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On the control of desiccant wheels in low temperature drying processes

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ABSTRACT

Desiccant wheel based air handling units are of great interest in drying processes, such as in the pharmaceutical and food industries, due to the significant energy savings that can be achieved compared to conventional systems. Units based on desiccant wheels are usually optimized in peak conditions, while little attention is given to operation at part load and off design conditions. The aim of this work is to analyze the effects of different control strategies of desiccant wheels on regeneration heat consumption. The analysis is performed through a phenomenological desiccant wheel model, which is validated with experimental data collected in typical working conditions of the drying room investigated in this work. Five control strategies are proposed, highlighting that each one leads to significantly different heat consumption. Finally, an additional simplified control is introduced, showing that it can effectively reduce thermal power consumption compared to conventional control strategies.

Régulation des roues déshydratantes dans le processus de séchage à basse température

Mots clés : Roue déshydratante ; Séchage ; Simulation ; Régulation ; Hors-conception ; Charge partielle

1. Introduction

Desiccant evaporative cooling (DEC) cycles are of great interest due to the possibility of realizing low environmental impact HVAC systems, which can be driven by low temperature heat and renewable sources (Ge et al., 2014; Daou et al., 2006). Such technology is particularly suitable for air cooling and dehumidification processes, due to the possibility of exploiting low grade heat (Jeong et al., 2011; White et al., 2011) and of realizing high energy efficiency systems (Bourdoukan et al., 2010; Elgendy et al., 2015; Goldsworthy and White, 2011; Ling et al., 2013; Liu et al., 2007). In these systems, air dehumidification is generally obtained through a desiccant wheel, which is a rotating honeycomb device made of a supporting material coated with an adsorbent substance. The device is crossed in counter current arrangement by two air streams: the process air, which is dehumidified and heated, and the regeneration air, which removes water from the honeycomb structure.

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Nomenclature

Acronyms

COP coefficient of performance [–]
MRC specific moisture removal capacity [kg s^{-1} m^{-2}]
GSR gas side resistance
DEC desiccant evaporative cooling

Symbols

$A_{DW,tot}$ desiccant wheel total cross section area [m^2]
A net channel area [m^2]
cp specific heat [J kg^{-1} K^{-1}]
EXP experimental
D mass diffusivity [m^2 s^{-1}]
D_h net channel hydraulic diameter [m]
f mass per unit of length [kg m^{-1}]
h enthalpy [J kg^{-1}]
h_T heat transfer coefficient [W m^{-2} K^{-1}]
h_m mass transfer coefficient [kg m^{-2} s^{-1}]
k thermal conductivity [W m^{-1} K^{-1}]
L desiccant wheel length [m]
$\dot{m}$ mass flow rate [kg s^{-1}]
N revolution speed [rev h^{-1}]
Nu Nusselt number [–]
NUM numeric
P inner channel perimeter [m]
q_{reg} specific power for regeneration [W m^{-2}]
Q_{ads} isosteric heat of adsorption [J kg^{-1}]
Sh Sherwood number [–]
t time [s]
T temperature [°C]
v face air velocity [m s^{-1}]
v' channel air velocity [m s^{-1}]
W water content [kg kg^{-1}]
X humidity ratio [kg kg^{-1}]
z channel length [m]

Greek symbols

ΔT_{pro} process flow temperature rise [°C]
ΔX_{pro} process flow humidity ratio drop [kg kg^{-1}]
λ latent heat of vaporization [J kg^{-1}]
ρ density [kg m^{-3}]
σ wheel porosity [–]
φ relative humidity [–]

Subscripts

a ambient (drying room) air
ads adsorbed water
D desiccant
e outdoor air
FD fully developed flow
in inlet
max maximum at design conditions
min minimum
out outlet
opt optimal
pro process air
reg regeneration air
w channel wall

Drying processes require a proper control of air humidity and temperature in order to obtain the desired product quality. The use of desiccant wheels has been widely investigated for product drying (Dai et al., 2002; Misha et al., 2015; Nagaya et al., 2006; Wang et al., 2011) and it has been highlighted that significant energy savings can be achieved (De Antonellis et al., 2012). However, little attention is focused on how optimal control of desiccant wheels can be performed. Over the entire operating life, desiccant units mainly work far from design conditions: in fact they typically work at off-design and part load conditions, due to the variation of outdoor air and latent load conditions. It is well known that desiccant wheel performance is strongly affected by operating parameters, namely air flow rates, regeneration temperature and revolution speed, as shown in many research works (Chung et al., 2009; De Antonellis et al., 2010; Lee and Kim, 2014; Ruivo et al., 2007). Therefore, system efficiency can significantly decrease if desiccant wheel operating parameters are not controlled properly.

At present, recent research works on desiccant wheel mainly focus on phenomenological models, simplified correlations, experimental tests, new materials, innovative system configurations and potential energy savings, as clearly summarized in recent review papers (Rambhad et al., 2016; Sultan et al., 2015; Zouaoui et al., 2016). Instead, little attention is addressed to the optimization of operating parameters in off design and part load working conditions. A few works deal with the analysis and discussion of the control strategy and related performance of desiccant systems. New control strategies have been proposed for desiccant wheels-based systems for air conditioning purpose (Panaras et al., 2011; Vitte et al., 2008) or have been discussed in case of energy efficiency analysis of complex trigenerative systems (Angrisani et al., 2011; Hands et al., 2016; Intini et al., 2015). Anyway, in these works, the analyses focus on the entire system control, while the desiccant wheel dehumidification capacity is typically controlled as in conventional applications, modulating the regeneration air temperature at constant regeneration air flow or vice versa.

Due to the substantial lack of work in this field, in this paper, different desiccant wheel control strategies are evaluated in a low temperature product drying application. The analysis is performed considering five different control strategies that act on the following operating parameters:

- Regeneration temperature.
- Regeneration air flow rate.
- Wheel revolution speed.

Performance of each proposed control strategy is compared and, finally, an additional simplified control method is proposed.