The inlet temperature and humidity ratio of both process and regeneration streams were set using cooling and heating coils (CC, HC), an electric heater (EH) and a steam humidifier (SH) [12]. The process and regeneration airflow rates were set using variable speed fans (F). Two Pitot tubes (PT) were used to measure the airflow rate.

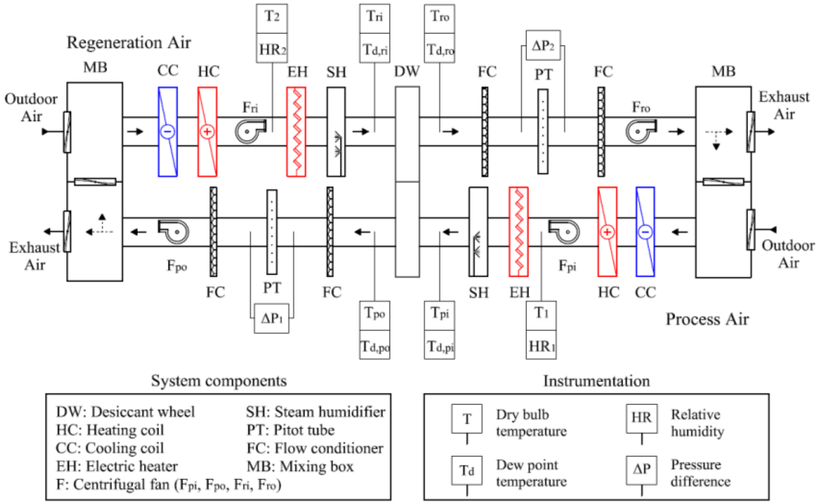

Fig. 1 Layout of test facility.

The DW is divided into two equal partitions and rotates at a constant speed of 42 rph. The matrix of the DW consists of alternate layers of flat and corrugated sheets of silica gel and metal silicates, chemically bonded into a tissue of inorganic fibres. Physical and operational characteristics of the DW are shown in Table 1.

Table 1. Characteristics of the desiccant wheel.

Parameters	Value	Unit
Rotor diameter	550	[mm]
Rotor length	200	[mm]
Desiccant material	Silica gel	
Channel shape	Honeycomb	
Nominal capacity	15	[kg h^{-1}]
Nominal air flow	2300	[m^3 h^{-1}]
Rotation speed	42	[rph]
Weight	57	[kg]
Power supply	230	[Vac]

The sensors locations are shown in Fig. 1. Temperature was measured using PT100 sensors, dew point temperature using chilled mirror hygrometer sensors, relative humidity using capacitive sensors, and pressure difference using pressure transmitter sensors [12]. All the experimental tests were carried out at steady-state conditions. The sampling time step was 3 s and the values were averaged every 20 min.

2.2. Design of Experiment

The statistical technique DOE was used to identify and analyze the influential variables on MRC of a DW [13,14]. The number of required experimental tests can be reduced if they are optimally designed. In this work, two case studies were carried out with four input variables: inlet air process temperature, T_{pi}, inlet air process humidity ratio, ω_{pi}, inlet air regeneration temperature, T_{ri} and inlet air regeneration humidity ratio, ω_{ri}. In case 1 low regeneration temperatures were considered, and in case 2 high regeneration temperatures were considered.

Two regression models were obtained from both case studies. Regression models illustrate the relationship between MRC and the set of process parameters.

In both case studies, the effect of the four input variables was studied applying a factorial design [13]. These designs were carried out defining two grids to cover the range of validity of the process and regeneration air streams, as shown in Fig. 2. Four inlet limit states for the process airflow were selected, P1 to P4, and an additional fifth inlet state P5 located inside the four-sided polygon previously defined. The regeneration inlet conditions were defined introducing another set of five points R1 to R5.

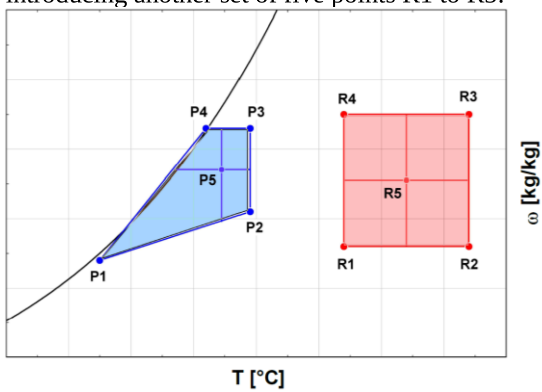

Fig. 2 Grid considered for the inlet states of the process and regeneration airflow for case studies 1 and 2.

The inlet process air flow temperature range was from 17.5 °C to 29.5 °C, and the humidity range from 12 g·kg^{-1} to 21.5 g·kg^{-1} for both case studies. For the regeneration air stream, the inlet air humidity ratio range was also considered the same in both cases: from 13 g·kg^{-1} to 22.5 g·kg^{-1}. However, the regeneration inlet air temperature ranges were different in each case. The case study 1 was carried out for low regeneration temperatures, from 34 to 42.5°C. The case study 2 was carried out for high regeneration temperatures, from 70 to 80°C, an increase of 60%. The air flow rate was set to 2100 m^3/h in both process and regeneration air streams for all cases.

2.3. Process Air Cooling Energy

In order to obtain the theoretical energy needed to achieve the supply air set conditions in a building, two case studies for MRC maximum values were carried out. The first case was evaluated for usual summer air supply conditions, T_{supply}=18 ºC and HR_{supply}=80 %. The second case was studied for usual winter air supply conditions, T_{supply}=27 ºC and HR_{supply}=20 %.

3. Results and Analysis

3.1. Statistical Analysis

The results of the statistical analyses for the two case studies are summarized in Table 2. This table shows the main estimated effects, the standard error of each effect, the statistical parameter F-Ratio, and the statistical parameter P-value and the lack-of-fit test. Positive and negative effects on MRC for the different input variables were observed. All variables were found significant at 95% confidence level, as the P-values were lower than 0.05 in all cases. The results for case studies 1 and 2 showed that the most influential variables on MRC were ω_{pi} and ω_{ri}. Both design of experiments were also found to be suitable for the observed data at 95 % confidence level, as the P-values for lack-of-fit tests were greater than 0.05 in all cases.

Table 2. Effects of input variables on MRC.

Case study 1				
Effect	Estimate	Stnd. Error	F-Ratio	P-value
Average	4.91	0.11		
T_{pi}	-1.44	0.27	28.93	0.0329
ω_{pi}	3.66	0.22	273.74	0.0036
T_{ri}	0.85	0.12	48.30	0.0201
ω_{ri}	-3.91	0.12	1024.81	0.0010
	Lack-of-fit P-value: 0.9991			
Case study 2				
Effect	Estimate	Stnd. Error	F-Ratio	P-value
Average	16.31	0.08		
T_{pi}	-3.19	0.19	271.90	0.0037
ω_{pi}	4.79	0.15	904.05	0.0011
T_{ri}	1.93	0.08	478.45	0.0021
ω_{ri}	-2.25	0.08	654.88	0.0015
	Lack-of-fit P-value: 0.9727			

3.4. Regression Model

The results of the set of experiments were used to fit the parameters of a first order model expressed by Eq. (1):

$$\hat{Y} = a_0 + \sum_{i=1}^{k=1} \sum_{\substack{i=2 \\ j>i}}^{k} a_{ij} \cdot X_i \cdot X_j \qquad (1)$$

Where k is the number of parameters, $a_i \ldots a_{ij}$ are the regression coefficients, showing the weight each one has in the equation, a_0 is the average response in the design of experiments, Xi are the single input variables or their interactions, and Ŷ is the output variable, corresponds to MRC.

The models adjusted by regression of the data obtained from the experimental tests are shown in Table 3. These show the relationship between MRC and the set of process parameters. It can be observed that the parameters with the highest weight were a_2 and a_4, ω_{pi} and ω_{ri} variables, respectively.

Table 3. Estimated parameters for case studies.

Estimated parameters	Xi	MRC ($x10^3$) of case 1 [kg h^{-1}]	MRC ($x10^3$) of case 2 [kg h^{-1}]
a_0	-	45719.00	12252.40
a_1	T_{pi}	146.52	260.75
a_2	ω_{pi}	-3017.17	698.15
a_3	T_{ri}	495.84	5.12
a_4	ω_{ri}	884.04	578.38
a_5	$T_{pi} \cdot \omega_{pi}$	45.87	13.55
a_6	$T_{pi} \cdot T_{ri}$	17.59	4.25
a_7	$T_{pi} \cdot \omega_{ri}$	20.42	5.45
a_8	$\omega_{pi} \cdot T_{ri}$	47.33	0.13
a_9	$\omega_{pi} \cdot \omega_{ri}$	28.96	6.45
a_{10}	$T_{ri} \cdot \omega_{ri}$	12.19	4.81

The results of the accuracy of the models are presented in Table 4. It can be observed that the accuracy of the designs was guaranteed. R^2 values greater than 99 % and standard errors of the estimate lower than 0.3 were obtained for both cases. R^2 values in very good agreement, 98% for T_{po} and 99% for ω_{po}, were obtained in a DW experimental model proposed by Beccali, called Model 54 [15].

Table 4. Correlation coefficients and standard errors of estimation.

Case study	R^2 [%]	Stnd. Error of Est.
1	99.91	0.22
2	99.89	0.16

3.2. Response Surfaces

The trends of the main effects on MRC for case studies 1 and 2 are shown in Fig. 3. It can be observed that the trends for both cases were similar. MRC increased when T_{pi} and ω_{ri} were reduced and ω_{pi} and T_{ri} were increased. This suggested that, if removing high amount of moisture were necessary, the inlet regeneration humidity ratio, ω_{ri}, did not have to be very high. These trends were found consistent with the positive and negative estimated effects in Table 2.

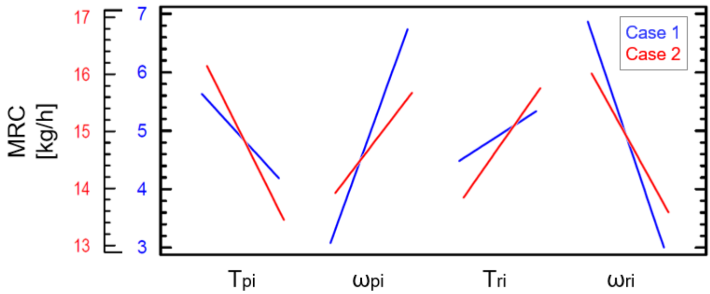

Fig. 3 Trends of the main effects on MRC for case studies.

The response surfaces for both case studies are shown in Fig. 4. In Fig. 4a, MRC is represented as a function of T_{pi} and ω_{pi}. T_{ri} and ω_{ri} were fixed at constant values: for case 1, 42.5 °C and 17.75 g kg^{-1}, respectively, and for case 2, 80 °C and 17.75 g kg^{-1}, respectively. The trends of MRC were similar for different values of T_{ri} and ω_{ri}. For case 1, it can be observed that MRC increased when ω_{pi} was increased. MRC values also increased when T_{pi} was reduced and ω_{pi} low values. The MRC trends obtained in case 2 were in good agreement with case 1, see Fig. 4a. In case 2, MRC increased as ω_{pi} was increased and T_{pi} was reduced.

Fig. 4b shows MRC as a function of T_{ri} and ω_{ri}. T_{pi} and ω_{pi} were fixed at constant values in both case studies, 23 °C and 17 g kg^{-1}, respectively. The trends of MRC were similar for different values of T_{pi} and ω_{pi}. In both case studies, MRC increased as T_{ri} was increased and ω_{ri} was reduced. It can be observed that in both cases MRC presented low gradients compared to the first response surface. This suggested that the influence of the regeneration air stream conditions on MRC was lower than that of the process air stream.

The MRC maximum value achieved for case study 1 was 8.3 kg h^{-1}, an acceptable value compared to the MRC nominal value, 15 kg h^{-1}, see Table 1. The MRC maximum value achieved for case study 2 was 21.5 kg h^{-1}, a difference of 61 % between both case studies. However, the sensible load generated in the adsorption process was delivered to the supply air when it passed through the process section of a DW outlet air process. For MRC maximum values, the air process outlet temperatures were 37 ºC and 54 ºC for case studies 1 and 2, respectively, a difference of 31.5 %.

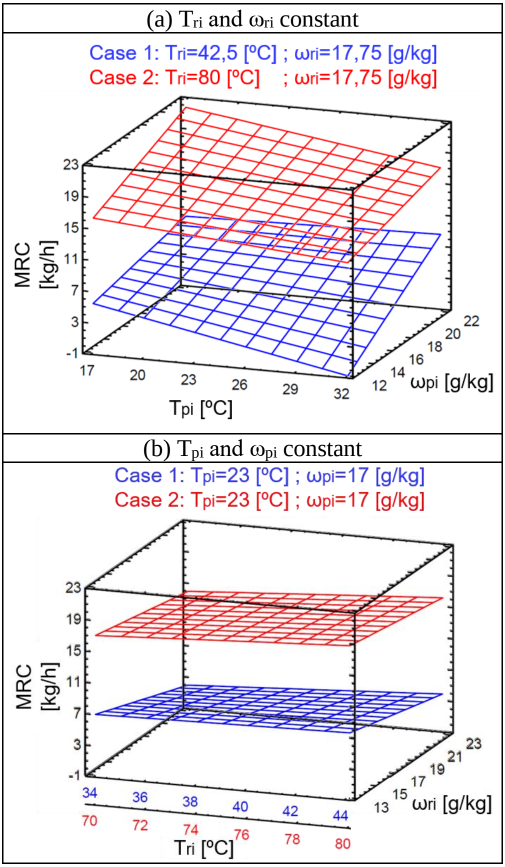

Fig. 4 Response surfaces for case studies 1 and 2 when (a) T_{ri} and ω_{ri} remain constant; (c) and (b) T_{pi} and ω_{pi} remain constant.

3.3. Cooling Energy

The theoretical cooling energy required for usual summer air supply conditions was 25.93 kW for case 1, and 28.42 kW for case 2, which was an increase of 9 %. The theoretical energy required for usual winter air supply conditions was 29.78 kW for case 1 and 32.07 kW for case 2, which was an increase of 7 %. The results showed that the DW activated at high temperature requires higher cooling energy, due to the high air process outlet temperatures derived from the higher heat rejection in the adsorption process.

4. Conclusions

In the present work, the moisture removal capacity of a DW was studied empirically for low and high regeneration temperature. Both cases were conducted varying the air process inlet temperature and humidity ratio and the air regeneration inlet temperature and humidity ratio. The methodology used is based on the statistical technique of design of experiments, DOE, which allowed to study the behaviour of DW with 19 experimental tests. The results allowed to reach the following conclusions:

- The methodology of DOE allowed the identification of the most influential psychrometric variables on MRC of a DW activated at low and high temperature. In both cases, the results showed a significant influence of the inlet humidity ratio of the air process and the air regeneration on MRC.
- MRC was analyzed from the influential variables. Using high regeneration temperatures, the MRC values were found 61% higher than using low regeneration temperatures. Nevertheless, with low temperatures MRC acceptable values were achieved compared to MRC nominal value.
- The theoretical cooling energy needed to achieve the supply air set conditions for MRC maximum values were obtained. The results showed that the DW activated at high temperature requires higher cooling energy, due to the high air process outlet temperatures derived from the higher heat rejection in the adsorption process.

In buildings where MRC extremely high is not required, a DW activated at low temperature needs lower cooling energy to achieve the supply air set conditions.

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