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Effectiveness of a symmetric desiccant wheel operating in balanced flow condition: Modeling and application

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ABSTRACT

Interest in desiccant evaporative cooling technologies is significantly increasing, thanks to the potential of realizing high energy efficiency systems and integrating renewable energy sources. The design of such HVAC systems is, however, not simple mainly due to the complex heat and mass transfer phenomena occurring in the desiccant wheel. For this reason, research effort is being focussed on the development of a simple and accurate model to predict the performance of desiccant wheels. In this work an effectiveness model is developed for the symmetric desiccant wheels operating in balanced flow conditions. Firstly, the effectiveness model is validated via comparison with a numerical model and secondly, its application is demonstrated in the experimental analysis of two different desiccant wheels. It is found that the model predicts well regardless of the differences in the technical specifications of the wheels. The model is considered appropriate for implementation in quick simulation and control programs thanks to its fast non-iterative characteristics.

Efficacité des roues déshydratantes dans des conditions de fonctionnement symétriques: modélisation et application

Mots-clés: Efficacité; Déshydratant; Roue; Adsorption; Déshumidification; Régénération

1. Introduction

A desiccant wheel is a rotary-type heat and mass exchanger that is particularly designed to remove moisture from humid air using heat as a primary energy source. Since it is able to produce dry air with relatively cheap low-temperature heat, its use is increasingly found in various applications where a large quantity of dry air is required, e.g. industrial drying and evaporative desiccant cooling (Goldsworthy and White, 2011; De Antonellis et al., 2012). Desiccant wheels have also been a popular research subject. Many theoretical and experimental studies are found in the literature (Daou et al., 2006; Ge et al., 2008). Much more is known about desiccant wheels thanks to the efforts in the meantime. However, there is still no simple and generally applicable design tool (De Antonellis and Joppolo, 2017). Manufacturers provide a data sheet or an empirical formula for each of their products. Many researchers and engineers use numerical models with varying degrees of complexity. As the application is expanding in the field, demand of a simple tool, which would neither require excessive computing resources nor wheel-specific empirical factors, is growing. A methodology comparable to the effectiveness-NTU method for sensible heat exchangers would be an ideal choice. In general, effectiveness is defined to measure the change of a variable in an actual process in relation to that of an ideal process. Certainly, the variable is chosen depending on the actual process of interest. For sensible heat exchangers, it is obviously fluid temperature but for desiccant wheels, a few different choices have been considered including moist air enthalpy, humidity and water fraction in desiccant as well as air temperature (Sphaier and Worek, 2009; Ruivo et al., 2012; De Antonellis et al., 2015a). For desiccant wheels, effectiveness is not well defined yet. In the literature, variously

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Nomenclature

a	channel height, m
A_s	half surface area in a desiccant wheel, m^2
b	channel base, m
C_{DW}	thermal capacity of a whole desiccant wheel, kJ K^{-1}
C_r	thermal capacity ratio, –
C_p	specific heat, kJ kg^{-1} K^{-1}
c	moisture concentration, kg m^{-3}
D	mass diffusivity, m^2 s^{-1}
d	diameter, m
f_m	mass fraction of desiccant, –
h	transfer coefficient, kW m^{-2} K^{-1}
i_{ads}	heat of adsorption, kJ kg^{-1}
i_{fg}	heat of evaporation, kJ kg^{-1}
Ja	Jakob number, –
K	ratio of heat of adsorption to heat of evaporation ($=i_{ads}/i_{fg}$), –
k	thermal conductivity, kW m^{-1} K^{-1}
L	channel length, m
Le	Lewis number, –
M	molar mass, g mol^{-1}
m_s	half mass of a desiccant wheel, kg
N	number of transfer units, –
Nu	Nusselt number, –
$\dot{m}_a$	mass flow rate (dry air), kg s^{-1}
$\dot{n}$	mass flux, kg m^{-2} s^{-1}
p	pressure, kPa
$\dot{Q}$	heat flow rate, kW
$\dot{q}$	heat flux, kW m^{-2}
R	universal gas constant, kJ $kmol^{-1}$ K^{-1}
T	temperature, K
t	time, s
t^*	dimensionless time ($=t/\tau$), –
u	mean velocity in a channel, m s^{-1}
v	face velocity, m s^{-1}
W	mass of adsorbed water in a desiccant wheel, kg
w	water uptake (mass ratio of water to dry desiccant), –
x	coordinate in flow direction, m

Greek symbols

β	equilibrium constant, –
δ	half thickness of wall or air channel, m
τ	process (half cycle) period, s
ρ	density, kg m^{-3}
σ	fraction of the channel volume in a desiccant wheel, –
Φ	performance index, –
ϕ	relative humidity, –
θ	dimensionless heat flux, –
χ	humidity ratio, –
Ω	rotating speed, s^{-1}
ω	dimensionless mass flux, –

Super- and subscripts

0	initial condition
τ	final condition
a	dry air
ch	channel
DW	desiccant wheel
eq	equilibrium
i	inlet
lat	latent heat
m	mass transfer
o	outlet
p	process air or dehumidification process
r	regeneration air or regeneration process
s	solid
sen	sensible heat
t	heat transfer
w	water

defined effectiveness factors are given either in tables (Sphaier and Worek, 2009) or empirical formulae (Ruivo et al., 2012; De Antonellis et al., 2015a) for some limited ranges of operating conditions. It is notable that the effectiveness formulae in Ruivo et al. (2012) and De Antonellis et al. (2015a) explicitly contain inlet air temperature and humidity, which is different to common concept of effectiveness. As is the case with a heat exchanger, development of an effectiveness correlation requires an analytical solution or an empirical formula to reproduce a large amount of simulation (or experimental) data. For example, Kays and London (1984) lists tables of simulation data for the effectiveness of rotary heat exchangers and also provides an empirical correlation for practical use. It would be helpful to have a similar tool for desiccant wheels.

In this study, an effectiveness model is developed based on the analytical model of Lee and Kim (2014). Lee and Kim (2014) obtained analytical solutions for the dehumidification and regeneration processes in a symmetric desiccant wheel operating in balanced flow condition and combined the two solutions to predict the heat and mass exchange rates in the wheel. However, instead of deriving explicit expressions for the combined solution, they obtained the final solution numerically, which is a clear disadvantage for practical application. For this reason, this study is intended to derive the explicit expressions for the combined solution and to develop an effectiveness model from the results. As the original model is valid for the symmetric wheels under balanced flow conditions, so will be the effectiveness model. The model will provide a simple and flexible tool for design and analysis of those wheels being used in many low-temperature applications (Kuma et al., 1998). Finally, the effectiveness model is applied to two different desiccant wheels in order to evaluate the agreement between the model and the experimental data available in the literature. It is found that the model predicts well for the desiccant wheels regardless of the differences in technical specifications. The model is considered appropriate for implementation in simulation software, worksheets and even in control systems thanks to its fast non-iterative characteristics.

2. Governing equations and the solution

2.1. Approximate solution (Lee and Kim, 2014)

Fig. 1 shows a longitudinal section of a single channel in a desiccant wheel, where δ_a denotes half channel height, δ_s denotes half

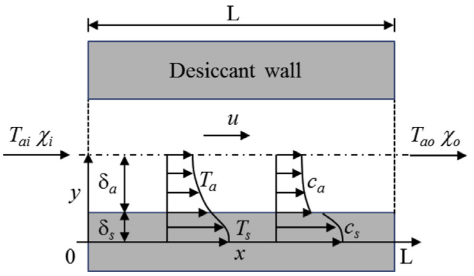

Fig. 1. A single channel in a desiccant wheel.