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Gray-box state-space model and parameter identification of desiccant wheels

Christian Ghiaus [a], Roula Ghazal [a,b,*], Patrice Joubert [c], Mohamed Yasser Hayyani [b]

[a] INSA-Lyon, CETHIL, CNRS, UMR5008, F-69621 Villeurbanne, France
[b] Aleppo University, Syria
[c] La Rochelle University, LaSIE, CNRS, FRE 3474, F-17000 La Rochelle, France

HIGHLIGHTS

► A non-linear state space-model is obtained from energy and mass balance.
► Data for non-linear model identification are obtained experimentally.
► Model parameters are identified by least squares and Gauss-Newton methods.
► A single gray-box model captures the dynamics of the desiccant wheel for each side.
► This allows to use in control loops a single model on the entire operating range.

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ABSTRACT

A Desiccant Air Unit (DAU) may provide complete control of temperature and humidity in air-conditioned spaces. The key element of the DAU is the desiccant wheel. Its control needs models adapted to the analysis and synthesis of control algorithms. Such models can be obtained by a gray-box approach in which the structure of a state-space model and some of its parameters are derived from first principles and physical laws, while the rest of the parameters are experimentally identified. Identification procedure is simpler and more robust for linear models. In order to develop a non-linear model for the desiccant wheel, parameters of linear local models were first identified. Since the values of the parameters identified for the local models are almost the same, the nonlinear model does not bring more information than a simple and unique model that can be usefully used for control purposes.

1. Introduction

Desiccant cooling is a technique which uses heating, humidification and dehumidification for air conditioning. When solar energy is used as the heating source, this solution is an interesting alternative to conventional vapor-compression refrigeration; the feasibility of this technique in different climates was proven by a literature review [1]. However, the desiccant cooling systems do have some disadvantages: inefficiency in highly humid climates and large size of the system. Moreover, their modeling for control purposes needs more development, which affects the quality of simulation, sizing and control of these systems.

Desiccant air-handling units (DAU) exist in different configurations. Fig. 1 presents a typical constant air solar aided DAU composed of a desiccant wheel (DW), a rotating sensible heat exchanger or sensible wheel (SW), two humidifiers (HUM1, HUM2), two fans (F1, F2), a regeneration heater (RH) formed from a water–air heat exchanger coupled to a solar heating system (SHS), and a regeneration air heater (RAH) which may act as a back-up for SHS. The RH controls the temperature and HUM2 controls the humidity of the air entering the regeneration side of the desiccant wheel.

Experimental investigation and modeling efforts were concentrated mainly on the desiccant wheel, which is the crucial element in a desiccant cooling system. In literature, the estimation of the performance of the adsorptive dehumidifier has been mainly done by means of computer simulations. Wheel models were developed by using analytical methods such as "Analogy Theory" [2,3], or numerical methods such as "Finite Difference Method" [4]. A desiccant wheel can also be modeled by coupling heat conduction with surface and gas diffusion in both axial and radial directions. A two-dimensional thermodynamic analysis takes into account the heat conduction and the gas diffusion in the channel wall in the axial and radial directions, which allows the comparison of the

* Corresponding author. Bât. Sadi CARNOT, 9 rue de la Physique, 69621 Villeurbanne Cedex, France. Tel.: +33 4 72 43 81 83; fax: +33 472 43 88 11.
E-mail address: roula.ghazal@insa-lyon.fr (R. Ghazal).

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Nomenclature

a	channel height [m]
b	channel width [m]
A	adsorption potential [J mol^{-1}]
A_c	air pass-through area of the channel (taken perpendicular on the axis of the wheel) [m^2]
A_d	cross-section area for the desiccant layer in a channel [m^2]
A_g	cross-section area for air flow [m^2]
c	isobaric specific heat [J kg^{-1} K^{-1}]
d_t	thickness of the desiccant coating [m]
D_h	hydraulic diameter of a channel [m]
h	heat transfer coefficient [W m^{-2} K^{-1}]
h_m	mass transfer coefficient [kg m^{-2} s^{-1}]
κ	thermal conductivity [W m^{-1} K^{-1}]
Le	Lewis number [–]
Nu	Nusselt number [–]
P	pressure [Pa]
Q_{sor}	adsorption heat [kJ kg^{-1}]
R	gas constant [kJ kmol^{-1} K^{-1}]
t	time [s]
T	temperature [°C]
U	velocity of air in the channel [m s^{-1}]
L	depth of the rotor [m]
w	water content of the desiccant material [kg kg^{-1}]

Greek notations

φ	relative humidity [%]
ρ	density [kg m^{-3}]
ω	humidity ratio of the air [kg kg^{-1}]
ω_s	humidity ratio of the air in equilibrium with the desiccant at saturation [kg kg^{-1}]

Subscripts

d	desiccant
r	regeneration
g	gas (air)
i	inlet
o	outlet
s	saturation
v	water vapor

performances of desiccant wheels between dehumidification and enthalpy recovery processes [5,6]. If these models are useful for simulation, there is however a lack of models derived from physical laws effective for process control.

A model used in a model-based control may come from white-box, black-box or gray-box approach. The white-box models, which are based on theoretical considerations, are generally found in thermal simulation software for buildings such as TRNSYS [7]. However, they are not well suited for control purposes because their parameters cannot be adjusted based on online experiments. On the other hand, black-box models, which represent input–output relations that fit the measurements, are generally used in practical applications of control. Their parameters are adjustable in function of experimental measurements but lack physical significance. Therefore, these models are valid within the range of conditions for which their parameters are identified. The gray-box models have their structure and some of their parameters obtained from physical laws, while the rest of the parameters are obtained from experiments. A gray-box approach reduces the number of parameters to be identified because, on one hand, it reveals the independent parameters and their interrelations and, on the other hand, it shows the parameters which have fixed values derived from physical considerations.

This paper presents a state-space model of a desiccant wheel obtained from physical laws and expressed in a way which allows the experimental identification of its parameters. The desiccant wheel is modeled as a multi-input multi-output (MIMO) system. At constant air-volume, it has (Figs. 1 and 2a):

- two command inputs, the air temperature, T_{rgi}, and the humidity ratio, ω_{rgi}, on the regeneration side, which are controlled by the regeneration battery (RB) and the humidifier (HUM2) – point 8 in Fig. 1,
- two uncontrolled inputs, the air temperature, T_{dgi}, and the humidity ratio, ω_{dgi}, of the inlet air on the desiccation side – point 1 in Fig. 1,
- four outputs, the outlet air temperature, T_{rgo} and T_{dgo}, and the humidity ratio, ω_{rgo} and ω_{dgo}, on the regeneration (point 9 in Fig. 1) and desiccation (point 2 in Fig. 1) sides.

2. Heat and mass balance equations

The desiccant wheel is composed of channels containing silica gel, a desiccant material (Fig. 2b). The desiccant wheel rotates continuously around its axis; during a full rotation, each channel of the wheel is successively in the process adsorption–desiccation and desorption–regeneration (Fig. 2a).

The model is constructed for a honeycomb channel (Fig. 3b). Considering the channel as the control volume delimited by the air input section, air output section and the mantle of the channel

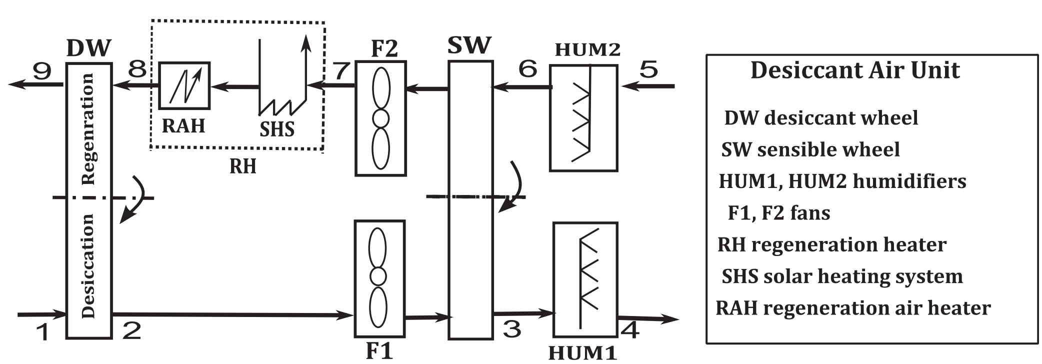

Fig. 1. Schematic of the desiccant cooling system.