Energy 76 (2014) 942–948

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A parametric analysis of periodic and coupled heat and mass diffusion in desiccant wheels

Carlos E.L. Nóbrega*

Departamento de Engenharia Mecânica, Centro Federal de Educação Tecnológica, CEFET-Rio, Av. Maracanã, 229, Bloco E, 20271-110 Rio de Janeiro, Brazil

ARTICLE INFO

Article history:
Received 21 October 2013
Received in revised form
26 July 2014
Accepted 3 September 2014
Available online 26 September 2014

Keywords:
Diffusion
Desiccants
Dehumidification
Mass transfer

ABSTRACT

Solid sorbents are frequently adopted for gas component separation in the chemical industry. Over the last decades, solid sorbents have also been applied for the benefit of indoor air quality and humidity control in modern building design. Adsorptive rotors have been designed for the removal of water vapor, CO and VOCs from indoor environments. Although the adsorption of water vapor by a specific adsorbent (particularly silica-gel) has been extensively studied, a non-dimensional parametric analysis of humidity adsorption on a nonspecific hygroscopic material appears to be an original contribution to the literature. Accordingly, a mathematical model using non-dimensional parameters is built from energy and mass balances applied to elementary control volumes. The periodic nature of the cyclic adsorption/desorption processes requires an iterative solution, which is carried out by comparing temperature and mass distributions at the onset to the distributions by the end of the cycle.

1. Introduction

Desiccant rotors have been increasingly used in HVAC (Heat Ventilation and Aor Conditioning) design, allowing for a temperature independent humidity control. Moreover, increasing concern with indoor air quality has led to increased ventilation rates in modern building design [1,2], which can result in excessive indoor moisture in tropical climates. Accordingly, a suitable scenario for desiccant wheels is pictured, since they allow for the unburdening of the cooling coil from the excessive moisture featured in the ventilation air stream. As a consequence, numerical and experimental investigations on desiccant wheels performance have been extensively reported over the last three decades, aiming either at energy consumption reduction on HVAC systems [3] or alternative applications, such as food drying [4] and dishwasher machines [5]. As for the numerical simulations, a mathematical model needs to be set under a number of simplifying assumptions, so as to achieve a relative mathematical simplicity while retaining physical reasoning as much as possible. One approach to the problem consists in the transformation of the energy and mass conservation equations into the same form of energy equations for sensible heat regenerators [6]. This is done by defining new characteristic potentials F_1 and F_2, and a set of non-linear algebraic equations is obtained, which is solved for the process air outlet temperature and absolute humidity [7]. This solution has been adopted in many research efforts, so as to evaluate achievable thermal comfort conditions with desiccant cycles for a given outside air condition [8], or to establish a comparison between enthalpy recovery wheels and heat pipes [9]. It has been also used in a desiccant cooling system design procedure [10], and as a component of a non-linear algebraic system for desiccant cooling cycle simulation [11]. The correlation has also been applied in simulation of hybrid Brayton–Desiccant cycles [12,13], and has shown a good agreement with experimental results for process air outlet temperature but poor agreement for outlet absolute humidity [14]. The distributed solutions, obtained from the solution of energy and mass conservation equations, can be further categorized under one or two-dimensional models. In one-dimensional models [15–17], the mass and temperature are assumed to be distributed exclusively along the flow direction and time. As for bi-dimensional models, both heat and mass diffusions through the hygroscopic layer are accounted for. Although the effects of the resistance to diffusion within the desiccant layer have been targeted by previous efforts, it has been addressed by using dimensional parameters [18–20]. A bi-dimensional formulation in Cartesian coordinates with non-dimensional parameters has been proposed [21], which however disregarded the influence of the adsorptive material isotherm and its relation to the heat of adsorption.

---

* Fax: +55 (0) 21 2568 1548.
E-mail address: nobrega@pobox.com.

http://dx.doi.org/10.1016/j.energy.2014.09.008
0360-5442/

Nomenclature

a	constant
A	heat and mass transfer area (m^2)
A_f	flow area (m^2)
A_p	adsorption potential energy (kJ/kg)
C_p	Air specific heat, (kJ/kg K)
E	Characteristic free energy of adsorption (kJ/kg h$_2$o)
Fo	Fourier number
G	heat generation (W/m^3)
h	heat transfer coefficient (kW/m^2 K)
h_y	mass transfer coefficient (kg/m^2 s)
i	specific enthalpy (kJ/kg)
Ja	Jacobs number
k	Thermal conductivity (W/m K)
k_y	Mass diffusivity (m^2/s)
L	Flow channel length (m)
$\dot{m}$	Mass flow rate (kg/s)
Le	Lewis number
Nu	Nusselt number
P	period of revolution (s)
Pe	Peclet number
Q	heat of adsorption (kJ/kg)
R	Radial coordinate (m)
R_g	Gas constant (kJ/Kmol K)
Sh	Sherwood number
t	time (s)
T	temperature (°C)
u	air flow velocity (m/s)
U	global heat transfer coefficient (W/m^2 °C)
U_y	global mass transfer coefficient (s^{-1})
W	desiccant local moisture content
x	longitudinal coordinate (m)
Y	air absolute humidity

Greek symbols

α	thermal diffusivity (m^2/s)
ϕ	air relative humidity
λ	isosteric adsorption heat (kJ/kg)
θ	non-dimensional temperature
ρ	density (kg/m^3)

Subscripts and superscripts

*	non-dimensional
d	dwell time
dh	dehumidification
f	flow
fg	vaporization
cin	inlet to the wheel (cold stream)
cout	outlet to the wheel (cold stream)
h$_2$o	water
hin	inlet to the wheel (hot stream)
hout	outlet to the wheel (hot stream)
i	inner (channel radius)
in	inlet to the wheel
o	outer
out	outlet to the wheel
reg	regeneration
rev	revolution
s	desiccant material (solid)
sat	saturation
w	air layer in close contact with the desiccant
ws	water saturation
y	relative to mass transfer

2. Mathematical modeling and numerical solution

2.1. Mini-channel and desiccant layer energy and mass transport

For the sake of the mathematical model development, a single desiccant mini-channel, detached from the desiccant wheel is considered in Fig. 1, to which mass and energy balances are respectively performed on the following premises:

- All physical properties are assumed to be constant.
- The air flow is thermally developed.
- Temperature and mass are distributed along the channel and uniform in the perpendicular direction within the flow channel. This assumption has been proved to be valid for typical desiccant wheel length-channel width ratios [19].
- Temperature and mass are distributed along both directions in the desiccant layer, although diffusion in the layer in the x^* direction is neglected. This assumption has been proved to be valid for typical desiccant wheel substrate-channel width ratios [21].

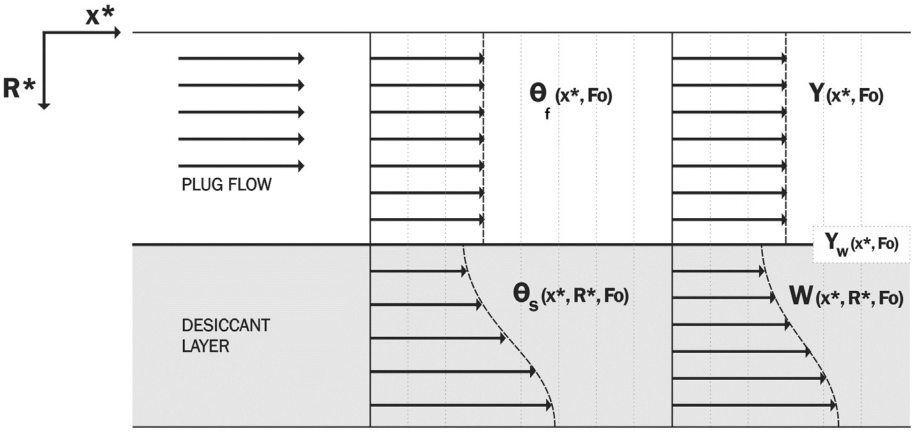

Fig. 1. Schematic representation of a micro channel with a hygroscopic porous wall.