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Desiccant wheels for air humidification: An experimental and numerical analysis

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ABSTRACT

In this work the use of a desiccant wheel for air humidification is investigated through a numerical and experimental approach. In the proposed humidification system, water vapour is adsorbed from outdoor environment and it is released directly to the air stream supplied to the building. Such a system can be an interesting alternative to steam humidifiers in hospitals or, more generally, in applications where air contamination is a critical issue and therefore adiabatic humidifiers are not allowed. Performance of the proposed system is deeply investigated and optimal values of desiccant wheel configuration parameters are discussed. It is shown that in the investigated conditions, which are representative of Southern Europe winter climate, the system can properly match the latent load of the building. Finally, power consumption referred to the primary source of the proposed humidification system is compared to the one of steam humidifiers. The present analysis is carried out through experimental tests of a desiccant wheel in winter humidification conditions and through a phenomenological model of the device, based on heat and mass transfer equations.

1. Introduction

In cold climates air humidification is essential to prevent low relative humidity levels in building environments, in particular in hospitals, museums, laboratories and storage buildings. Low humidity can lead to occupants' discomfort, such as dry nose, throat, and eyes, headaches and skin irritation.

Conventional humidification devices are classified on the process imposed to the moist air that flows through them: namely adiabatic systems and isothermal systems [1]. In the adiabatic systems, the moist air undergoes a near isenthalpic process with a contemporary increase in humidity ratio and decrease in dry bulb temperature. The moist air is put in contact with liquid water, which evaporates in the air stream that directly supplies the energy required for water phase transition. On the other hand, in the isothermal system the moist air undergoes an increase in humidity ratio at almost constant dry bulb temperature. This process is achieved mixing the moist air with steam produced in appropriate equipment.

Comparing the two systems, the adiabatic humidifier is particularly diffused because it is generally cheaper and more efficient (in terms of primary energy consumption) than the isothermal one. However, in some applications the adiabatic humidifiers cannot be used due to risk of bacterial growth related to the entrainment transport of contaminated water droplets. This issue is solved with an isothermal humidifier since both the steam molecules are generally smaller than bacteria and the steam temperature is so high that it kills the pathogens. In hospital *HVAC* systems, steam humidifiers are strictly required [2] while adiabatic humidifiers are not allowed.

In the present paper, an innovative air humidification system based on a desiccant wheel is analyzed through a numerical and experimental approach. The desiccant wheel is a device obtained rolling up sheets of a supporting structure coated with a sorption material, which is crossed in counter current arrangement by two air flows [3]. Such a component is conventionally used to dehumidify an air stream in desiccant evaporative cooling (*DEC*) cycles or in industrial drying processes. Instead, in this work, it is properly integrated in an air handling unit (*AHU*) in order to humidify an air stream, by extracting water vapour from outdoor environment. The proposed system, described in detail in Section 2, is particularly suitable for hospital applications because it does not incur in air contamination risks. In fact:

- There is not presence of water droplets.
- Water vapour is adsorbed from outside air, rather than from the exhaust air stream leaving the building which can be contaminated.

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Nomenclature

a_c	channel height (mm)
A	desiccant wheel area (m^2)
A, B	experimental tests
AH	adiabatic humidifier
AHU	air handling unit
b_c	channel base (mm)
cp	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
$c1, c2$	adsorption isotherm equation coefficient
DEC	desiccant evaporative cooling
DWH	desiccant wheel humidification
$e1, e2$	adsorption isotherm equation exponents
EXP	experimental
ESH	electric steam humidifier
f	mass per unit of length ($kg\,m^{-1}$)
GSR	gas side resistance
h	enthalpy ($kJ\,kg^{-1}$)
h_m	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_T	mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
$k1, k2$	pressure drop equation coefficient
Le	Lewis number (–)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
N	revolution speed ($rev\,h^{-1}$)
N_{test}	number of tests
Nu	Nusselt number (–)
P	channel perimeter (m)
$\dot{Q}$	power (kW)
Q_{ads}	isosteric heat of adsorption ($J\,kg^{-1}$)
t	time (s)
u	measurement uncertainty
SIM	simulation
Sh	Sherwood number (–)
SSH	steam to steam humidifier
T	temperature (°C)
v	face air velocity ($m\,s^{-1}$)
v'	channel air velocity ($m\,s^{-1}$)
W	water content ($kg\,kg^{-1}$)
x_i	measured quantity (–)
X	humidity ratio ($kg\,kg^{-1}$)
y	goal function (–)
z	channel length (m)

Greek letters

ΔP	pressure drop (Pa)
ΔT	temperature difference (°C)
ΔX	humidity ratio difference ($kg\,kg^{-1}$)
η	efficiency (–)
ε	calculated quantity (–)
λ	water latent heat of vaporization ($kJ\,kg^{-1}$)
ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
σ	wheel porosity (–)

Superscripts

EXP	experimental
SIM	simulation

Subscripts

15	at 15 °C
100	at 100 °C
a	air
ad	adsorbed water
amb	indoor ambient air conditions
AH	adiabatic Humidifier
ads	desiccant wheel sorption material
D	desiccant
DW	desiccant wheel
$DWHS$	desiccant wheel humidification system
e	outdoor air condition
el	electric
ESH	electric steam Humidifier
EXP	experimental
fan	fan
fil	filter
HC	heating coil
hum	humidifier
in	inlet
$inst$	instrument
l	liquid
max	maximum
out	outlet
p	primary source
pro	process air stream
reg	regeneration air stream
s	supply air condition
SSH	steam to steam humidifier
th	thermal
th,v	thermal – water vapour production
v	vapour
w	channel wall
x_i	measured quantity (–)

In addition, it can be driven by low temperature heat, leading to possible energy savings compared to steam humidifiers.

At present there is great interest in *DEC* cycles for air cooling and dehumidification applications. Angrisani et al. [4] analyzed a micro-trigeneration system based on a reciprocating engine and a desiccant wheel *AHU*. They put in evidence that primary energy savings can be achieved compared to conventional technologies. El-Agouz and Kabeel [5] evaluated performance of a hybrid system integrating a desiccant wheel, solar collectors and geothermal energy, showing the effects of different climates. Elgendy et al. [6] discussed the effect of different evaporative cooling arrangements in desiccant wheel based *AHU*. Liu et al. [7] evaluated the integration of a desiccant wheel with existing technologies and discussed the importance of operating conditions on system performance. Ruivo et al. [8] recently investigated the importance of desiccant wheel modeling in energy system simulations, highlighting that simplified approaches lead to questionable results.

Further studies deal with the use of desiccant wheels for drying in food industry. De Antonellis et al. [9] investigated different system configurations and highlighted the optimal solutions as a function of sensible to latent heat ratio and ambient conditions. Dai et al. [10] evaluated performance of a system coupling solar collectors and a desiccant wheel, showing it is suitable for grain drying in regions with high solar irradiation. Wang et al. [11] showed that desiccant wheel systems can be effectively used for air drying in food industry packaging. Guan et al. [12] evaluated that energy efficiency in steel plants is increased by using desiccant wheels to dry and pre-heat air for blast furnace. It has been investigated that COP of refrigerating chillers can be improved by the integration with a desiccant wheel in case of a trans-critical CO_2 cycle