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Experimental investigation and introduction of a similarity parameter for characterizing the heat and mass transfer in polymer desiccant wheels

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A R T I C L E I N F O

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The desiccant wheels made of a polymer desiccant were investigated at a low regeneration temperature with a purpose of utilizing low grade thermal energy. Three polymer desiccant wheels with different wheel thicknesses and different desiccant contents were tested for the dehumidification performance at various conditions of air velocity and rotation speed in a dedicated test facility placed in a climate chamber. The measured performance was compared with those of other desiccant wheels reported previously in literature. The polymer desiccant wheels were shown to display relatively higher dehumidification performance with smaller sensible temperature increase. In order to facilitate understanding the effects of the various test parameters, a single dimensionless parameter adapted from a theoretical work was introduced. It was shown that the effects of the wheel thickness, the air velocity and the rotation speed can be represented integratively by the single parameter. Similarities in the psychrometric states among the cases with different conditions were also addressed.

1. Introduction

Desiccant dehumidification has been paid attention as a thermally activated technology with the advantages of low primary energy consumptions. When the desiccant is regenerated by the waste heat recovered from the power plant or other industrial processes, or the renewable heat such as from the solar collectors, the primary energy consumptions can be saved substantially compared to the conventional dehumidification based on mechanical compression cycles [1–3]. It also has advantages in not using chemical refrigerants with ozone depleting and/or global warming potentials.

The desiccant wheel is a core component of the desiccant dehumidification and air conditioning applications. As the desiccant wheel rotates across the process and regeneration air streams, the desiccant experiences periodically the moisture adsorption and desorption by the cyclic change in the vapor pressure difference between the air stream and the desiccant surface. Latent heat transfer also occurs accompanying the vapor adsorption and desorption. The dehumidification performance of the desiccant wheel has been found to be maximized at a specific rotation speed. The optimal speed has been reported to be dependent on various design and operation parameters of the desiccant wheel. The distinct feature attracted a plenty of relevant researches for the optimization of dehumidification performance with both experimental and analytical approaches.

Early ones of the experimental works were reported by *Kodama* and his colleagues [4–6]. They showed the existence of an optimal rotation speed minimizing the ratio between outlet and inlet humidity ratios of the process air. *Ahmed* et al. [7] carried out the performance tests on a solar desiccant dehumidification system. With the validation through the test data, a numerical model was developed and parametric studies were conducted for the optimization of the wheel performance. The experimental study of *Enteria* et al. [8] investigated the effects of the regeneration temperature, the air flow rate and the wheel rotation speed on the moisture removal capacity of a desiccant wheel. *Eicker* et al. [9] conducted performance tests on several commercially available desiccant wheels, and determined the best rotation speeds for different DWs. In a series of experimental works, *Angrisani* and his colleagues investigated the performance characteristics of the desiccant dehumidifier coupled to a micro combined heat and power system. Their studies reported the variations of the performance as a

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Nomenclature

A_v	void area of flow channel, m^2
C_p	specific heat, J/kg K
D	wheel diameter, m
D_h	hydraulic diameter of flow channel, m
$\dot{E}$	change in enthalpy flow, W
f	fiction factor
f_m	mass fraction of desiccant in the wheel, kg/kg
g	unit mass of desiccant-coated laminate, kg/m^2
h	convection heat transfer coefficient, W/m^2 K
i	specific enthalpy, J/kg
k	thermal conductivity, W/m K
L	desiccant wheel thickness, m
$\dot{m}$	mass flow rate, kg/s
N	number of transfer units
Nu	Nusselt number
P	perimeter of the flow channel, m
Pr	Prandtl number
p	pressure, Pa
Q	volume flow rate, m^3/s
Re	Reynolds number
T	temperature, ℃
t_{cyc}	cycle period, s
u_a	air face velocity, m/s
w	channel width, m
Y	humidity ratio, kg/kg(DA)
z	axial coordinate in channel, m

Greek letters

α	ratio of channel height to width
β_r	fractional area of regeneration zone
γ_Y	gradient of water content with respect to humidity ratio at a constant temperature
δ	thickness of desiccant-coated laminate, m
ε	porosity
η_T	thermal effectiveness
η_Y	dehumidification effectiveness
θ	dimensionless temperature
κ	relative thermal capacity of desiccant wheel to that of process air
Λ	relative thermal capacity defined by [4]
μ	viscosity, Pa · s
ρ	density, kg/m^3
σ	relative sorption capacity of desiccant wheel to that of process air
ψ	representative gradient of relative-humidity line in psychrometric chart
ω	dimensionless humidity ratio

Subscripts

a	air
ent	entrance effect
i	inlet
$ideal$	the theoretically lowest humidity ratio point of dehumidified process air
fd	fully developed laminar flow
m	representative mean value
o	outlet
p	process
r	regeneration
w	desiccant wall
0	standard air condition

function of the process and regeneration air temperatures and air flow rates [10,11]. They also conducted tests to highlight the effect of rotation speed on its performance [12]. *Yamaguchi and Saito* [13] conducted a comprehensive experimental study on the dehumidification performances of various silica gel wheel samples with different thicknesses focusing on the effects of the regeneration temperature, air flow velocity, wheel thickness and wheel rotation speed.

Recently, with a particular purpose of utilizing low grade thermal energy, desiccant wheels with new desiccant materials were developed and investigated. *White* et al. [14] compared the dehumidification performance of three desiccant wheels each with zeolite, superabsorbent polymer and conventional silica gel as the desiccant materials. They reported the polymer desiccant wheel achieved greater dehumidification than others especially at low regeneration temperature conditions. *Cao* et al. [15] evaluated the performance of thin polymer desiccant wheels with the thicknesses less than 100 mm. A synthetic zeolite based-desiccant wheel was investigated experimentally and numerically by *Intini* et al. [16]. *Al-Alilli* et al. [17] investigated the optimization and evaluation of a desiccant wheel utilizing a new type of zeolite as the desiccant material.

Though there have been performed various experimental works as mentioned above, the experimental characterization of a desiccant wheel is still a challenging task. The measurement of each outlet state of the airflow exiting the desiccant wheel is not easy to be carried out with reliable accuracy, mainly due to the strong dependency of the air state on the angular position at the downstream of the wheel resulting from the rotation through adsorption and desorption sections [4,5,13]. This feature causes difficulties in measuring accurately the mean outlet state with a few number of sensors fixed at particular positions. Moreover, the air leakage through seals between the wheel and the casing causes imbalances in mass and energy between the process and regeneration air streams. Very few works indicate mass and energy imbalance errors or the whole set of data that would enable the evaluations. An exhaustive experimental research showed significant mass and energy imbalance between the regeneration and the process air streams crossing a desiccant wheel [18].

Numerical approaches based on mathematical models validated from a few limited experimental data have thus been more common in the investigation of the desiccant wheel. Numerous mathematical models have been proposed with various levels of depth and complexity from one-dimensional to more complicated ones taking various effects into account [19–21]. Even with a plenty of numerical investigations, however, comprehensive understanding has not been yet completed due to the wide variety of the relevant parameters and the complicated physics involved with the parameters.

Apart from the comprehensive understanding, there has been another approach to develop simple and handy models for characterization of a desiccant wheel [22–27]. These models can be easily implemented in engineering practices, such as the optimization of the wheel to maximize the whole system performance for a given application or the dynamic energy simulation of the HVAC&R system incorporating a desiccant wheel. Most of the