Applied Thermal Engineering 75 (2015) 826–838

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Entropy parameters for desiccant wheel design

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HIGHLIGHTS

- Steady state entropy generation based on effectiveness parameters for heat and mass transfer.
- Definition of a new entropy generation number N_L for desiccant wheel.
- Least irreversible features for a defined dehumidification rate of the desiccant wheel.
- N_L can be used as an optimization parameter for desiccant wheels design and control.

ARTICLE INFO

Article history:
Received 18 July 2014
Accepted 6 October 2014
Available online 16 October 2014

Keywords:
Entropy generation
Thermodynamic analysis
Irreversibility
Desiccant wheel

ABSTRACT

In this work a thermodynamic analysis of a desiccant wheel is proposed to investigate and identify the optimum size and operating regime of this device. A steady state entropy generation expression, based on effectiveness parameters suitable for desiccant wheels operability, is obtained applying a control volume approach and assuming perfect gas behaviour of the binary air–vapour mixture. A new entropy generation number N_L is defined using a minimum indicative value of the entropy generation $S_{L,min}$ and investigated in order to obtain useful criteria for desiccant wheels optimization. The effectiveness-NTU design method is employed by combining solution of thermal exchange efficiency for rotary heat exchanger with the characteristic potential method, under the conditions of heat and mass transfer analogy. The analysis is applied to a specific desiccant wheel and N_L variation with NTU is explored under various operative conditions and wheels characteristics in terms of dimensionless velocity and flow unbalance ratio.

1. Introduction

Pertaining to the study of energy systems, energy conversion can be achieved only as a result of irreversible processes, realizing the required transformations along with an unavoidable degradation of the original amount of energy. The second law of thermodynamics allows to study the limitations imposed to a real process, to determine the maximum possible efficiency of such a process and to compare it to the actual achieved. Therefore, entropy can be used to evaluate the irreversibility introduced, to describe the quality of energy-conversion and to develop consistent criteria for system optimization and control. The efficiency enhancement, generally describing the technological development, can be considered as a secondary result of the actual engineering effort of entropy generation minimization. The corresponding definition of "optimum" condition outlines the least exergy destroying condition which can still assure the system operability.

Devices in which simultaneous heat and mass exchange occur are commonly used in the power and refrigeration industries. In recent years, increasing attention has been paid to energy recovery, or enthalpy recovery, in which both the sensible and the latent heat are recovered. The HVAC&R systems rely on these devices to control the temperature and humidity of the conditioned space in a more efficient way. Most frequently, the latent load of an air-conditioned space constitutes a large fraction of the total thermal load; hence it is substantial to manage latent as well as sensible heat transfer. Conventional air-conditioning systems cope with the issue inefficiently, performing dehumidification process by lowering air temperature below its dew point. Desiccant materials can be an alternative approach which enables the system to achieve the desired air dehumidification rate in a direct way, independently from the dew point of the inlet air stream. Rotary desiccant-cooling systems employ a wheel whose frontal profile is divided in two working sections, one for process stream and the other for

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http://dx.doi.org/10.1016/j.applthermaleng.2014.10.025
1359-4311/

Nomenclature

A_e	exchange surface area $[\mathrm{m}^2]$
B	frontal channel area $[\mathrm{m}^2]$
C	heat capacity $[\mathrm{J\ K^{-1}}]$
C_m^*	wheel dimensionless speed
c_p	constant pressure specific heat $[\mathrm{J\ kg^{-1}\ K^{-1}}]$
d_h	air channel hydraulic diameter [m]
f	fanning frictional factor
Fi	potential functions
G_s	entropy generation group $[\mathrm{J\ kg^{-1}\ K^{-1}}]$
H^x	operating condition factor
i	specific enthalpy $[\mathrm{J\ kg^{-1}}]$
L	channel length [m]
Le	Lewis number
$\dot{m}$	mass flow rate $[\mathrm{kg\ s^{-1}}]$
M	total mass [kg]
n	number of channels
N_L	entropy generation number
NTU	number of transfer units
p	pressure [Pa]
Pr	Prandtl number
R	ideal gas constant $[\mathrm{J\ mol^{-1}\ K^{-1}}]$
Re	Reynolds number
S	entropy generation $[\mathrm{J\ K^{-1}\ s^{-1}}]$
s	specific entropy $[\mathrm{J\ kg^{-1}\ K^{-1}}]$
St	Stanton number
t	temperature [°C]
T	temperature [K]
v	specific volume $[\mathrm{m^3\ kg^{-1}}]$
Y	air absolute humidity
z	dry air specific heat ratio
z_v	vapour specific air ratio

Greek symbol

ε	effectiveness
γ	operating wheel parameter
η	potential function effectiveness
θ	temperature ratio
μ	mass flow rate ratio
ν	cinematic viscosity $[\mathrm{m^2\ s^{-1}}]$
ρ	density $[\mathrm{kg\ m^{-3}}]$
χ	absolute humidity ratio
Ω	rotational speed $[\mathrm{rad\ s^{-1}}]$

Subscripts and superscripts

0	reference variable value
a	related to ambient
c	channel
CF	counter-flow
d	dry air
δ	desiccant
evap	evaporation
f	related to fluid friction
gen	generation
H	related to enthalpy
i	inlet value
L	latent/related to mass transfer
max	maximum
min	minimum
o	outlet value
p	related to process stream/constant pressure process
r	related to regeneration stream
s	sensible
v	related to vapour

regeneration stream. The value of vapour pressure at the desiccant interface can be expressed as a function of the moisture content by the equilibrium isotherm of the specific desiccant material coated onto the wheel matrix.

Besides the heat transfer due to conduction and mixing between process and regeneration streams, during sorption of water vapour in desiccant materials, heat of sorption is released. The heat generated in the desiccant is transmitted through the material which decreases the sorption capacity. Therefore, the heat and mass transfer processes are coupled and desiccant wheel performance can be affected by rotor configuration, desiccant material thermo-physical properties and contingent operating conditions. For these reasons desiccant operability is not easy to be characterized. Influence of inlet temperature and humidity, as well as the possibility to independently vary flow rates, the ratio between regeneration and dehumidification areas and rotational speed shall be investigated in order to approach an optimized design and control of the whole system.

Kodama et al. [1] have analysed the effect of increasing rotational speed on the outlet air state for a silica gel coated desiccant rotor and developed equations to estimate the process air outlet state when working at the optimal rotational speed. Eicker et al. [2] have characterized newly developed rotors composed of different desiccant material, i.e. titanium silicate, lithium chloride, silica gel and silica gel–lithium chloride compound, providing detailed maps for dehumidification capacity, regeneration specific heat input, dehumidification efficiency and enthalpy change of process air at different operating conditions.

Due to the complexity and nonlinearity of differential equations, characterizing the energy and mass conservation laws, in modelling such systems, analytical solutions are restricted to oversimplified formulations. Numerical methods have been applied to solve the partial differential governing equations based on the thermal and mass balance in a small volume element of the wheel in steady state conditions, under different simplifying assumptions [3]. Recently, Ge et al. [4] have reviewed over 20 desiccant wheel models and classified them according to their level of complexity. One-dimensional physical models, also known as Gas Side Resistance (GSR), handle the spatial variations of air and desiccant properties only in the channel axial direction, assuming uniform properties within the desiccant layer thickness. Two-dimensional models, also known as Gas and Solid Side Resistance (GSSR), characterize heat and mass transfer resistance in the direction normal to airflow as well. Sphaier and Worek [5,6] have developed a fully normalized system of equations for the GSSR wheel model and investigated the effect of varying the sorbent mass fraction in composite felt for an enthalpy wheel. However, the use of detailed numerical methods presents several critical issues limiting its applicability, such as the lack of accuracy in the knowledge of the hygroscopic porous medium real properties and the high computational cost. Moreover, HVAC designers would like to refer to physics-based mathematical models suitable to design and estimate the energy consumption summarizing the couplings between the system performance and the sorption characteristics of desiccant material, in a plausibly enough-extended range of operative