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Performance comparisons of honeycomb-type adsorbent beds (wheels) for air dehumidification with various desiccant wall materials

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A B S T R A C T

This study aims at comparing the performance of honeycomb type adsorbent beds (or desiccant wheels) for air dehumidification with various solid desiccant wall materials, from a viewpoint of system operation. A mathematical model is proposed and validated to predict the cyclic behaviors of the cycling beds or wheels. The influences of regeneration air temperature, process air temperature, and humidity on the coefficient of performance (*COP*), specific dehumidification power (*SDP*) and dehumidification efficiency (ε_d) are predicted with various desiccant wall materials. Totally ten most commonly used desiccant materials are considered, with different adsorption and thermophysical properties. It is found that of the 10 materials, the silica gel 3A and silica gel RD perform better than other desiccants for air dehumidification under typical working conditions and driven by low grade waste heat. The results provide some insights and guidelines for the design and optimization of honeycomb type adsorption beds or desiccant wheels.

1. Introduction

Air-conditioning in hot and humid environment is an essential part for human health and comfort [1–3]. Humidity control is a major task for air conditioning [4]. Outside air humidity stays above 80–90% continuously for a dozen of days in subtropical regions like South China. It is necessary to dehumidify fresh air before it can be supplied to buildings. Air dehumidification has played a crucial role in modern air conditioning industry which tends to separate the treatment of latent load from sensible load [5]. In fact, air dehumidification accounts for 40–60% of the cooling load for air conditioning in hot and humid regions like Southern China.

Solid desiccants, either in the form of cycling honeycomb beds or revolving desiccant wheels, are the most common technology for air dehumidification. Various desiccants have been analyzed. Ng et al. [6] investigated the adsorption isotherm characteristics of silica gel–water pair. Tashiro et al. [7] assessed the performance of three types of silica gel, a zeolite with various molar ratios of Si/Al, and an activated carbon with silica gel added. Nakabayashi et al. [4] improved the water vapor adsorption ability of a natural mesoporous material, Wakkanai siliceous shale, by impregnating it with chloride salts. Zhang et al. [8] studied the silica gel-calcium chloride composite desiccant wheel. It was found that the new composite desiccants can be effectively used in a rotary wheel dehumidifier and the performance was improved. Chan et al. [9] predicted the performance of a new zeolite 13X/$CaCl_2$ composite adsorbent for adsorption cooling systems. Yadav and Bajpai [10] compared the regeneration performance of silica gel, activated alumina, and activated charcoal by an evacuated solar air collector and air dehumidification system. It is easy to conclude that though many desiccants have been analyzed, they were investigated only as a “raw material”, rather than as a “system”. Previous work concentrated on the analysis of adsorption isotherms of various desiccants, by neglecting their performance in a real desiccant system. It should be noted that the real performance should be analyzed from the viewpoint of a “system”. The performance of a desiccant system is related not only to the basic adsorption properties of the raw materials, but also to the operating conditions and the heat and mass transfer properties in the beds. Different materials, even having the same adsorption capabilities, may have different performances if they are made into adsorbent beds and operated under real working conditions. Therefore, it is more significant to compare these desiccants from the viewpoint of a “system”.

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Nomenclature

A_{tot}	the total heat and mass transfer area in adsorbent bed (m^2)
C	constant in sorption curve
COP	coefficient of performance
c_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D	diffusivity ($m^2\ s^{-1}$)
D_h	hydrodynamic diameter of a channel (m)
f	desiccant content
H	height of the solid adsorption bed (m)
H_{sc}	height of a single sinusoidal channel (m)
h	convective heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
k	convective mass transfer coefficient (ms^{-1})
k'_m	internal mass transfer coefficient based on humidity difference (s^{-1})
k_m	internal mass transfer coefficient of adsorbents (s^{-1})
K_p	partition coefficient [(kg water/kg material)/(kg vapor/kg air)]
P_{heater}	maximum power of the regeneration heater (kW)
L	length of the solid adsorbent bed (m)
L_v	latent heat of water vapor ($kJ\ kg^{-1}$)
$\dot{m}$	mass flow rate of process or regenerating air stream ($kg\ s^{-1}$)
m_d	mass of the bed (kg)
n	number of ducts in a bed
Nu	Nusselt number
q_{st}	adsorption heat ($kJ\ kg^{-1}$)
SDP	specific dehumidification power ($kg\ kg^{-1}\ h^{-1}$)
Sh	Sherwood number
t	time (s)
T	temperature (K)
u_a	bulk air velocity (ms^{-1})
$u_{p,\ i}$	process air inlet velocity (ms^{-1})
$u_{r,\ i}$	regeneration air inlet velocity (ms^{-1})
W	width of the solid adsorbent bed (m)
W_{sc}	width of a single sinusoidal channel (m)
w	water uptake in adsorbent (kg water/kg dry adsorbent)
w_{max}	maximum water uptake of adsorbent ($kg\ kg^{-1}$)
x	axial coordinate (m)
z	thickness coordinate (m)

Greek letters

ϕ	relative humidity
λ	thermal conductivity ($kW\ m^{-1}\ K^{-1}$)
ε_d	dehumidification efficiency
ε_t	total porosity
ρ	density ($kg\ m^{-3}$)
δ	half thickness of solid wall (m)
ω	humidity ratio (kg moisture/kg dry air)

Subscripts

a	air
ad	adsorption
cyc	cycle
d	desiccant wall
de	desorption
eq	equilibrium
gf	glass fiber paper
i	inlet
ide	ideal
max	maximum
min	minimum
o	outlet
p	process air
r	regeneration air
s	surface, solid
th	thermal
v	vapor
w	water
z	thickness

In this paper, the dehumidification performances with ten kinds of solid desiccants, namely the silica gel B (developed in our Lab), silica gel 3A, silica gel RD, silica gel/LiCl (10 wt.%) composite, silica gel/$CaCl_2$ (27.3 wt.%) composite, zeolite 5A, zeolite 13X, zeolite 13X/$CaCl_2$ (41.5mol.%) composite, $CaCl_2$ and LiCl, as the wall materials for honeycomb-type adsorbent beds, are compared.

The physical structures of silica gels B, 3A and RD are presented in Table 1. From Table 1, we can see that the specific surface area of silica gel B is less than that of silica gel 3A and RD, but the average pore diameter and porous volume are larger than that of silica gel 3A and RD. These differences will affect their adsorption equilibrium, and result in a different dehumidification performance indirectly.

Lithium chloride and calcium chloride have a higher hygroscopic capacity, but the lyolysis phenomenon, which leads to the loss of desiccant materials and may reduce the performance, often takes place after the formation of solid crystalline hydrate [11]. So the weight or molar loading of lithium chloride or calcium chloride for the silica gel/LiCl, silica gel/$CaCl_2$ and zeolite 13X/$CaCl_2$ composite adsorbent should be considered. According to references [11,12,9], in this paper, we choose 10 wt.% as the weight loading for silica gel/LiCl composite, 27.3 wt.% for silica gel/$CaCl_2$ and 41.5 mol.% as the molar mass loading for zeolite 13X/$CaCl_2$. These concentrations are the best feasible choices and were tested. Their thermophysical properties are available.

To predict the dehumidification performance, a one-dimensional, transient heat and mass transfer model [13] is proposed in this paper. The advantages of such a model lay in the fact that it considers the dominant mechanisms for heat conduction and mass diffusion in the wall thickness, while using the air side Nusselt and Sherwood numbers developed specially for the adsorbent ducts. With the validated model, the dehumidification performances of cycling honeycomb adsorbent beds with these materials are compared.

Table 1
Physical structures of silica gels B, 3A and RD.

	Specific surface area ($m^2\ g^{-1}$)	Porous volume ($ml\ g^{-1}$)	Average pore diameter (nm)	Ref.
Silica gel B	476	0.61	4.78	–
Silica gel 3A	606	0.45	3.0	[6]
Silica gel RD	650	0.35	2.1	[6]

2. Mathematical model

2.1. The system and the test rig

A honeycomb type adsorbent bed consisted of numerous flow channels as shown in Fig. 1 is fabricated in our laboratory. A series