CHEMICAL ENGINEERING TRANSACTIONS
VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976120

Effect of Regeneration Conditions on Dehumidification Desiccant Packed Bed

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In the present study, dynamic performance of a dehumidification desiccant regeneration system has been investigated theoretically. The simulation of the combined heat and mass transfer that occur in a solid desiccant packed bed is carried out with MATLAB. The presented model takes into account only forced convection along the bed without heat conduction and heat loss across the wall. The simulated results are validated with the previous published studies. Using the explicit finite differential numerical method, the performances of dehumidification systems are presented by moisture removal capacity (MRC). The dynamic systems have been studied at the regeneration temperatures between 60 to 120 °C and air flow ratio between 0.2 to 2. Increasing the regeneration temperature and the regeneration air flow ratio are shown to have positive effect to MRC. However, excessively increase these values leads to the constant of MRC. Therefore, optimum values for these manipulated parameters has been examined. The result of this study help reducing heat consumption for regenerating heated air; as well as, reducing electric consumption used by the fan.

1. Introduction

Air dehumidification can be achieved by two methods: (1) conventional vapour compression systems, cooling the air below its dew point and removing moisture by condensation, or (2) sorption by a desiccant material. The dehumidification desiccant systems have attracted the interest of the researchers due to its low regeneration temperature. The ability to use the waste heat or solar energy is the main advantages of these systems over the conventional vapour compression systems. Desiccant material in the dehumidification system should undergo both adsorption and desorption processes. For industrial applications, solid desiccant cycles use dual-column packed-bed dehumidifiers; however, the most appropriate dehumidifier configuration for air-conditioning applications is the rotary wheel (Pesaran, 1994). The packed bed can deal with a great amount of moisture adsorption, while the honeycomb rotary wheel gets more uniform humidity in process air. Both desiccant dehumidifiers have certain advantages and disadvantages. The low operational and initial costs constitute important advantages that clearly justify the use of packed bed (Yeboah and Darkwa, 2016). However, issues relating to heat effects, pressure drop and the residence time of the fluid in the bed present significant challenges to the efficient adsorption of water vapour within them (Baghapour et al., 2018).
Many investigators have studied on heat and mass transfer in solid desiccant packed bed (San and Jiang, 1994). In this study the solid desiccant packed bed is applied. Silica gels and zeolites have been utilized for dehumidification processes in industrial and residential applications because of their high moisture adsorption capacity. In general, the regeneration temperature for silica gels is less than that of zeolites. In order to discuss the system of low-temperature regeneration, the silica gel bed is used in this study. As silica gel adsorbs the moisture from the air, it releases heat and raises the air temperature, resulting in the decreasing of adsorption capacity. After it has become saturation with the moisture, the bed is regenerated or reactivated by heat. Engineers notice that the operating cost of this process is dependent on the amount of the regeneration energy. It is seen that the most of the previous works are mainly focused on the dynamic response of a simple adsorption process. To date, little experimental research has been done on the cyclic operation of the packed bed system. Ramzy et al. (2013) have analysed the heat and mass transfer for cyclic operation of a desiccant packed bed using theoretical results which have been supported by the experimental data. In the present work, the

Paper Received: 15/03/2019; Revised: 11/06/2019; Accepted: 24/06/2019
Please cite this article as: Murathathunyaluk S., Junjiewchai J., Kitchaiya P., 2019, Effect of Regeneration Conditions on Dehumidification Desiccant Packed Bed, Chemical Engineering Transactions, 76, 715-720 DOI:10.3303/CET1976120

performance of cyclic operation using packed bed of silica gel particles, express in the amount of water vapour adsorption and process efficiency, is investigated. The numerical model of heat and moisture transfer in packed bed is described and analyzed. Previous experimental data are used to validate the theoretical models. Finally, the effect of operating parameter, (i.e. regeneration air temperature and velocity), on the performance of the bed is investigated numerically.

2. Mathematical model

2.1. Governing equations

Air dehumidification system consists of two solid desiccant packed bed, exchange the operation mode with control valves: one operates as adsorber while the other bed functions as desorber. The heat and mass transfer processes can be modelled into one-dimensional formulations in axial coordination, **z** direction, which is defined as the air flow direction along the bed length. It is assumed a negligible pressure drop along the bed and Lumped capacitance method is adopted. For adiabatic system, the heat and mass transfer take place only forced convection to or from the air flowing through the bed, as follow.

$$\frac{\partial w_a}{\partial t} = -\frac{\dot{m}_a}{\rho_a \varepsilon A_b}\frac{\partial w_a}{\partial z} - \frac{h_m a}{\rho_a \varepsilon}\left(w_a - w_s\right) \tag{1}$$

$$\frac{\partial T_a}{\partial t} = -\frac{\dot{m}_a}{\rho_a \varepsilon A_b}\frac{\partial T_a}{\partial z} + \left(\frac{ha}{\rho_a c_a \varepsilon} + \frac{c_v h_m a}{\rho_a c_a \varepsilon}\left(w_a - w_s\right)\right)\left(T_s - T_a\right) \tag{2}$$

$$\frac{\partial q}{\partial t} = \frac{\dot{m}_a}{m_s}\left(w_{a,z} - w_{a,z+dz}\right) \tag{3}$$

$$k_b \frac{\partial^2 T_s}{\partial z^2} + H_A h_m a\left(w_a - w_s\right) + ha\left(T_a - T_s\right) = c_s \rho_s \left(1-\varepsilon\right)\frac{\partial T_s}{\partial t} \tag{4}$$

Eqs.(1) and (2) are mass and energy conservation equations on gas side and Eqs. (3) and (4) are desiccant side conservation equations, where w_a, T_a, q and T_s are air humidity, air temperature, silica gel moisture content and silica gel temperature, respectively. This model has been validly shown for solid desiccant packed bed with thin desiccant bed, less than 0.15 m, at this condition the pressure drop across the bed is small (Ramzy et al., 2011b). The complete differential equations of mathematical model have the boundary and initial conditions during dehumidification and regeneration processes, as follow:

$$w_a(z=0,t) = w_{a,in} = w_{ambient\ air} \tag{5}$$

$$T_a(z=0,t) = \begin{cases} T_{deh,in}(dehumidification\ \ process) \\ T_{reg,in}(regeneration\ \ process) \end{cases} \tag{6}$$

$$\left.\frac{\partial T_s}{\partial z}\right|_{z=0} = \left.\frac{\partial T_s}{\partial z}\right|_{z=L} = 0 \tag{7}$$

$$\begin{aligned} &w_a(z,t=0) = w_{a0}, \quad q(z,t=0) = q_0 \\ &T_a(z,t=0) = T_{a0}, \quad T_s(z,t=0) = T_{s0} \end{aligned} \tag{8}$$

It should be noted that the final conditions of axial variation in the bed after dehumidification period, as bed temperature and bed water content, are considered as the initial conditions for the next regeneration period and vice versa. To simplify, the time periods of the dehumidification process and the regeneration period are set equal in this study.

2.2 Auxiliary data and relations

The relation between the density of the bed and the density of the particle is

$$\rho_b = \left(1-\varepsilon_b\right)\rho_p \tag{9}$$

The relationship between the equilibrium air humidity ratio (w_s) and the relative air humidity (RH_s) can be expressed as follows:

$$w_s = \frac{0.622 RH_s \times P_{sat}(T_s)}{P_a - RH_s \times P_{sat}(T_s)} \tag{10}$$

where P_a is the atmosphere pressure. P_{sat} is the saturated water vapour pressure calculated using Antoine equation as expressed:

$$\ln P_{sat}(kPa) = 16.2886 - \frac{3,816.44}{T_s(°C) + 227.02} \quad (11)$$

Isotherm for regular density silica gel was studied by Ramzy et al. (2013). Relative humidity at surface of silica gel (RH_s) was correlated to the average water content in silica gel particles as given in the following equation:

$$RH_s(\%) = 55.61 - 2,069q + 27,864q^2 - 169,543q^3 + 560,955q^4 - 968,999q^5 + 682,782q^6 \quad (12)$$

The heat of adsorption of water vapor on silica gel is calculated from the relations presented as follows (Pesaran and Mills, 1987),

$$H_A = \begin{cases} 1,000(3,500 - 12,400q) & q \le 0.05 \\ 1,000(2,950 - 1,400q) & q > 0.05 \end{cases} \quad (13)$$

The specific heats of silica gel and humid air are calculated as follow (Pesaran and Mills, 1987),

$$c_s = 4,186q + 921 \quad (14)$$

$$c_a = 1,884w_a + 1,004(1 - w_a) \quad (15)$$

The thermal conductivity of bed is as follows (Ramzy et al., 2013),

$$k_b = k_a^{\varepsilon} k_s^{1-\varepsilon} \quad (16)$$

where k_s=0.37+0.97q+0.0014T_s, k_a= 0.029 W/(m K)

The convective heat and mass transfer coefficients in cylindrical packed bed of spherical particles are calculated using the following equations (Ramzy et al., 2013),

$$h = 0.683\rho_a v c_a Re^{-0.51} \quad (17)$$

$$h_m = 0.704\rho_a v Re^{-0.51} \quad (18)$$

The input data for experimental conditions derived from references are presented in Table 1.

Table 1: The experimental conditions data of bed

Test	Ref	L (m)	d_b (m)	d_s (m)	v (m/s)	ε	ρ_s (kg/m^3)	q_0 (kg_w/kg_s)	T_{s0} (°C)	$w_{a,in}$ (kg_w/kg_a)	$T_{deh,in}$ (°C)	$T_{reg,in}$ (°C)
1	A	0.0775	0.13	0.0038	0.21	0.31	1,200	0.0417	23.3	0.010	23.3	-
2	B	0.055	0.16	0.003	0.75	0.35	1,200	0.10	31.0	0.020	42.0	-
3	A	0.050	0.13	0.0052	0.67	0.31	1,200	0.26	25.4	0.0007	-	25.4
4	B	0.060	0.16	0.0030	0.75	0.35	1,200	0.283	34.5	0.018	-	85.0

Reference A: (Pesaran and Mills, 1987)
Reference B: (Ramzy et al., 2013)

2.3 Performance indices

In this paper, the performances of dehumidification desiccant packed bed are evaluated base on moisture removal capacity, that can be expressed as

$$\mathrm{MRC} = \dot{m}_a \int_0^{\Delta t} |w_{ai} - w_{ao}|\, dt \quad (19)$$

Where, Δt is the cycle time of dehumidification and regeneration processes which set $\Delta t_{deh} = \Delta t_{reg}$, w_{ai} and w_{ao} are inlet and outlet humidity ratio of the process air and regenerated air. For cyclic operation of a desiccant packed bed, the processes are operated until MRC_{deh}=MRC_{reg} that means the systems are consecutively equal moisture operated.

The purpose of this work is to analyze MRC dependency on the regeneration air temperature and regeneration to process air velocity, which are only two parameters that can be arbitrary set, while the other parameters are kept constant.

3. Validation of the analytic solution

Eqs.(1)-(4) are the mathematical model of heat and mass transfer for adsorption and desorption in a desiccant packed bed. Explicit finite difference method is used to solve this set of coupled nonlinear partial differential equations. In addition, computer programming in MATLAB is developed to assist in the simulation and calculation of the numerical model. The packed bed is segmented into 100 steps based on bed length. Less than 1.5 mm grid mesh and 1 sec. time increment are applied in this simulation to ensure numerical stability and accuracy. Numerical simulation begins with parameter definition settings and initialization for all variables. Eventually, variables w_a, q, T_a and T_s at current grid point are then calculated.

Experimental data for different values of the experimental conditions reported by (Pesaran and Mills, 1987) and (Ramzy et al., 2013) have been used as standard to validate the accuracy of the model which will be used in the bed performance prediction during adsorption and desorption processes. This experimental data shows the variable of exit air in adsorption and desorption processes for silica gel with regular density. The input data for experimental conditions derived from references are presented in Table 1.

The comparison of experimental data and theoretical results of exit air humidity and temperature during adsorption process is shown in Figures 1-2. It can be seen that the numerical results from the current study are consistent with the experimental data and results from previous works, with the errors of exit air humidity and exit air temperature found to be approximately 2.77-4.23 % and 1.31-4.08 %, respectively. For desorption process, the experimental data and theoretical results are shown in Figures 3-4. The errors of exit air humidity and exit air temperature are found to be approximately 6.62-7.46 % and 2.74-4.56 %, respectively.

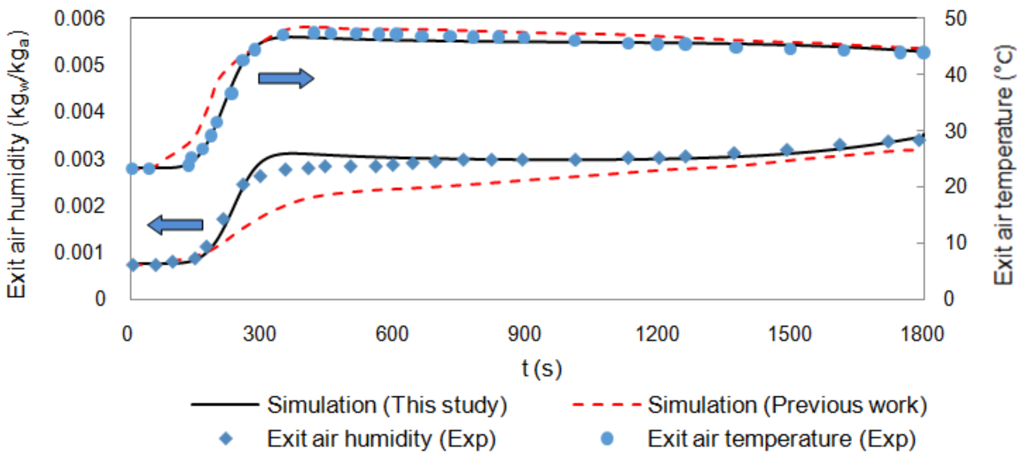

Figure 1: Model predictions compared with experimental (Test 1)

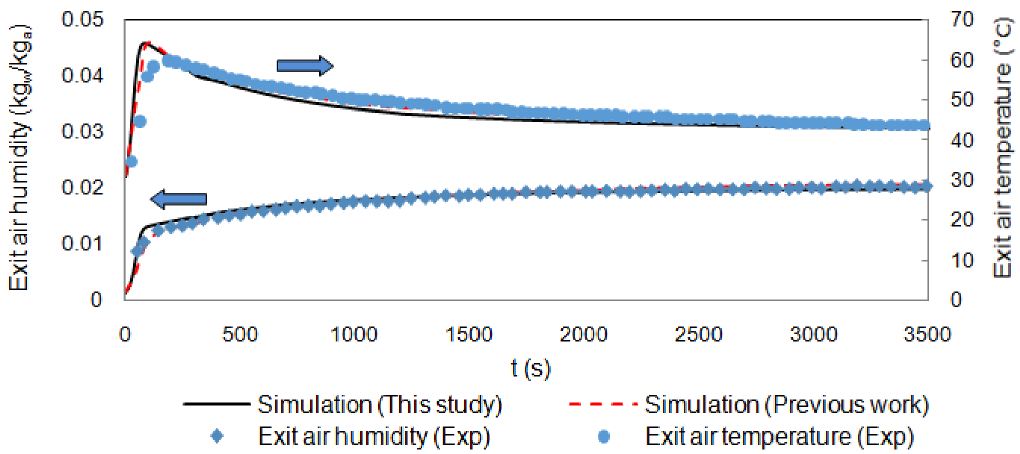

Figure 2: Model predictions compared with experimental (Test 2)

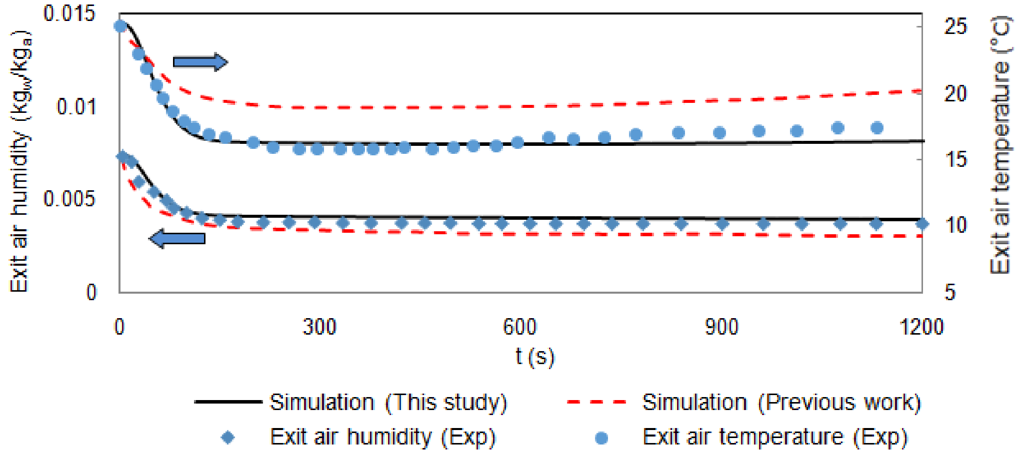

Figure 3: Model predictions compared with experimental (Test 3)

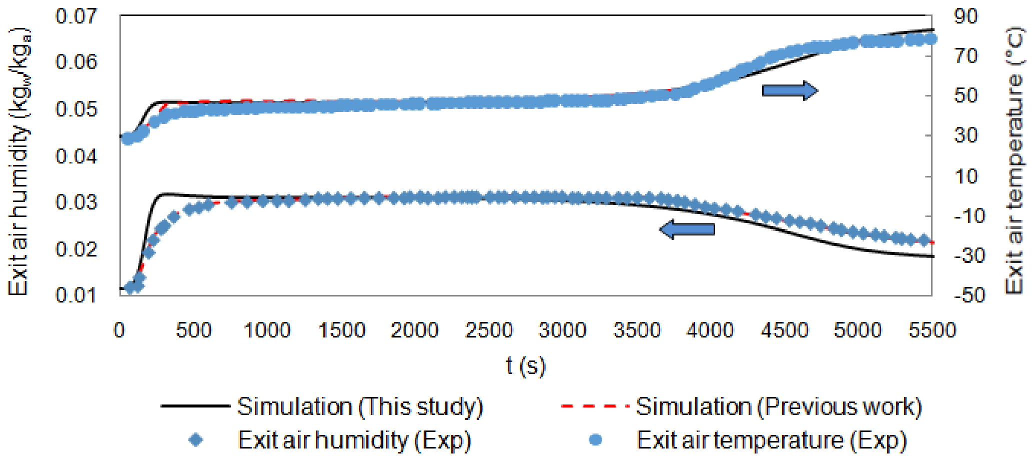

Figure 4: Model predictions compared with experimental (Test 4)

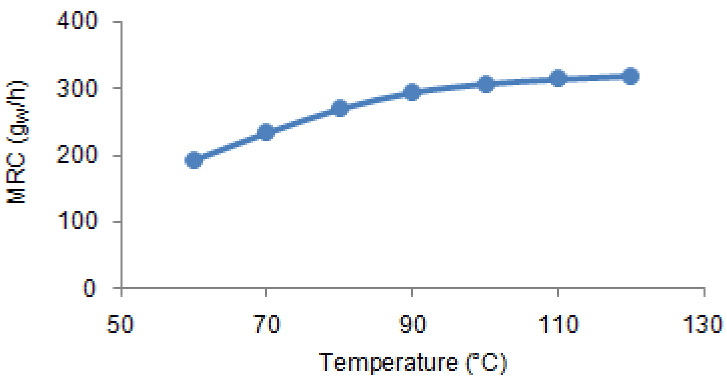

Figure 5: Effect of regeneration temperature on desiccant system performance (L = 0.2 m, $T_{a,in}$ = 30.0°C, $w_{a,in}$ = 0.018 kg$_w$/kg$_{dry}$ air, v = 0.75 m/s)

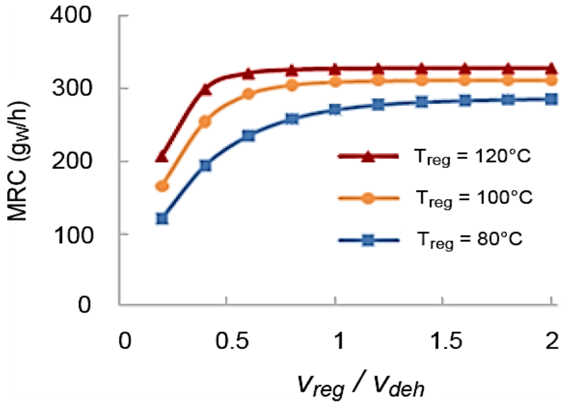

Figure 6: Effect of regeneration to process air flow ratio on desiccant system performance (L = 0.2 m, $T_{a,in}$ = 30.0°C, $w_{a,in}$ = 0.018 $kg_w/kg_{dry\ air}$, v_{deh} = 0.75 m/s)

4. Results and discussion

Based on the obtained results from this explicit finite difference method, trend of factors affecting dehumidification system performance is plotted to evaluate parameters that affect the system behaviour. In Figure 5, MRC based on regeneration temperature is shown. When the regeneration temperature is raised, moisture adsorbed by silica gel is removed out by heating because of high driving force of the adsorbed water vapour and make the desiccant active again. MRC in process air goes up at high regeneration temperature.

In Figure 6 depicts MRC as a function of regeneration to process air flow ratio for difference regeneration temperatures. Increasing the regeneration air flow rate at the same process air flow rate, provides more energy from hot air of which moisture should be removed by the bed, thus MRC increase. However, the system is limited by the bed adsorption capacity, thus excessively increasing air flow ratio becomes ineffective depending on the regenerative air temperature.

5. Conclusions

The dynamic model for predicting the behaviours of dehumidification system has been simulated. The simulated results have been validated and are in reasonable agreement with the experimental data. Two operational parameters: regeneration temperature and regeneration to process air flow ratio have been studied. It was found that increase these parameters lead to the improvement of the dehumidification system performance. The optimum values of these parameters have been found based on different operation scheme.

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