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Analytic solution to predict the outlet air states of a desiccant wheel with an arbitrary split ratio

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ABSTRACT

To comprehend the underlying physics of desiccant wheel operation, a feasible analytic solution has been developed from a gas-side resistance model. As a continuation of development, in this study, the analytical model of the previous work is improved by extending the existing model to arbitrary split ratio case. Furthermore, to improve the accuracy for extended operation range of desiccant wheel, the humidity lines on psychrometric chart are separately represented by two gradients, ψ_p and ψ_r, from process region and regeneration region. The analytic solution explicitly predicts the temperature and humidity ratio of the outlet air with a simple linear algebra calculation. The outlet air states from the analytical solution are compared with experimental results and with numerical results predicted by a gas-side resistance model according to various design and operation parameters. For various operation condition, the analytic solution demonstrates transient behaviors of the temperature and humidity ratio within the margin of 10% with respect to the root mean square error during whole cycle period, and shows the better prediction in the practical operation range. The simple time-averaged errors, which are more meaningful in practical sense, are surely observed even smaller than the root mean square errors, within 5%.

1. Introduction

The desiccant wheel (DW) is a primary constituent of desiccant-based dehumidification and cooling systems [1,2]. As the desiccant wheel continuously rotates, dehumidification section of the wheel adsorbs moisture from the process air stream, while the rest of the wheel, regeneration section, releases the adsorbed moisture to the regeneration air stream. In DW operation, the difference in vapor pressure between the air stream and the desiccant surface drives both the adsorption and release of moisture [3]. To understand the moisture kinetics in such processes, the accompanied heat and mass transfer in DW, including latent heat transfer, should be thoroughly examined. Developing a model for DW from a mathematical point-of-view has always been a research topic of great relevance. From an aspect of system engineers who find a “rule-of-thumb” to set key parameters to design desiccant cooling systems; to scholars in academia of whom are trying to uncover underlying physics of the dehumidification processes of desiccant materials, finding proper mathematical models to represent DW has been a bottleneck in desiccant cooling research for past several decades. Generally, the mathematical models for DW are categorized into two groups: (1) Gas Side Resistance (GSR) model and (2) Gas and Solid-Side Resistance (GSSR) model which can be further classified into Pseudo-Gas-Side (PGS) model, Gas and Solid-Side (GSS) model and Parabolic Concentration Profile (PCP) model [4]. Although GSSR model claims to show higher precision than GSR model, because of its complexity, GSR model is still more preferred by most of desiccant cooling research group.

To solve the established models as above, various approaches such as empirical [5–8], numerical [9–14], and analytical [15–22] methods have been suggested and applied. Mostly commonly, numerical methods are accepted as the most conventional way of solving the system because it guarantees the highest precision to solve complex physical problems and also have broad consensus in international research community on its availability by widely available computing tools. However, constructing and solving numerical problems of DW fails to manifest physical implications of DW processes because of its complexity for users to directly draw physical intuition from numerical solving steps, even though it can yield immediate numeric answer to user. In order to decipher complex physics during dehumidification processes of DW operation, comprehensive, qualitative understanding of the phenomenon is pre-requisite. Analytical models, if they are properly established, in spite of its lower precision than numerical modeling,

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Nomenclature

C_p	specific heat, J/kg K
f_m	mass fraction of desiccant in the wheel
h	convection heat transfer coefficient, W/m^2 K
h_D	mass transfer coefficient, kg/m^{2}s
i_{fg}	latent heat of evaporation, kJ/kg
L	desiccant wheel thickness, m
m	mass, kg
N	Number of transfer unit
T	temperature, ℃
t	time, s
t_{cyc}	total cycle period, s
t_p	dehumidification period, s
t_r	regeneration period, s
u	air face velocity, m/s
W	water content of the desiccant material, kg/kg
x	axial coordinate, m
Y	humidity ratio, kg/kg(DA)

Greek letters

α	specific surface area, 1/m
β	area split ratio of the desiccant wheel
Δ	Root mean square value of error
ε	porosity
θ	dimensionless temperature
ρ	density, kg/m^3
τ	dimensionless time
ϕ	relative humidity
ω	dimensionless humidity ratio

Subscripts

a	air
i	inlet
ideal	theoretical ideal outlet condition of process air as described in Fig. 2
o	outlet
p	process side
r	regeneration side
v	vapor
w	desiccant wall

the set-up model itself can illustrate key physical processes in DW operation.

Several previous works [18–21] on analytical studies have mainly discussed the method to construct a simplified model of the heat and mass transfer in DW. They have been aiming to reduce calculation loads of numerical modeling, thus, hard to argue those are fully explicit analytical models. The most recent work by *Kang* et al. [22], which is based upon the most common mathematical model for DW operation, GSR model, explicitly modeled the dehumidification process in a desiccant wheel by setting a set of linear differential equations under linearization assumptions on the temperature and humidity profiles in DW channel and the psychrometric relation. This model, however, was limited to the case in which the split ratio of process and regeneration air of DW is set to equal, which is not common in most of desiccant cooling case.

In this work, to the extent of the existing analytical model [22], an advanced GSR-based fully explicit expressions for temperature and humidity ratio of the outlet air from a DW is developed by embracing more general case in which the split ratio of section area of the desiccant wheel is set arbitrary. Several existing works [21,23–31] that discuss the effect of split ratio to the performance of DW are based upon numerical or empirical methods, hence, they fail to provide its methodology to general users, who are most likely, not equipped with computing facilities or computational skills. The presented model in this manuscript is anticipated to help system engineers to design parameters of DW without delving into details of complex mathematic model as well as complicated problem-solving steps.

2. Analytic solution

A desiccant wheel, cylindrical shape consisting of multiple channels, constantly rotates to alternate periodically the dehumidification and regeneration processes. Desiccant in the channels adsorbs moisture from the process air to dehumidify it during the dehumidification period and then is regenerated by warm air stream removing the moisture from the desiccant during the regeneration period. The air flow direction of each air stream is opposite to the other. When the air-passage is assumed as a straight channel and symmetric adiabatic, the schematic diagram of heat and mass transfer processes in a channel is expressed as Fig. 1(a). *Zheng and Worek* simulated the heat and mass transfer processes using the following equations [32], which can be categorized as a GSR method.

$$\rho_a\left(\varepsilon\frac{\partial W_a}{\partial t}+u_a\frac{\partial W_a}{\partial x}\right)=\alpha h_D(W_w-W_a) \tag{1}$$

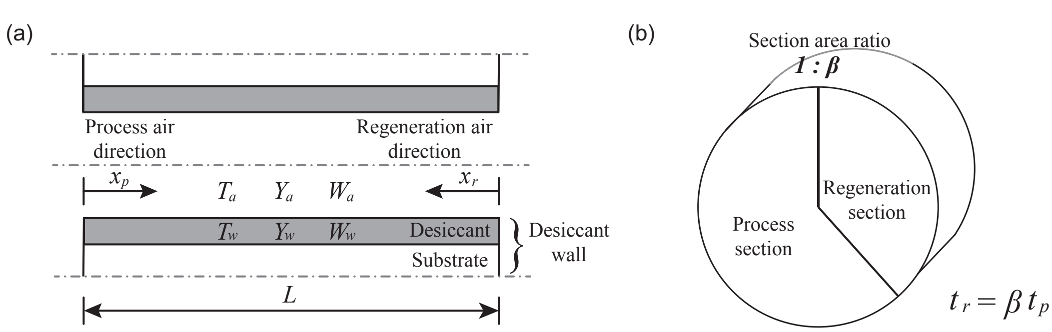

Fig. 1. (a) Schematic diagram of the channel of desiccant wheels (b) illustration of a desiccant wheel in which the split ratio between process area and regeneration area is set as 1:β.