# EXPERIMENTAL DESIGN AND PERFORMANCE ANALYSIS OF A DESICCANT DEHUMIDIFICATION COLUMN UNDER CYCLIC OPERATING CONDITIONS

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## Abstract

Sorption processes in packed beds are inherently transient and the maximum vapor removal occurs at the beginning of the adsorption cycle. Consequently, temperature swing adsorption (TSA), consisting of charging (adsorption) and regeneration (desorption), is required in order to frequently refresh the packed bed and provide sustainable dehumidification. In this study, the effectiveness of thin desiccant columns in controlling air humidity under periodic charge and regeneration cycles is analyzed. An experimental apparatus was designed to measure the rate of adsorption and desorption under different operating conditions. The TSA strategy is imposed by low and high temperature heat sources. Moreover, a numerical one-dimensional transient model is provided and validated by the experiments under different ambient conditions. Using this model, the effect of design factors such as cycle time, airflow, and regeneration temperature are investigated in order to optimize the performance of the desiccant dehumidifier.

## KEYWORDS

Desiccant Dehumidification, Adsorption, Cyclic Condition, Experiments, Modeling

## INTRODUCTION

Desiccants have received much attention for their industrial applications in purification processes, and in air conditioning and refrigeration systems [1,2]. State-of-the-art dehumidifiers exploit the high hydrophilicity of desiccants to adsorb water from the air. A desiccant dehumidifier reduces the latent heat load on a conventional air conditioning system by reducing the humidity of the air entering the evaporator coil so that water does not condense on the coil. Adsorption systems can operate using low-grade thermal energy sources like solar energy and waste heat [3,4], and they are rather simple in design. Milani et al. recently developed experimental models for solar assisted desiccant dehumidifiers [4]. The main purpose of their device was to extract the water vapor from the atmospheric air entering an air-conditioning system, to reduce the latent heat load in conditions with high relative humidity (80%) and lower the humidity to the human comfort level (≤60%).

Desiccants can be categorized into two main groups, i) liquid desiccants, such as hygroscopic salts and glycols; and ii) solid desiccants like silica gel, zeolite, and activated carbon. Solid desiccants are usually used as adsorbate systems in porous packed columns [5], coated layers [6], and rotating discs (wheels) [7]. Although rotary discs (wheels) are commonly used in recently developed dehumidifiers, desiccant columns are preferred in cases when moving parts are not desirable. One major application of desiccant columns is in mass storage of water vapor or specific gas components of mixtures [8].

Many researchers have reported the sorption properties of desiccant materials [9-11]. For dehumidification purposes, with an adsorption pair of humid air and silica gel, Pesaran [12] proposed using characteristics curves and came up with a useful closed form relation for the relative humidity with respect to temperature and water uptake of the packed bed. Pesaran and Mills proposed a comprehensive and widely used finite-difference model for the heat and mass transfer inside silica-gel desiccant columns [13,14]. Hamed [15] studied transient adsorption inside a packed bed with spherical particles impregnated with calcium chloride as an adsorbate. Recently, Ramzy et al. [16] developed a quasi-steady state numerical model and studied the effect of thermal diffusion on characteristics of desiccant columns [17]. They also studied the performance of a two-bed adsorption with an intercooling unit [18] and showed that a multi-step sorption process helped the overall performance, even considering the extra complexity compared to the conventional system.

Since the sorption process inside packed systems is a transient process, the highest dehumidification potential only can be expected at the very beginning of adsorption (charging), when the maximum concentration difference between the packed bed and the air stream occurs. Therefore, to have a continuous and acceptable rate of drying, the whole process time should be controlled in a periodic operation. One strategy is to utilize a temperature swing mechanism, which is widely used in gaseous mixture drying [2]. This mechanism uses heat as the input energy to break the bond between water molecules and desiccant surface and refresh the bed. In this paper, a test bed is designed to provide the targeted periodic operation by switching between hot and cold sources. These sources have been chosen as representatives of naturally available heat sources like solar or waste heat. The technical issues regarding stabilization of the desiccant column, in terms of humidity and temperature when it interacts with different temperature sources are discussed and the performance of the desiccant system is presented for different climate conditions.

## 1. THEORITICAL BACKGROUND

The adsorption process is an exothermic phenomenon, which can affect the uptake rate inside desiccant pores if the heat is not removed quickly and efficiently. Moreover, desorption of the saturated medium requires a considerable energy from a heat source. Consequently, mass transfer during a dehumidification process is tightly coupled with heat transfer. This leads to a system of complicated transient nonlinear governing equations. There have been many attempts to solve the system of equations, such as the work of Ramzy [16] and Pesaran [12].

The governing equations include moisture and heat transfer inside both the gas and solid phases. A non-homogeneous temperature condition is considered in which convective heat transfer connects the phases. The following equations are used to simulate the mass transfer in the gas and solid phases, respectively:

$$\varepsilon \frac{\partial \rho_a w}{\partial t} + \frac{\partial \rho_a u_a w}{\partial x} = -\rho_s (1-\varepsilon) \frac{\partial q}{\partial t} \tag{1}$$

$$\rho_s (1-\varepsilon) \frac{\partial q}{\partial t} = h_m a_s \left( w - w_{eq} \right) \tag{2}$$

Equation (2) considers the gas-side mass transfer resistance for uptake in the solid phase [13]. In Eq. (2) $a_s$ is the averaged area per unit of volume of the porous media [14] and $h_m$ represents the convective mass transfer coefficient. For an equilibrium isotherm ($w_{eq} = f(T_s, q)$), the formula proposed by Pesaran [13] is used for silica gel with regular density, as is the silica gel used here.

Heat conduction is neglected in both phases. This is a reasonable assumption when the uptake rate is much faster than the rate of heat conduction [10], as is the case here because the thermal conductivity of sorption particles is low (<0.1 W/m·K) [22]. Considering $\gamma_a = \rho_a c_a$ and $\gamma_s = \rho_s c_s$, heat transfer in solid and gas phases are modelled as follows:

$$(1-\varepsilon)\gamma_s \frac{\partial T_s}{\partial t} = \rho_s (1-\varepsilon) \Delta H_a \frac{\partial q}{\partial t} + h_c a_s (T_a - T_s) \tag{3}$$

$$\varepsilon \gamma_a \frac{\partial T_a}{\partial t} + u_a \gamma_a \frac{\partial T_a}{\partial x} = \rho_s (1-\varepsilon) c_v \frac{\partial q}{\partial t} (T_a - T_s) - h_c a_s (T_a - T_s) \tag{4}$$

The first term at the right-hand-side of Eq. (4) is the heat released due to water condensation in the solid phase [10]. Moreover, the non-equilibrium thermal condition is modeled by the last terms in Eqs. (3) and (4), where a convective heat-transfer mechanism between the gas and solid phases is considered [16]. The spatial terms are discretized using a finite-difference method, following the work of Ramzy et al. [16], while the whole system of equations marches through the time using a third-order Runge-Kutta scheme [21]. Radial heat and mass transfer within the bed are neglected, leaving a 1D model of the bed.

## 2. EXPERIMENTAL SETUP

To establish a series of cyclic experiments on a single adsorption bed, two different temperature sources are required, a cold source for adsorption (charging) and a hot source for desorption (regeneration). Two relative humidity sensors were installed to measure the temperature and relative humidity of the air at the inlet and outlet of the column. An anemometer was used to measure the velocity of the air at the outlet of the column. A pressure transducer was also installed at the inlet of the column and the outlet is to atmosphere, allowing the pressure drop of the column to be measured.

Figure 1 schematically shows the switching strategy for adsorption and regeneration periods. For a specific amount of water in air, $w$, two chambers are set to provide low temperature ($T_c$, $RH_c$) and high temperature ($T_h$, $RH_h$) conditions such that $w_c = w_h$. In another word, the system mimics the actual conditions for desiccant dehumidifiers where the ambient air is heated up to regenerate the bed.

The desiccant column was insulated using three layers of polyester core with black polyethylene jacket insulation. The maximum temperature difference between the outer surface of the insulation and the environment was about 4°C with an environment temperature of 24°C and an inlet flow temperature of 80°C.

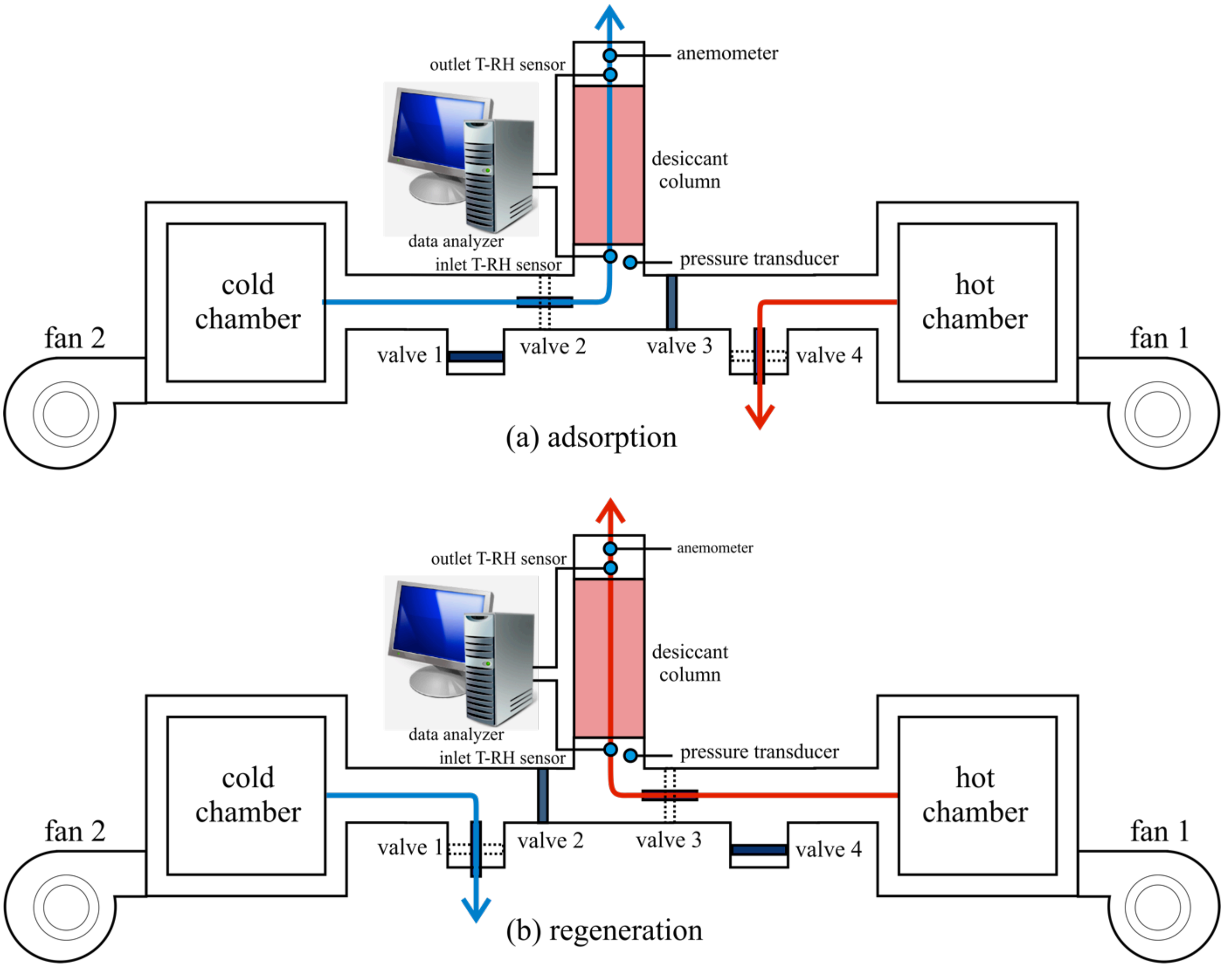



Fig. 1. Experimental setup: schematic of switching between two chambers in adsorption and regeneration processes

## 3. RESULTS AND DISCUSSIONS

Table 1 shows the experiment details for the desiccant column. Three different climate conditions were imposed and designated as test cases 1 to 3 in Table 2. The test cases are typical of summer days in 1) Southern Florida, USA, 2) Vancouver, British Columbia, Canada, and 3) Winnipeg, Manitoba, Canada.

Figure 2(a) and 2(b) show the changes in the temperature and relative humidity before and after a 250 g silica gel desiccant column due to switching between the cold and hot sources. The maximum temperature differences occur near the beginnings of the adsorption and desorption steps. During adsorption, water vapor binds to the desiccant pore surfaces and releases heat, which results in higher outlet air stream temperature. In contrast, desorption requires energy to detach water vapor from the desiccant, which cools down the supply air. The maximum temperature difference in adsorption and desorption are 10°C and 17°C, respectively. The sudden change in inlet air temperature at the beginning of each desorption period leads to a rapid increase in the relative humidity of the outlet air as the hot air picks up a considerable amount of water vapor from the desiccant.

The time variation of the water content of the outlet air, *w*, as well as the total water uptake of the column, *q*, is shown Fig. 3. The water content is calculated by

$$w = \frac{0.622 \cdot RH \cdot P_s}{P_{atm} - RH \cdot P_s} \tag{5}$$

with the saturation pressure calculated from [19]

$$\text{Ln}(P_s) = 2058.96 - \frac{5098.26}{T}. \tag{6}$$

The water uptake is then calculated as

$$q(t) - q_0 = \frac{1}{M_s} \int_{t=0}^{t} \dot{m}_a \left( w_{in} - w_{out} \right) d\tau, \tag{7}$$

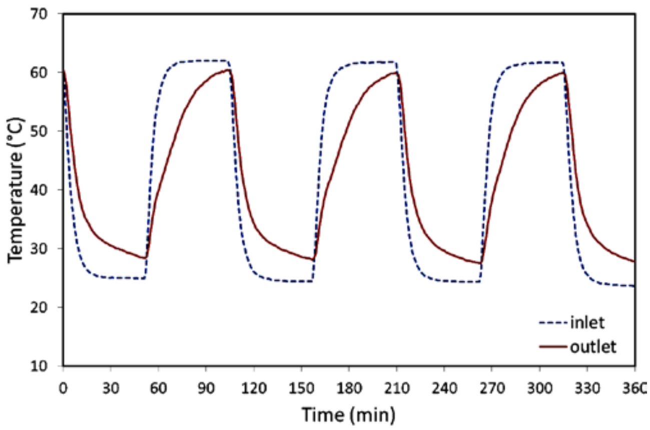
where $q_0$ is the initial uptake.

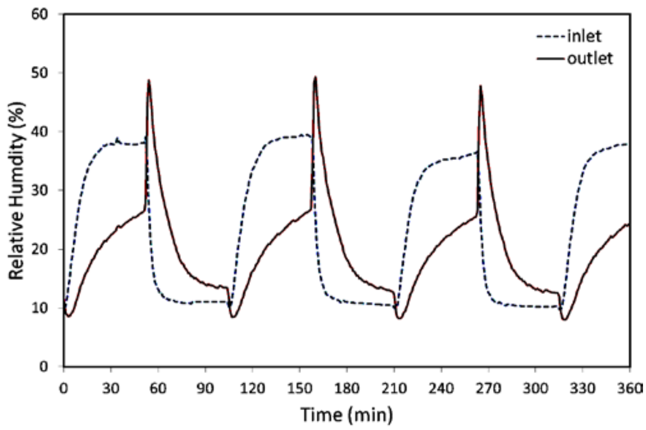
Table 1. Characteristics of the desiccant column.

| Bed diameter (cm) | Mass of dry silica-gel (kg) | Inlet velocity (m/s) | Bulk porosity | Particle diameter (mm) | Desiccant bulk density (kg/s) |
|---|---|---|---|---|---|
| 10.16 | 0.25 – 0.5 | 0.3 | 0.375 | 3.0 | 800 |

Table 2. Test conditions for charging and regeneration of the desiccant bed at different ambient conditions.

| Test Condition | Charging Temperature (°C) | Charging Humidity (%) | Regeneration Temperature (°C) | Regeneration Humidity (%) | Air Humidity ($kg_w/kg_a$) |
|---|---|---|---|---|---|
| Case 1 | 33 | 56 | 60 | 14 | 17.88 |
| Case 2 | 23 | 58 | 60 | 8 | 10.21 |
| Case 3 | 29 | 42 | 60 | 8.5 | 10.55 |




(a) (b)

Fig. 2. (a) Air Temperature and (b) relative humidity versus as the inlet swings between the cold (25°C) and hot (60°C) sources

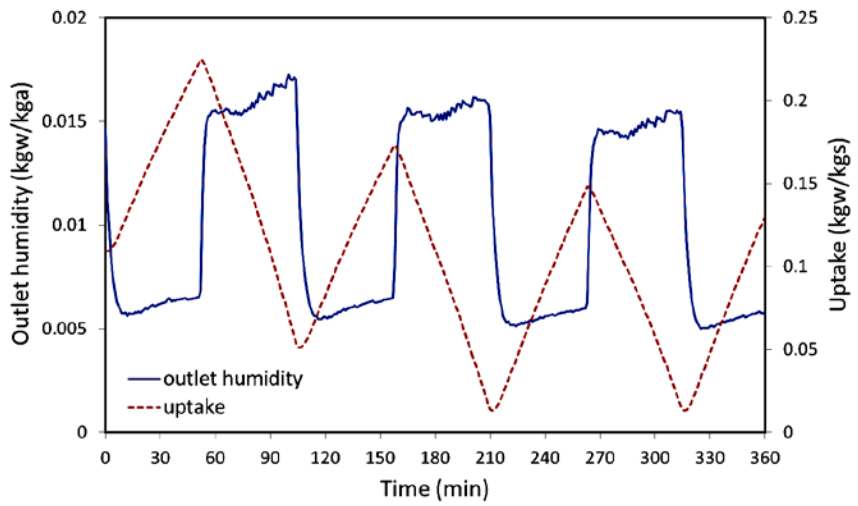


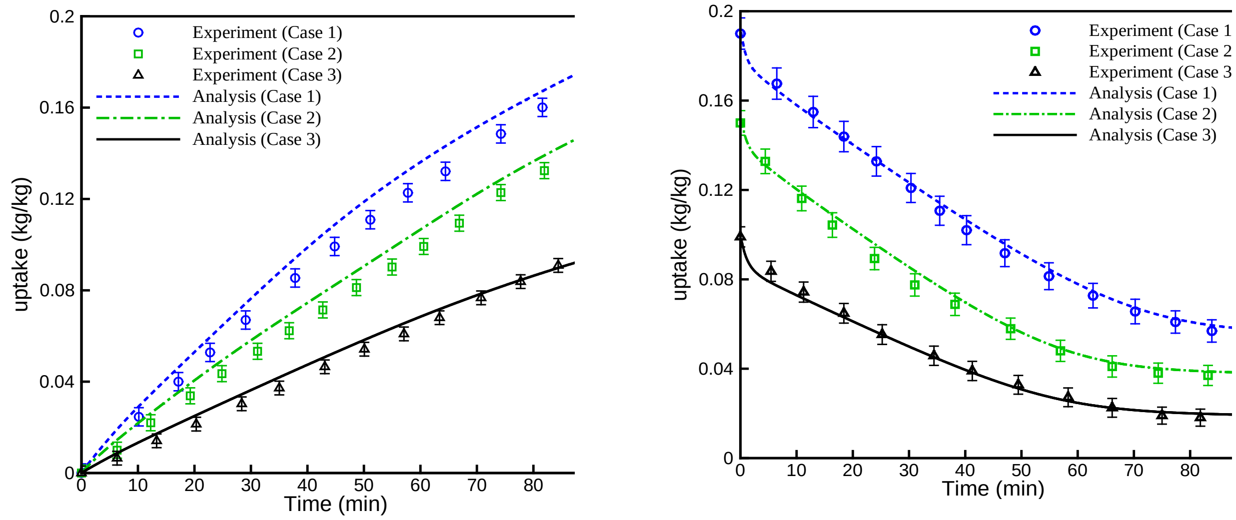

Fig. 3. Absolute humidity at the outlet of the desiccant column and the water uptake in the column

## 4. MODEL DEVELOMENT

In order to validate the numerical analysis, the result of the Runge-Kutta scheme is compared with the experimental data for 500 g of silica gel. Figure 4 shows the uptake for both the experiment and the numerical analysis. A good agreement between the results of 1D model and experiments has been achieved.

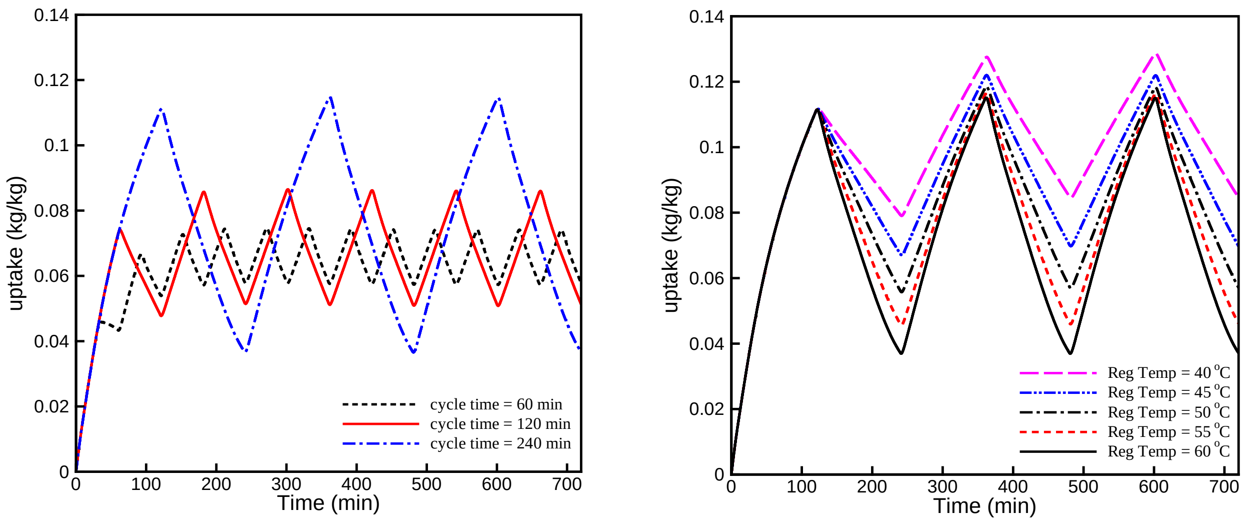
Figure 5(a) illustrates the effects of cycle time on the water uptake of the desiccant column. Increasing cycle time leads to a noticeable increase in water uptake and discharge from the desiccant column. Figure 5(b) shows the effect of regeneration temperature on the water uptake. Increasing regeneration temperature results in greater desorption, which in turn leads to greater adsorption. Thus the system operates better with a higher desorption temperature.

Figures 6(a) and 6(b) show the effect of air velocity on water uptake for two different regeneration temperatures. Both figures demonstrate the positive effect of a velocity increase on the effectiveness of the desiccant column, where the column effectiveness is defined as the uptake change from the beginning of the adsorption to the beginning of the desorption process. As can be seen in Figs. (6) a and b, by increasing the velocity from 0.3 to 0.6 m/s, the effectiveness is improved by 114% at regeneration temperature of 40°C and 55% at 60°C.




(a) adsorption (b) regeneration

Fig. 4 Water uptake for different test conditions in charging and regeneration processes.

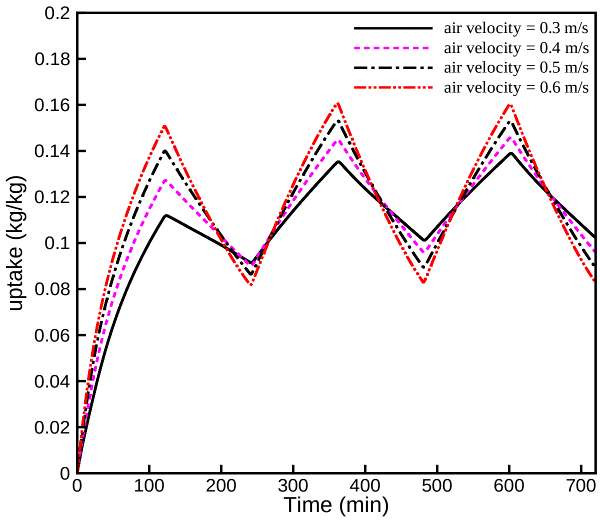



(a) (b)

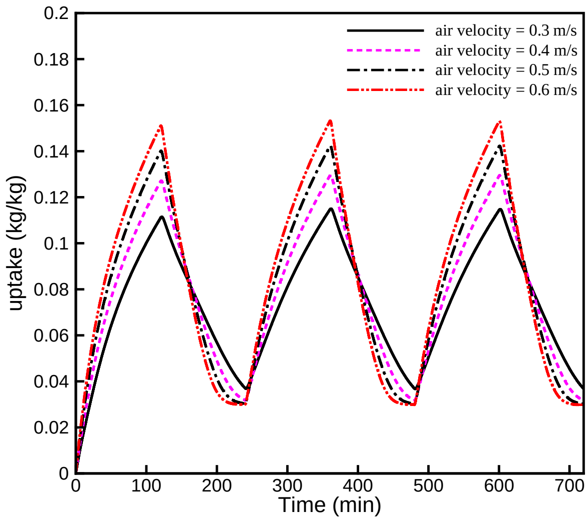
Fig 5 (a) Effect of cycle time on water uptake at a regeneration temperature of 60°C, (b) Effect of regeneration temperature on water uptake at air velocity of 0.3 m/s.

## CONCLUSIONS

The effectiveness of the desiccant dehumidification columns was investigated for periodic charging/regeneration. Two heat sources with constant temperature and humidity were used to impose temperature swing adsorption (TSA). A 1D-model was prepared and validated with the experimental data. The model suitably describes the dynamics of the system under the cyclic conditions. According to both experimental and numerical analysis, the regeneration temperature plays an important role in maintaining suitable performance. Moreover, increasing the inlet air velocity can be helpful to optimize the effectiveness of desiccant dehumidifiers.




(a)




(b)

Fig. 6. (a) Effect of air velocity on water uptake at regeneration temperature of 40°C, (b) Effect of air velocity on water uptake at regeneration temperature of 60°C.

## Nomenclature

| | |
|---|---|
| $t$ | time (s) |
| $x$ | axial coordinate (m) |
| $\rho$ | density (kg/m$^3$) |
| $\varepsilon$ | porosity |
| $w$ | humidity ratio (kg/kg) |
| $RH$ | Relative humidity (%) |
| $q$ | uptake (kg/kg) |
| $T$ | temperature (°C) |
| $a_s$ | surface area per volume (m$^2$/m$^3$) |
| $\Delta H_a$ | enthalpy of adsorption (kJ) |
| $c$ | specific heat (kJ/kgK) |
| $P_s$ | saturation pressure (Pa) |
| $h_c$ | convective heat transfer coefficient (W/m$^2$K) |
| $h_m$ | convective mass transfer coefficient (kg/m$^2$s) |
| $P_{atm}$ | atmosphere pressure |
| $M_s$ | mass of dry silica gel |
| $q_0$ | initial uptake |
| $\dot{m}_a$ | air mass flowrate |

*Subscripts:*

| | |
|---|---|
| $s$ | solid phase |
| $a$ | gas phase |
| $v$ | water vapor |
| $eq$ | equilibrium |

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