Energy Conversion and Management 174 (2018) 649–660

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Desiccant-wheel optimization via response surface methodology and multi-objective genetic algorithm

Alireza Zendehboudi*, Xianting Li

Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Desiccant-wheel design
Dehumidification
Response surface method
Central composite design
Multi-objective optimization

ABSTRACT

A two-step computational framework based on the combination of response surface methodology and multi-objective optimization is proposed to model the outlet-air state of desiccant wheels and subsequently optimize their operation. Regeneration temperature, surface area ratio, rotational speed, and wheel diameter are considered as decision parameters in the genetic algorithm. The central composite design and response surface methods have been employed to design experiments, establish predictive empirical models, and determine interactive effects of decision variables on response variables—process outlet temperature and humidity ratio. Several experiments have been performed to verify applicability of the proposed methodology and validate obtained results. A value of the coefficient of determination exceeding 0.95 demonstrates high reliability and accuracy of the modeling process involved in the proposed methodology. Results obtained demonstrate greater dominance of the surface area ratio compared to other decision variables in terms of their influence on response variables. After successful validation against experimental data, the developed models have been considered as a combination of two objective functions. A fast and elitist non-dominated sorted genetic algorithm II-based optimization technique has been employed to simultaneously determine optimum values of decision variables. A Pareto-optimum front has been presented to select the best value of each decision parameter from available points of optimum operation, and a valuable equation for Pareto-optimal points has been deduced for each material to assist designers develop an optimum design of desiccant cooling systems.

1. Introduction

Today, vapor-compression systems represent the dominant technology employed in residential, commercial, and legislative buildings to satisfy cooling requirements via simultaneous removal of latent- and sensible-heat loads [1]. Environmental and performance problems associated with the operation of such systems, however, emphasize the need for development of alternate environment-friendly and cost-effective substitute technologies. Utilization of desiccant cooling systems offers one such solution to address such environment- and energy-related concerns as global warming and energy crises. These systems possess the ability to control sensible- and latent-heat loads separately.

A desiccant wheel refers to a rotor filled with solid desiccant material, thereby forming key component of solid desiccant cooling systems for dehumidification based on the adsorption–desorption principle [2]. The wheel constantly rotates through two separate air streams. The process section removes moisture from process air flowing through the unit owing to differences in vapor concentration between process air and desiccant material. Post removal of the latent load from process air, an air-to-air heat pump (operating in the cooling mode), direct–indirect evaporative cooler, or an air-cooled water chiller is adopted to handle the sensible load [3]. To assure continuous operation of the system, a regeneration section is considered to operate in parallel with the dehumidification process, thereby desorbing water vapor from desiccant materials and activating the desiccant again when saturated with water vapor [4]. Thermal energy required to heat regeneration air and drive out moisture can be provided by different heat sources. Kang and Lee [5] experimentally evaluated performance of three desiccant wheels regenerated by means of a hot-water heat exchanger. Angrisani et al. [6] utilized low temperature thermal energy recovered from a micro-cogenerator to regenerate desiccant material. In the study reported by Uckan et al. [7], the heat required for heating of regeneration air to desired regeneration temperature was supplied by an electric heater unit. Kabeel et al. [8] used a solar air collector as thermal energy source to regenerate desiccant material.

Owing to the operational importance of desiccant wheels in solid desiccant cooling systems, many numerical and experimental studies have been performed in recent years to evaluate their performance.

* Corresponding author.
E-mail address: a-l15@mails.tsinghua.edu.cn (A. Zendehboudi).

https://doi.org/10.1016/j.enconman.2018.07.078
Received 8 March 2018; Received in revised form 10 July 2018; Accepted 25 July 2018

Nomenclature

ANOVA	analysis of variance
A_R/A_P	surface area ratio
CCD	central composite design
D	diameter (cm)
GA	genetic algorithm
MS	molecular sieve
NSGA II	non-dominated sorted genetic algorithm II
R^2	determination coefficient
RPH	revolution per hour (rev/h)
RSM	response surface method
SG	silica gel
T	temperature (°C)

Greek symbols

Ω	rotational speed (RPH)
ω	air humidity ratio (g/kg)
ε	error in response

Subscripts

out	outlet
P	process
R	regeneration

Beccali et al. [9] developed empirical models to predict the outlet temperature and humidity ratio for silica gel desiccant wheels based on derived correlations between relative humidity and enthalpies of the process and regeneration air streams. Enteria et al. [10] experimentally evaluated a 30-cm diameter silica gel desiccant wheel operating at regeneration temperatures measuring 60, 70, and 80 °C on the basis of moisture removal capacity, moisture removal regeneration, moisture mass balance, and some other indices. In the study reported by Panaras et al. [11], validation of a 63-cm diameter silica gel desiccant-wheel model was performed using experimental data recorded in a test facility, and a satisfactory comparison between experimental results and manufacturer data was performed. Parmar and Hindoliya [12] employed an artificial-neural-network approach to predict the process outlet temperature and humidity ratio of a desiccant wheel. Eicker et al. [13] studied several commercially available desiccant wheels by considering specific-heat input during regeneration, process-air enthalpy change, dehumidification effectiveness, and moisture removal indices as functions of rotational speed, inlet humidity ratio, volume flow ratio, and regeneration temperature. Koronaki et al. [14] used an artificial-neural-network model based on training of an experimental black-box model with experimental data to predict state conditions of air in the process and regeneration streams. Angrisani et al. [15] assessed different performance parameters as functions of the inlet process-air humidity ratio and temperature, regeneration temperature, and ratio between the regeneration- and process-air flow rates. Yamaguchi and Saito [16] designed and validated mathematical model of a silica gel desiccant wheel via comparisons against experimental data. Antonellis et al. [17] developed a model for predicting desiccant-wheels outlet condition based on experimental data. Jani et al. [18] proposed another artificial-neural-network-based approach to estimate the process-air outlet temperature and humidity ratio, dehumidification effectiveness, regeneration outlet temperature and humidity ratio, and moisture removal capacity. Zendehboudi [19] introduced a novel yet simple model based on the least square support vector machine definition to simulate and predict different operating parameters for desiccant wheels.

Desiccant-wheel performance, during actual operation, is influenced by numerous design parameters and operating variables. Efficient operation of the desiccant wheel at the design point is, therefore, highly important to satisfy the high-thermal-efficiency requirement of desiccant cooling systems. Kodama et al. [20] estimated the optimum rotational speed and performance of a rotary absorber by visualizing changes in state of the end product or exhaust air on a psychrometric chart. Chung et al. [21] performed numerical simulations to investigate methods for optimizing the rotational speed and surface area ratio by considering the moisture removal capacity of desiccant wheel as the only objective function. Stefano et al. [22] investigated the optimum rotational speed and process-air angular sectors by considering different indices. Ge et al. [23] developed a mathematical model for estimating performance of a silica gel haloid compound desiccant wheel whilst considering both, gas-side and solid-side resistances of the model. In their study, it was observed that there exists an optimum rotational speed measuring approximately 12 RPH at which maximum moisture removal can be realized. Goldsworthy and White [24] analyzed and optimized the performance of a combined solid-desiccant–indirect-evaporative cooler system. Angrisani et al. [25] investigated the effect of rotational speed on dehumidification effectiveness at low regeneration temperatures. As observed, depending on operating conditions, rotational speeds that tend to optimize dehumidification performance vary in the range of 5–10 RPH. Cao et al. [26] experimentally indicated that a 50 °C regeneration temperature represents optimum working conditions for thin-polymer desiccant wheels (measuring 30, 50, and 70 mm). Tu and Hwang [27] optimized desiccant-wheel performance in terms of its surface area ratio and stage number when regenerated using three different heat sources.

Although desiccant-wheel systems have been subjected to much research, studies concerning multi-objective optimization, wherein achievement the optimum operating conditions forms the prime objective whilst optimizing more than one target variable, are far few in month. The traditional one-variable-at-a-time method of optimization is time consuming owing to a large number of experiments required to be performed. The essential reasoning behind defining such a multi-objective optimization problem can be explained as follows. Desiccant wheels, in their process sections, remove moisture from air flowing through them. Outlet temperature of this process air, therefore, exceeds that of the inlet air, because the heat of sorption of moisture removed from process air is converted into sensible heat. This heat of sorption comprises latent heat of condensation of removed moisture and additional chemical heat, which varies depending on the desiccant type and process-air outlet humidity. Moreover, some heat is carried over into process air via the regeneration sector. Therefore, considering that the outlet temperature and humidity ratio of process air are not independent of each other, a desiccant wheel must be optimized by considering state conditions of outlet air in the process stream to allow the desiccant wheels to work in a high-efficiency mode. However, comparison of these two objective functions at different values of input variables increases the complexity involved in their simultaneous optimization by considering the effects of multiple input parameters. In other words, minimization of these two objective functions involves performing trade-offs, because it is difficult to minimize both these parameters at the same time, since realization of one objective causes failure of another. Therefore, to achieve optimum trade-offs between conflicting objectives, a two-step computational framework, based on a combination of multi-objective optimization and response surface methodology is proposed. With regard to desiccant-wheel optimization, use of the response surface method generates comprehensive information and establish predictive models that help gain better understanding of different parameters influencing desiccant-wheel operation. The established models can subsequently be utilized to design, optimize, and enhance thermal performance of this component in actual applications.

The proposed study aims at investigating the effects of four design