The effect of inlet velocity and unbalanced flows on optimal working conditions of silica gel desiccant wheels

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1. Introduction

Desiccant wheels are crucial components in solar desiccant cooling systems since there exist plenty of parameters to take into account for a desiccant cooling system optimization. Given the maximum available temperature for regeneration flow and the supply volume flow rate to be processed, optimization mainly consists in finding out the optimal AR (Area Ratio) and optimal revolution speed ω.

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Nomenclature

H.R., φ	Humidity Ratio [$g/kg_{d.a.}$]
MRC	Moisture Removal Capacity [g/s]
m	Dry Air Mass Flow Rate [kg/s]
W	Adsorbed Water Vapour [kg/kg]
h	Convective heat or mass transfer coefficient [$W/(m^2K)$ or $kg/(m^2s)$]
P	Desiccant Wheel Channel Perimeter [m]
f	Mass fraction per unit length in axial direction[kg/(kg m)]
T	Flow temperature, Temperature
c_p	Specific Heat [J/(kg K)]
ΔH_{ads}	Heat of Adsorption [J/kg]
z	Axial Coordinate [m]
u	Channel Flow Velocity [m/s]
v	Surface Flow Velocity [m/s]
RH	Relative Humidity [%]
ρ	Density [kg/m3]
A	Desiccant Wheel Channel Cross Section Area [m^2]
Le	Lewis Number
Sh	Sherwood Number
Nu	Nusselt Number
a_i	Isotherm Equilibrium Curve Coefficient
W_{el}	Electrical Power Consumption [W]
Q_{reg}	Regeneration heat [kW]
AR	Area Ratio (Process to Total Cross Section Area ratio)
ω	Revolution Speed [RPH]
Θ	Angular Sector [°]
IVR	Inlet Velocity Ratio

Subscripts

pro	Process Air Flow
reg	Regeneration Air Flow
M	Mass Transfer
T	Heat Transfer
DA	Dry Air

Superscripts

v	Water Vapour
D	Desiccant
S	Substrate
In	Inlet
Out	Outlet
w	Adsorbed Water
i	Isotherm Equilibrium Curve Exponent
opt	Optimal

It is known from Chung et al. [1] that keeping AR constant, optimal revolution speed increases with regeneration temperature. MRC (Moisture Removal Capacity) defined as

$$MRC = \dot{m}_{pro}(HR_{pro}^{in} - HR_{pro}^{out}) \tag{1}$$

is almost constant in a wide range of ω values at low regeneration temperature, however at higher regeneration temperatures it is always possible to find an optimal revolution speed. Ge et al. [2] focused on the effect of volume flow rates on optimal ω but only humidity ratio difference has been investigated and no variations in AR have been included.

To authors' knowledge the effect of inlet velocities on optimal operating conditions (in terms of ω and AR) has not been deepened so far. Moreover, no insights are available in case of unbalanced inlet velocities, that is when regeneration to process inlet velocity ratio is not equal to one. In order to get a better understating of the inlet surface velocity effect, a 1-D unsteady Gas-Side-Resistance numerical model [3] has been adopted to perform simulations in a wide range of conditions in terms of Regeneration Temperature and Revolution Speed.

In the present work three performance indices are mainly used as efficiency indicators:

- MRC has been adopted since it is the most common parameter which accounts for overall latent cooling load. Dehumidification efficiency is a widely used parameter as well [4], [5], however it does not convey the amount of total latent cooling achievable.
- W_{el}/MRC provides the specific electrical consumption for moisture removal and should be kept as low as possible. A fan efficiency of 0.6 is assumed for following calculations
- Q_{reg}/MRC conveys the specific thermal energy to supply to regeneration flow per unit mass of water vapor removed from the process flow. It consists in the inverse of thermal COP [5] and it should be kept as low as possible. Since an open loop cycle is considered, regeneration flow stream is supposed to be drown from outside, therefore Process Inlet Temperature is chosen as a reference temperature to calculate regeneration heat.

The simulated device is a Si-Gel desiccant wheel with sinusoidal channels and a net cross section area of $1m^2$. Further references can be found in [3]. Defining IVR (Inlet Velocity Ratio) as the ratio of regeneration to process surface inlet velocity the investigation process has been set as follows:

- Keeping process inlet condition (T_{pro}, HR_{pro}) constant and IVR=1, simulations have been performed for different regeneration temperatures and inlet velocity to find the optimal operating pair (ω, AR)
- For each of the foregoing cases, an alternative solution with the same process and regeneration volume flow rate but AR=1 was compared to the reference case. The aim is to verify if performance is still good switching from optimal process Angle (at IVR=1) to AR=1 (which implies IVR<1)
- Starting from the optimized configuration at IVR=1, the unbalanced velocity effect is discussed in order to achieve revolution speed adjustment in off-design conditions.

2. Desiccant wheel numerical model

The model adopted for the following analysis is a GSR (Gas-Side Resistance) model according to Ge et al. [6]. Here lay the main assumptions the model is based on:

- An equivalent sinusoidal channel is assumed to be representative of the whole desiccant wheel (no interactions are considered among adjacent channels)
- Air Flow is assumed one-dimensional (uniform in radial direction)
- Air flow quantities (velocity, temperature, humidity) are assumed uniform at the inlet section
- Diffusive transport in gas and solid side are negligible
- No contamination between the two counter-current flows occurs

Here follows the set of partial differential equations and algebraic constitutive laws.

Adsorbed water continuity on solid side (desiccant and substrate):

$$\frac{\partial W}{\partial t} - \frac{h_M P(\varphi - \varphi_{int})}{f^D} = 0 \tag{2}$$

Energy Balance on solid side (desiccant and substrate):

$$\frac{\partial T_D}{\partial t} - \frac{c_p^v P[(T - T_D) + \Delta H_{ads}] h_M P(\varphi - \varphi_{int}) + h_T P(T - T_D)}{f^S c_p^S + f^D (c_p^D + W c_p^w)} = 0 \tag{3}$$

Water Vapor Continuity on gas side:

$$\frac{\partial \varphi}{\partial t} + u \frac{\partial \varphi}{\partial z} + \frac{h_M P(\varphi - \varphi_{int})}{\rho_{DA} A} = 0 \tag{4}$$

Moist Air Energy Balance:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial z} + \frac{c_p^v P T h_M (\varphi - \varphi_{int}) + h_T P(T - T_D)}{c_p^v \rho_{DA} A} = 0 \tag{5}$$

Mass transfer coefficient is obtained from Chilton-Colburn analogy:

$$Le^{1/3} = \frac{Nu}{Sh} \approx 1 \tag{6}$$

where Nusselt number is a function of channel width and height [7], set at 1.8 and 3.2 mm respectively.
Relative humidity at the solid-gas interface is obtained from isotherm equilibrium curve of regular density silica gel [8]

$$R.H. = \sum_{i=1}^{n} a_i W^i \tag{7}$$

The foregoing set of equations is solved iteratively with Matlab® programming language. The set of partial differential equations is discretized with implicit Euler scheme. Convergence is achieved when water mass and heat transferred from the desiccant material during the regeneration period are equal to water mass and heat transferred in the process period plus a prefixed error. Numerical Model has been validated on regular density Silica Gel experimental data provided by Kodama and al. [9], [10]. Further details can be found in the previous work by De Antonellis et al. [3].

3. Optimal operating conditions with balanced and unbalanced inlet velocities

Given a certain design operating condition (inlet velocity, temperature, humidity ratio) an optimal pair of A.R. and ω can be found. In order to assess desiccant wheel performance, the aforementioned performance indices are calculated for a given inlet condition as a function of process angle Θ_{pro} and revolution speed, as shown in Fig 1.

At constant inlet velocity optimal A.R. is strongly dependent on regeneration temperature: the higher T_{reg}, the higher AR^{opt}. Keeping balanced inlet velocity, as it can be seen in Table 1, no variation of AR^{opt} as a function of velocity are encountered.

Since AR^{opt} is close to 1 especially for moderately high regeneration temperature, it is now briefly discussed the effect of non-optimal process angle in design conditions. Adopting AR=1 may be an interesting solution to simplify desiccant wheel installation and overall air handling unit arrangement. Switching from optimal AR condition to

AR=1 and keeping volume flow rates constant, pressure drop grows up on process flow side and lowers down on regeneration side. This brings about an overall increase in electrical power consumption of few percentage points with almost unchanged MRC as shown in Table 1.

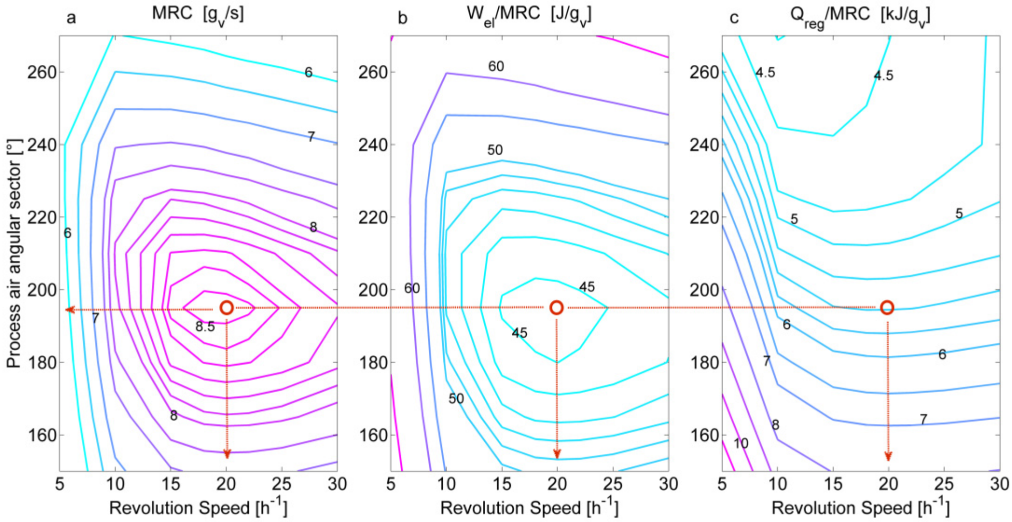

Fig 1. Contours of MRC (a), W_{el}/MRC (b) and Q_{reg}/MRC (c) as a function of revolution speed and process angular sector (inlet velocity 2m/s, Regeneration Temperature 80°C, Process Inlet Temp 30°C, inlet Humidity ratio 15g/$kg_{d.a.}$)

Table 1. Optimal area ratio and revolution speed as a function of inlet velocity for different T_{reg}. Process inlet temperature 30°C, inlet humidity ratio 15g/$kg_{d.a.}$ balanced inlet velocities scenario

Inlet Velocity [m/s]	Regen. Temp. [°C]	$A.R.^{opt}$	ω^{opt}
	80	0.58	10
1	100	0.60	12
	120	0.63	15
	80	0.58	20
2	100	0.60	25
	120	0.63	30
	80	0.58	28
3	100	0.60	35
	120	0.63	42

No relevant variation in optimal revolution speed has been observed when switching from the reference to the alternative case. It can be said that for relatively low AR (and therefore moderately high Regeneration Temperature) an Area Ratio equal to 1 does not affect at all moisture removal capacity and ventilation consumption with relevant advantage for desiccant wheel casing and air handling unit arrangement. For higher AR^{opt} values a raise in electrical consumption may not justify the alternative solution.

Regarding optimal revolution speed, T_{reg} brings about a similar increasing trend in ω^{opt} as seen before. However, optimal revolution speed is also strongly affected by inlet velocity according to Table 1. Moreover, in case of unequal inlet velocities the value of ω^{opt} may differ significantly from the optimal value achieved in balanced velocities scenario (with all of the other inlet quantities constant). This suggests there might be some off-design conditions in which Variable Air Volume Systems are likely to operate, leading to a detrimental drop in desiccant cooling efficiency.

Table 2. Percentage variation of MRC and electric consumption Wel with regards to reference case at IVR=1and optimal AR

Reference Case (IVR=1)					*Alternative Case (AR=1)*	
v_{pro} [m/s]	T_{reg} [°C]	AR ^{opt}	MRC [g/s]	W_{el} [W]	% MRC	$\%W_{el}$
1	80	0.58	4.9	146.7	+0.1%	+2.84%
1	120	0.63	7.3	149.2	-2.7%	+6.9%
2	80	0.58	9.0	589.1	-1.1%	+2.7%
2	120	0.63	13.4	594.4	-2.9%	+6.2%

In order to assess the effect of unbalanced velocities, the IVR index, defined as the regeneration to process inlet velocity ratio, is adopted. For given inlet conditions, A.R. and ω are optimized with balanced velocities. Then, a variation of regeneration flow inlet velocity is considered and performance indices are discussed in due course.

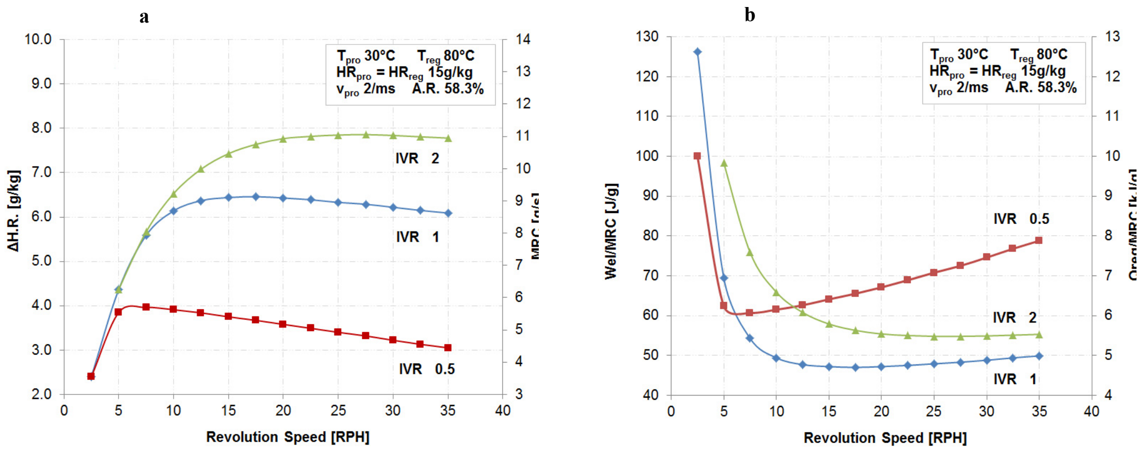

Fig.2 Effect of Unbalanced velocities on dehumidification performance (a) and on thermal and electrical specific consumption (b).

Regarding Fig 2.a and 2.b, lowering IVR is always detrimental for both moisture removal and specific energy consumption. In this unbalanced velocities scenario ω^{opt} is found to be lower than the design one. On the other hand, increasing IVR leads to a growth in MRC as a result of a better drying of the desiccant bed in the regeneration cycle. Interestingly, a higher revolution speed is essential to keep a low increase in thermal and electrical specific energy consumption.

As shown in Fig 3.a and 3.b ω^{opt} is an increasing function of inlet velocity (IVR=1). However, the optimal value varies significantly in the unbalanced velocity scenario and it is an increasing function of IVR. In addition, the range of optimal revolution speed as a function of IVR varies according to regeneration temperature: the higher T_{reg}, the higher ω^{opt} variation range in off-design conditions.

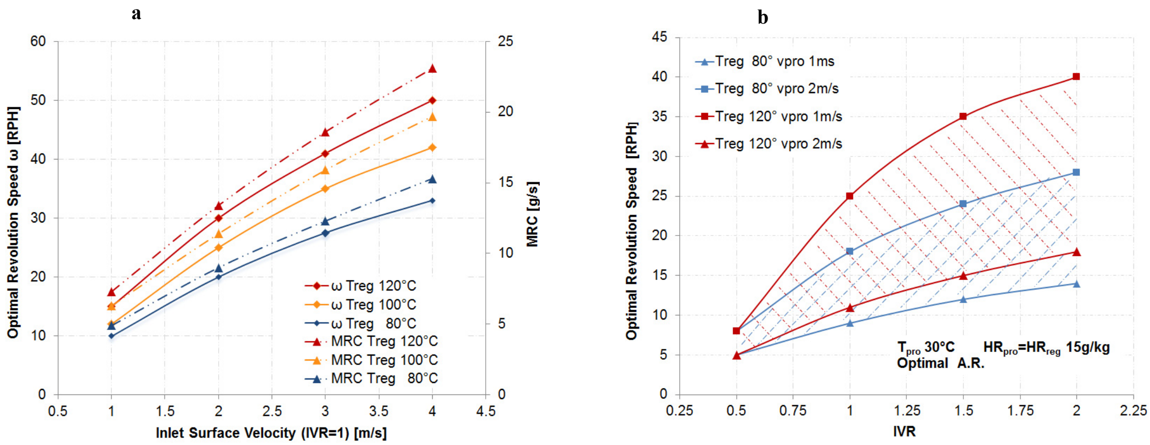

Fig.3 Optimal revolution speed and moisture removal capacity as a function of inlet velocity (a) and optimal revolution speed domain as a function of IVR(b).

4. Conclusions

The effect of inlet velocities has been discussed in the present work. It has been shown that finding an optimal pair of area ratio and revolution speed is fundamental to keep good dehumidification performance, both for balanced and unbalanced velocities. Area ratio is almost independent on the value of inlet velocity and it is mainly affected by regeneration temperature. For T_{reg}<80°C AR=1 may be a good trade-off between highest dehumidification performance and system simplicity.

Optimal revolution speed is strictly dependent on inlet velocity. For Variable Air Volume Systems, in which inlet velocities might be unbalanced for part load conditions, revolution speed needs adjusting to keep reasonable performance. The higher the design regeneration temperature, the wider the range of optimal revolution speed.

Further analysis should take into account the effect of outdoor conditions which have been kept constant in the current work.

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