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Numerical and experimental performance analysis of rotary desiccant wheels

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ABSTRACT

In air-conditioning field, a dehumidification has become increasingly important for human health and comfort especially in hot and humid climates. However, a conventional mechanical dehumidification with a vapor compression refrigerator has some problems. Therefore, much attention has been paid recently to a desiccant air-conditioning system as an alternative to the conventional system. In this paper, we focus on a rotary desiccant wheel which is the main component of the desiccant air-conditioning system and develop and validate the mathematical model by comparison with experimental results. The validation is conducted under various operating conditions. The mathematical model discussed in this paper includes, for example, the entrance region effect in air channel, detailed diffusion phenomenon in porous solid. In experiments, effects of the regeneration air temperature, air superficial velocity, wheel thickness and wheel rotational speed on the desiccant wheel performance are investigated. In addition, the temperature and humidity distribution at the outlet of the desiccant wheel are measured. As a result, an average relative error between the predicted and the measured humidity ratio difference distribution is 3.3% and temperature difference distribution 10.8%. Moreover, the effect of the regeneration air inlet temperature, the air superficial velocity, wheel thickness and wheel rotational speed on the desiccant wheel performance are clarified and the predicted results are totally in good agreement with the measured results.

1. Introduction

In air-conditioning field, a dehumidification has become increasingly important for human health and comfort especially in hot and humid climates. Sterling et al. [1] investigated the optimum relative humidity range for human health and reported that keeping the relative humidity at around 50% is effective to prevent the survival and growth of biological contaminants such as bacteria, viruses, fungi and mites. The optimum temperature and humidity range for human comfort is presented by ASHRAE [2]. In addition, the forced ventilation also has become necessary because the air tightness of buildings has been increasing. But, in hot and humid climates, the ventilation causes the increase of the cooling and dehumidification load in the room.

Moreover, a conventional mechanical dehumidification system using a vapor compression refrigeration cycle has some problems. The major problem is that the system efficiency becomes very low because it needs to decrease the evaporative temperature below the dew-point temperature of the process air. Furthermore, growth of mold on the surface of heat exchanger tubes or air ducts is also a serious problem for the human health.

From this viewpoint, much attention has been paid recently to a desiccant air-conditioning system as an alternative to the conventional mechanical dehumidification system. The desiccant air-conditioning system can dehumidify the humid air without water condensation by the direct contact between the dry desiccant and the process air. And the system can be driven by the low-grade heat source, for example, the solar thermal energy and the waste heat from a cogeneration system. Moreover, unlike the mechanical dehumidification system, the dehumidification process in the desiccant air-conditioning system is separated from the cooling process.

The desiccant air-conditioning system has two types: rotary type and batch type. The rotary type uses a rotary desiccant wheel and obtains temporally constant output. The batch type uses a desiccant packed bed filter and obtains periodic output because it needs to switch the air flow periodically. In this study, we focus on the desiccant air conditioning system with the rotary desiccant wheel. The main component of the desiccant air-conditioning system is the rotary desiccant wheel. The rotary desiccant wheel is operated under various conditions and the heat and mass transfer inside the rotary desiccant wheel is very complicated. Hence, to discuss an optimum design or an optimum operation for the desiccant air-conditioning system, both numerical and experimental performance analysis under various operating conditions are indispensable.

Ge et al. [3] reviewed the literatures on mathematical models for the rotary desiccant wheel and classified the models according to the modeling types of the heat and mass transfer between the

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Nomenclature

c	specific heat, J/(kg K)
c_p	constant pressure specific heat, J/(kg K)
D	diffusivity, m^2/s
d_h	hydraulic diameter of air channel, m^2/s
f	friction factor of air channel, –
h	specific enthalpy, J/kg
h_{ads}	heat of adsorption, J/kg
h_{eva}	heat of vaporization, J/kg
j_c	convective mass flux in air channel, kg/m^2
$\mathbf{j}$	vector of mass flux, kg/m^2
k	thermal conductivity, W/(m K)
M_w	molecular weight of water
$\mathbf{n}_y$,$\mathbf{n}_z$	unit vectors in y and z direction, –
q_c	convective heat flux in air channel, W/m^2
p	pressure, Pa
$\mathbf{q}$	vector of sensible heat flux, W/m^2
T	temperature, °C
u	velocity, m/s
w_a	water vapor mass fraction, –

Greek symbols

α	convective heat transfer coefficient, W/(m^2 K)
β	convective mass transfer coefficient, m/s
ε	porosity of porous solid, –
ρ	density, kg/m^3
γ	mean radius of pore, m
τ	tortuosity factor, –
ω_d	water content, –

Subscripts

a	humid air in pore
ac	humid air in air channel
d	desiccant
da	dry air
i	interface
k	Knudsen
m	molecule
p	pore
s	surface or solid
sw	solid and adsorbed water
v	water vapor in por
vc	water vapor in air channel
w	adsorbed water

humid air in air channel and the desiccant wall. For example, Holmberg [4] developed the mathematical model using the overall heat and mass transfer coefficients to express the heat and mass transfer between the humid air in air channel and the desiccant wall. The adsorption isotherm in this study is assumed to be linear function. San and Hsiau [5] considered the heat and mass transfer in air channel side and desiccant wall side separately and developed the mathematical model. In the air channel side, the model is one-dimensional and based on convective heat and mass transfer. In the desiccant wall side, the model is one-dimensional too and based on the mass diffusion and heat conduction. Only surface diffusion is considered inside the desiccant wall. They investigated the effect of several parameters, for example the number of transfer units, on the performance of the desiccant wheel using the mathematical model that they developed.

Charoensupaya and Worek [6] developed the mathematical model considering both side heat and mass transfer separately. In the air channel side, the convective heat and mass transfer coefficients are assumed to be constant. In the desiccant wall side, both the pore diffusion and surface diffusion are considered. The model is validated by comparison with experimental data of isothermal adsorption. Then they analyzed the effect of several important parameters, especially heat and mass transfer Biot numbers, on the performance of the desiccant cooling system. Sphaier and Worek [7] suggested the mathematical model considering both side heat and mass transfer separately too. The dimensionless governing equations are derived in their study. Especially in the desiccant wall side, the heat and mass diffusions of the water vapor in the pore, adsorbed water on the solid surface and the solid material are carefully considered. Furthermore, the desiccant wall in their model includes not only the adsorbent but also the other solid material. This model is validated only with a few experimental data. They described that it was a big problem that the pressure drop is not evaluated in detail. Currently many size of a desiccant wheel have been developed from small thin type to large thick one. And driving conditions are quite different, depending on the utility. Therefore, we need the mathematical model that can be adopted with wide range of driving conditions.

Moreover, Ge et al. [8] developed a mathematical model for predicting the performance of silica gel haloid compound desiccant wheel that is newly suggested. In their model, both the gas side and the solid side resistances are considered. As results of simulation using their model, they clarified the effects of regeneration section angle, air inlet conditions, and wheel rotational speed on the moisture removal efficiency and the dehumidification coefficient of performance (DCOP).

Jeong et al. [9] focused on a hybrid dehumidification air-conditioning system with a four-partition desiccant wheel and conducted the performance evaluation using a simple mathematical model. In their model of the desiccant wheel, the heat and mass transfer resistances between the gas side and the solid side is considered as an overall resistance. Through their discussion, the mathematical model is validated because the simulation results using their model were in good agreement with the experimental results.

In this study, the numerical and experimental performance analysis of silica gel desiccant wheels are carried out under wider range of conditions than those of the previous studies. The mathematical model considering the convective heat and mass transfer in air channel side and the heat and mass diffusion in the desiccant wall side separately are developed. The model includes the effect of the entrance region on the local convective heat and mass transfer coefficients. These coefficients are derived from the separate CFD analysis. We also evaluate the pressure drop with CFD analysis that is very important design parameter, but was not investigated so far.

The experiments for the performance evaluation are conducted under wide range of conditions to clarify the impact of some important operating and structural parameters on the performance of the desiccant wheel-outlet air conditions and pressure drop to validate the mathematical model. The parameters and the ranges are as follows: The regeneration air temperature from 50 to 80 °C, the air superficial velocity from 1.0 to 4.0 m/s, the desiccant wheel thickness 20–400 mm and the wheel rotational speed from 3 to 200 rph. The regeneration air temperature is the one of the most important operating parameter, because it depends directly