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Investigation of adsorption isotherms and rotational speeds for low temperature regeneration of desiccant wheel systems

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ABSTRACT

Effects of adsorption isotherms, namely shape factor and maximum adsorption capacity, and rotational speed on regeneration temperature of desiccant wheel systems are investigated. Higher maximum adsorption capacity is beneficial for reducing regeneration temperature especially for deep dehumidification of single-stage systems under humid climate, while the influence is not obvious with small dehumidification capacity. Higher shape factor (=1) is recommended for dehumidification at high relative humidity, while lower shape factor is better for low relative humidity. Rotational speed in the range of 10–15 r h^{-1} is advised for single and two-stage systems under a wide range of working conditions for both deep and regular dehumidification applications when wheel thickness is 0.2 m and maximum adsorption capacity is 0.8 kg kg^{-1}. The reasons for different requirements of shape factor for regular and deep applications are discussed theoretically. Rotational speed ranges for different wheel thickness and maximum adsorption capacity are recommended.

1. Introduction

Solid desiccant wheel is an effective air processing component instead of low-dew point dehumidification. Thermal energy in a certain temperature range is used to regenerate the desiccant wheel for continuous air dehumidification. Therefore, the required regeneration temperature (t_{reg}, temperature of regeneration air entering desiccant wheels) is a key factor affecting selection of heat sources and performances of desiccant wheel systems. With the same dehumidification requirements, lowering t_{reg} is essential for the utilization of low grade waste heat or renewable energy.

t_{reg} is determined by a variety of factors, such as desiccant wheels' dimensions (Cao et al., 2014), structure of air channels (Zhang, 2008), rotational speed (Cao et al., 2014; Tu et al., 2013b; Ruivo et al., 2015), inlet states of process and regeneration air (Tu et al., 2014; Ruivo et al., 2014), mass flow rate of regeneration air (Tu et al., 2015a), area ratio of regeneration section (Tu et al., 2014; Chung et al., 2009), purge section (Yadav and Yadav, 2016) and adsorption materials' properties (Al-Alili et al., 2015). It was reported that under the same wheel dimensions and working conditions, the lowest t_{reg} can be achieved by using equally divided desiccant wheels when two air streams have the same mass flow rate (Tu et al., 2015a). Besides, t_{reg} is also significantly influenced by system designs. It is suggested to adopt pre-cooling (Tu et al., 2015a) and cooling devices are preferred to be indirect evaporative cooling or heat exchangers other than direct evaporative cooling (Tu et al., 2015b, 2016; Jain and Dhar, 1995). It is found that t_{reg} can be reduced from over 110 °C of systems with direct evaporative cooling to around 70 °C of systems with indirect cooling under the discussed working conditions (process air inlet: 33 °C and 19 g kg^{-1}, supply air: 10 g kg^{-1}) (Tu et al., 2016). Multi-stage desiccant dehumidification systems have been a hot topic for the reduction of t_{reg} as compared with the single stage desiccant wheel system (Tu et al., 2014, 2015a, 2015c, 2017; Ge et al., 2010). Process air is dehumidified by the desiccant wheel and cooled by the cooling coil in each stage. In this way, the desiccant material works at relatively high water content and be regenerated at a lower temperature. As the increase of stage number, air handling processes will be closer to those of inner cooling desiccant beds (Tu et al., 2013b, 2015a). Tu et al. (2015a, 2015d) has conducted thorough investigations to explain influences of stage number on t_{reg} and suggested optimal stage number when different cooling and heating fluids are adopted. Other researches (Zhang and Niu, 1999; Chen et al., 2016a) showed that t_{reg} could be reduced to about 60 °C.

This makes the adoption of low grade heat possible. Tu et al. (2014) investigated a heat pump driven two-stage desiccant wheel system, showing that t_{reg} can be reduced to lower than 50 °C with 10 g kg^{-1} supply humidity ratio and coefficient of performance (*COP*) can be 4.3 and 7.3 under Beijing summer condition and AHRI

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Nomenclature

A	area
a	pore radius, m
BSC	Beijing Summer Condition
WSC	Washington airport Summer Condition
C	shape factor of desiccant material
COP	Coefficient of Performance
c_p	specific heat, kJ kg^{-1} K^{-1}
d_h	hydraulic diameter, m
D_A	ordinary diffusion coefficient, m^2 s^{-1}
D_S	surface diffusion coefficient, m^2 s^{-1}
f	area ratio, dimensionless
G	volume flow rate, m^3 s^{-1}
h	heat transfer coefficient, kW m^{-2} K^{-1}
h_m	mass transfer coefficient, kg m^{-2} s^{-1}
h_v	heat of vaporization, kJ kg^{-1}
k	thermal conductivity, kW m^{-1} K^{-1}
L	wheel thickness, m
Le	Lewis number
m	mass flow rate, kg s^{-1}
M	mass of desiccant wheel, kg
Nu	Nusselt number
ORS	Optimal Rotational Speed
Pa	standard atmospheric pressure, Pa
P_{vs}	saturated vapor pressure, Pa
P	process air
R	regeneration air
r_s	adsorption or desorption heat, kJ kg^{-1}
RS	Rotational Speed
t	Celsius temperature, oC
u	velocity, m s^{-1}
W	adsorption capacity of desiccant materials, kg$_{water}$ kg$_{dry\ adsorbent}$$^{-1}$
x	volume ratio of adsorption material
x^*	mass ratio of adsorption material
Z	thickness, m

Greek symbols

ω	humidity ratio, g kg^{-1}
φ	relative humidity ratio
τ	time
ρ	density, kg m^{-3}
σ	porosity
ξ	tortuosity factor, dimensionless

Subscripts

a	air
ave	average
ad	adsorption material
c	cold
d	desiccant material
p	process
reg	regeneration
in	inlet
out	outlet
max	maximum
min	minimum
w	water
DW	desiccant wheel

(The Air-Conditioning, Heating, and Refrigeration Institute) summer condition.

Apart from system configuration study, developing novel desiccant materials has attracted many attention. It is suggested that desiccant wheels with lower specific heat and lower thermal conductivity are beneficial for dehumidification (Tu et al., 2013a). Novel adsorption materials, such as silica gel-polymer composite desiccant (Chen et al., 2016a), silica gel-lithium chloride composite desiccant (Jia et al., 2006b), and polymer-alumina composite desiccant (Chen et al., 2016b) have been developed. Jia et al. (2006a) reported that the composite material, which is the mixture of silica and lithium chloride, can remove 50% more moisture than silica gel. Polymer has been widely studied as an effective alternatives of silica gel for superabsorbent property. It is found by White et al. (2011) that zeolite and a superabsorbent polymer were more effective in dehumidification than silica gel at low regeneration temperature (50 °C) and high relative humidity (>60%). And test results of Lee and Lee (2012) showed that a superabsorbent polymer had two to three times higher sorption capacity than that of silica gel. Ge et al. (2010) studied the application of silica gel-haloid composite desiccant adopted in two-stage desiccant wheel cooling systems. Cao et al. (2014) investigated the performance of thin polymer DWs (30, 50 and 70 mm) at low regeneration temperatures (40, 50 and 60 °C), and reported that a 50 °C regeneration temperature was the optimum working condition because it can provide good moisture removal capacity (*MRC)* and latent *COP* simultaneously.

Compared with single stage systems, air in two-stage systems is handled in a higher relative humidity range. Besides, for deep dehumidification application, air is treated in a lower relative humidity range as compared with the regular dehumidification application. Therefore, recommended physical parameters for desiccant materials applied for low relative humidity dehumidification and high relative humidity dehumidification should be analyzed. Effects of the adsorption isotherms on the regeneration temperature of single stage and two-stage desiccant wheel systems under humid- and mild-climate for regular and deep dehumidification applications are discussed in this paper through simulation. Moreover, effects of rotational speed are taken into consideration. The results provide guidelines for selecting desiccant materials regarding shape factor, maximum water capacity, and rotational speed ranges for low temperature regeneration of desiccant wheel dehumidification systems.

2. Mathematical model and experiment validation of the desiccant wheel

2.1. Mathematical model

Transient heat and mass transfer processes happen between the air and the desiccant material across the air channels of desiccant wheels. These processes can be numerically described by four governing equations: heat transfer, mass transfer, thermal balance and mass balance equations, shown as Eqs. (A1), (A2) and (A5), (A6) in Appendix A. The mathematical model, which is used for simulation analysis in the present paper, was developed based on the four governing equations and the details have been reported in previous papers (Tu et al., 2013b, 2014, 2016).

Apart from Eqs. (A1)–(A11) in Appendix A, equilibrium isotherms of desiccant materials are required to calculate equilibrium humidity ratio (ω_d) under specific temperature (t_d) and water capacity (W, defined as the mass of water adsorbed by 1 kg of dry adsorbent), with which mass transfer capacities between the air and the desiccant material can be calculated. Adsorption isotherm equations for silica-gel are summarized in Table 1, which connect W with equilibrium relative humidity (φ).

Eq. (1) is a common equilibrium isotherm equation for adsorption materials (Zhang, 2008):