International Journal of Heat and Mass Transfer 103 (2016) 501–515

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Determination of air-to-air energy wheels latent effectiveness using humidity step test data

Farhad Fathieh [a,*], Mohamad Rafati Nasr [a], Saeid Sadeh [b], Robert W. Besant [a], Richard W. Evitts [c], Jens Müller [d], Carey J. Simonson [a]

[a] Department of Mechanical Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada
[b] Department of Chemistry, University of British Columbia, 2036 Main Mall, Vancouver, BC V6T 1Z1, Canada
[c] Department of Chemical & Biological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada
[d] Department of Chemistry, University of Saskatchewan, 110 Science Place, Saskatoon, SK S7N 5C9, Canada

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 12 July 2016
Accepted 13 July 2016
Available online 9 August 2016

Keywords:
Energy wheel
Latent effectiveness
Silica gel
Transient test
Sorption properties

ABSTRACT

Desiccant wheels are capable of recovering a considerable amount of moisture difference between two air streams. This study is aimed at determining the latent effectiveness of a rotary desiccant wheel through small-scale, transient testing. A coating of mesoporous silica gel particles (55 μm particle size-pore width 77.5 Å) was deposited on an aluminum substrate. The physical properties (particle size, pore width, surface area, and surface functional groups) of the silica gel were characterized and its sorption properties were investigated by nitrogen gas adsorption at 77 K. In addition, the equilibrium condition and the kinetics of water vapor sorption on the silica gel sample were studied at 23 °C. A test facility was developed to obtain the exchanger transient response during the dehumidification process and the data was used to determine the latent effectiveness of a regenerator constructed with the silica gel coated aluminum. Moreover, the latent effectiveness was determined using a cyclic test with both dehumidification and regeneration cycles. Good agreement was observed between the latent effectiveness values obtained through the single dehumidification and cyclic tests. A correlation from the literature was used to calculate the latent effectiveness of the silica gel coated regenerator. Comparison between the latent effectiveness determined by transient test data and the correlation showed good agreement when $Ntu_m < 4.3$ and $\omega > 4$ rpm.

1. Introduction

Rotary desiccant wheels are widely used in building ventilation systems and industrial air dryers to recuperate heat and/or moisture from exhaust air stream. The porous structure of a wheel matrix creates thousands of flow channels with hydraulic diameters that are few millimeters in size. Moisture transfer occurs on the surface of wheel channels coated with highly porous desiccant material with strong affinity for water vapor such as silica gel, molecular sieve, zeolite, and composite desiccants [1]. While humid air (supply air in summer or exhaust air in winter) flows through wheel channels, moisture is adsorbed by desiccant particles (the dehumidification process). During the regeneration process, the accumulated water vapor transfers to the dry air stream (supply air in winter or exhaust air in summer). The regeneration and dehumidification process occur continuously as the wheel rotates between the humid and dry air streams.

During the past decades, extensive research has been carried out to model heat and mass transfer in rotary wheels [2–9]. It has been found that the sorption properties of desiccant material have a large influence on the performance of wheels. In these studies, it was assumed that the driving force for moisture transfer was proportional to the gradient of water vapor partial pressure (relative humidity) in the air stream and the moist air in the vicinity of the adsorbent surface. The relative humidity at the desiccant surface was determined using the equilibrium sorption isotherm. However, during transient sorption processes in wheels, the moisture content in the desiccant may be different than its equilibrium sorption capacity as the sorption kinetics are reduced by water vapor in-pore diffusion and access to the internal sorption sites. In fact, the gas diffusion coefficient in microporous and mesoporous desiccants is significantly lower when the average pore width is reduced [10]. Another challenge in this research is that the heat of sorption calculation depends on surface functional

* Corresponding author.
E-mail address: farhad.fathieh@usask.ca (F. Fathieh).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.046
0017-9310/

groups of adsorbent material. A few correlations have been developed based on numerically simulated data that relate the performance of the wheels to the matrix thermal and physical properties, moisture diffusivity, desiccant sorption isotherms, and heat of sorption at different operating conditions [11–13]. Due to these reasons, the proposed correlations in the literature are only valid for certain types of desiccant and specific ranges of operating conditions.

Over the past few years, numerous studies have been conducted to determine the latent (moisture recovery) effectiveness through transient single step testing of rotary wheels [14–17]. During the transient single step testing, a stationary wheel is subjected to a step change in the inlet humidity and the response of the wheel is monitored by measuring the humidity at the outlet. It has been found that the wheel response to step changes in the inlet humidity can be modeled by a first order linear system. An analytical relation has been developed to relate the latent effectiveness to the response time constant of the wheel. Good agreement was seen between the latent effectiveness values obtained through transient testing [18,19] and ANSI/ASHRAE standard testing method [20,21]. Most recently, Fathieh et al. [22] performed the transient single step test on a small-scale heat exchanger to predict the sensible (heat recovery) effectiveness of the full-scale heat wheel with the same matrix materials and physical properties. To account for heat loss/gain during the transient testing, they considered a second mode and extended the analytical relation for latent effectiveness calculations [23,24]. It was verified that the sensible effectiveness values predicted by the transient testing of small-scale exchanger were consistent with data in the literature.

In this that study, the transient single step testing was applied to a desiccant coated small-scale energy exchanger to predict the full-scale wheel effectiveness with identical coating and channel geometry. A novel coating method was used to deposit mesoporous micron-size silica gel particles on the metallic substrate of an exchanger. Several tests were performed to determine the physical and sorption properties of silica gel. Moreover, a new experimental facility was developed to perform transient testing on the small-scale exchanger. The transient humidity measurements were corrected to account for the transient characteristics of the sensors and the latent effectiveness was predicted based on the wheel's response. In previous studies, a second mode was observed in moisture transfer at some operating conditions which could not be fully-described by available models [25]. In this regard, a second order linear model proposed for heat wheels [23] was applied to the energy exchanger to calculate the latent effectiveness. In addition to single step dehumidification and regeneration tests, the latent effectiveness values were obtained through several repeated cycles of dehumidification and regeneration steps (cyclic test) and the results were compared to the single step test. A correlation in literature [12] was used to determine the latent effectiveness and the values obtained through the transient testing and the correlation were compared.

2. Theory

2.1. Latent effectiveness calculation for the single step test

The moisture recovery performance of energy exchangers is often quantified by the effectiveness. The latent effectiveness is the ratio of actual moisture transfer rate to the highest possible moisture transfer rate between the humid and dry air streams [26]. The latent effectiveness of counter-flow energy exchangers for the balanced supply and exhaust air flow can be determined by [27]:

$$\varepsilon_l = \frac{Ntu_m}{1 + Ntu_m} \tag{1}$$

in which

$$Ntu_m = (h_m A_m)/\dot{m}_a \tag{2}$$

In Eq. (2), h_m is the convective mass transfer coefficient, A_m is the total area for mass transfer, and $\dot{m}_a$ is air mass flow rate. In fact, determination of h_m is a practical challenge in wheels with coated channels. Since different mechanisms are responsible for heat and mass transfer in coated channels of rotary wheels, the heat and mass transfer analogy may not be applicable to find h_m. Furthermore, the coating pattern, maldistribution in hydraulic diameter of airflow channels, and entrance effects alter h_m and, consequently, Ntu_m [28]. Fathieh et al. [23] presented an analytical relation to predict Ntu_m of rotary wheel through transient single test as follows:

$$Ntu_m = -\frac{1}{2} Ln\left[1 - \left(\frac{2\omega}{\pi}\right)\gamma_1\tau_1 \frac{\left(1 - e^{\frac{-\pi}{\omega\tau_1}}\right)^2}{1 - e^{\frac{-2\pi}{\omega\tau_1}}} - \left(\frac{2\omega}{\pi}\right)\gamma_2\tau_2 \frac{\left(1 - e^{\frac{-\pi}{\omega\tau_2}}\right)^2}{1 - e^{\frac{-2\pi}{\omega\tau_2}}}\right] \tag{3}$$

In Eq. (3), ω is the wheel angular speed and τ is time constant for wheel response to the step change in inlet humidity. Two time constants for wheel response are attributed to a fast mass transfer mode (for sorption on external surfaces and macro pores) followed by a slow mode (for sorption on micropore and mesopore sorption sites with large diffusion barriers). In addition, γ is the mass transfer weighting factor for these two modes which satisfies the following equation:

$$\gamma_1 + \gamma_2 = 1 \tag{4}$$

Fathieh et al. [23] showed that the wheel time constants and weighting factors can be determined by fitting the double exponential model (DEM) to the transient single step test data as follows:

$$W(t) = \begin{cases} 1 - \gamma_1 e^{-t/\tau_1} - \gamma_2 e^{-t/\tau_2}, & 0 \leqslant t \leqslant \infty \text{ step increase (dehumidification)} \\ \gamma_1 e^{-t/\tau_1} + \gamma_2 e^{-t/\tau_2}, & 0 \leqslant t \leqslant \infty \text{ step decrease (regeneration)} \end{cases} \tag{5}$$

where $W(t)$ is the normalized humidity defined by:

$$W(t) = \frac{w_{out} - w_{init}}{w_{final} - w_{init}} \tag{6}$$

and $w = kg_{water\ vapor}/kg_{dry\ air}$ is the air humidity ratio.

Since the wheel rotates continuously, the inlet humidity alters between the supply and exhaust humidity values in a periodic manner. Based on the fact that the response characteristics should be independent of the number of cycles, Abe et al. [14,15] showed that the time constants and weighting factors obtained through the transient single step test can be used to predict the Ntu_m and latent effectiveness of rotary wheels. Therefore, monitoring the humidity changes across the wheel during the step change, its response characteristics (time constant and weighting factors) can be determined through Eq. (4). Then, the latent effectiveness of a full-scale exchanger with same matrix materials and geometry can be predicted by Eqs. (1) with the Ntu_m given by (3). More details on the governing equations, simplifying assumptions, and analytical approach is available in the literature [23].

2.2. Latent effectiveness calculation for the cyclic tests

In addition to a single step test, the performance of a parallel-flow energy exchanger was also studied during dehumidification and regeneration cycles. The procedure and operating conditions for the cyclic experiment are provided in Section 3.3.2. The latent effectiveness for the parallel-flow exchanger can be calculated as the ratio of the amount of moisture recovered in a half of the nth cycle ($w_{out} - w_{init}$) to the maximum possible moisture transfer between the dry and humid air streams ($w_{humid} - w_{dry}$) within