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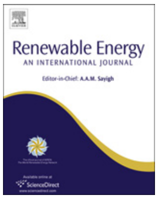

Improved utilization of desiccant material in packed bed dehumidifier using composite particles

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ABSTRACT

Solid desiccant dehumidifiers are widely used in drying processes. In most of these dehumidifiers, the desiccant material is used as packed bed of granule or spherical particles. Investigations of intra-particle heat and mass transfer processes has shown that the entire portion of the particle is not participating effectively during adsorption as well as desorption processes [Pesaran AA, Mills F. Moisture transport in silica gel packed beds-I. Theoretical study. International Journal of Heat and Mass Transfer 1987; 30: 1037–49]. This is because the diffusion rate is very small compared to that of convection. In the present work, a new desiccant composite particle, in which the unutilized portion of the spherical desiccant particle is replaced with an inert particle, is proposed. By replacing the conventional particles with composite particles for the same mass of desiccant material, the available area for heat and mass transfer increases and more amount of desiccant material is effectively utilized. Further, in order to ascertain the improvement in the performance of the desiccant bed using the composite particles, various factors like thermo-physical properties of the inert material, composite particle thickness ratio, bed configuration, bed volume, the pressure drop and the increase in total adsorbed or desorbed mass have to be considered. In view of this, a theoretical investigation of the operation of vertical solid desiccant packed bed dehumidifier, using both conventional silica gel particles as well as the new proposed composite silica gel particles has been reported. A modified solid side resistance (MSSR) model is developed for the prediction of intra-particle temperature and water content profiles. Results of the present theoretical models, when applied to packed bed of conventional silica gel particles, agree well with the experimental results from the literature for both desorption and adsorption processes. From the theoretical results, more utilization for the desiccant material is obtained when ordinary silica gel particles are replaced by composite silica gel particles. For the same amount of desiccant material and same mass flow rate of air, using particles of 0.2 thickness ratio the pressure drop decreases by about 60% for the case investigated. In addition, an increase of about 11.07% and 20.46% in total mass adsorbed and desorbed respectively are obtained. At the time when adsorption process ends, an increase of 15.5% in the bed effectiveness has been obtained. In addition, the expected improvement in total mass adsorbed and desorbed is observed to be dependent on the inert material thermo-physical properties for thickness ratio less than 0.5. An optimization technique relating the composite particle design, resulting savings in pressure drop and bed volume increase is proposed.

1. Introduction

Air conditioning loads can be divided into two components, namely sensible and latent loads. In order to remove the latent heat, traditional vapor compression system (VCS) cools the process air down below its dew point in order to condense out water vapor contained therein. Dehumidified air is then reheated to meet the required indoor conditions. If the latent load is handled by other means than by this deep cooling, two components of the burden on the conditioner brought about by the presence of latent load will be avoided. Desiccant based air conditioning systems give the ability to avoid this deep cooling process. The desiccant materials are used in diverse technological arrangements. One of typical arrangements uses the packing of solid desiccants to form a sort of adsorbent beds exposed to the incoming air stream, thus taking up its moisture. These beds need to be moved periodically in the direction of the regeneration air stream and then returned to the process air

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Nomenclature

A	bed cross section area [m^2]
a	volumetric surface area [m^2/m^3]
C	specific heat [kJ/kg K]
d	diameter [m]
D	diffusivity coefficient [m^2/s]
H_A	heat of adsorption [kJ/kg]
HTR	heat transfer rate
h	heat transfer coefficient [W/m^2 K]
h_m	mass transfer coefficient [kg/m^2 K]
i	counter
k	thermal conductivity [W/m K]
L	length of bed [m]
LC	lumped capacitance model
$\dot{m}$	mass flow rate [kg/s]
MTR	mass transfer rate
MSSR	modified solid side resistance model
n	number of bed layers
NTU_h	number of heat transfer units $ha_sA\Delta z/m_a$
NTU_m	number of mass transfer units $h_m a_s A\Delta z/m_a$
p	average pore diameter [m]
PD	pressure drop [Pa]
q	gel water content [kg_w/kg_s]
r	radial coordinate for spherical particle
Re	Reynolds number
RH	relative humidity [%]
SSR	solid side resistance model
T	temperature [°C]
TMA	total mass adsorbed [kg_v]
TMD	total mass desorbed [kg_v]
t	time [s]
V	superficial velocity [m/s]
VMTR	volumetric mass transfer rate [kg/m^3 s]
w	air humidity ratio [kg_v/kg_a]
z	axial position in bed [m]

Greek

ρ	density [kg/m^3]
β	volume fraction
δ	thickness ratio, $(d_p - d_m)/d_p$
ζ	$-NTU_h/C_a\Delta z$
φ_1	$a_s h_m/\rho_b\beta_s$
φ_2	$ha_s/C_{av}\rho_b\beta_s$
φ_3	$H_A h_m/h$
ε	porosity
v	volume [m^3]

Subscripts

0	initial state
a	air
av	average
b	bed
e	effective
i	inlet
k	Knudsen diffusion
m	inert material
new	new design
o	outlet
p	particle
pe	pore
s	silica gel, surface diffusion
t	total
v	water vapor

stream. Because of low energy requirements for vapor sorption systems (VSS), it becomes highly competitive for replacing the commonly used VCS [2]. A desiccant cooling system comprises three principal components namely, regeneration heat source, which can come from solar energy or any available waste heat, dehumidifier (desiccant material), and cooling unit (sensible heat exchanger). Since the adsorption process is exothermic (i.e. heat is released as the desiccant adsorbs water vapor) the enthalpy of adsorption heats up the bed and rises the exit temperature of the process air stream. In addition, as the temperature of the bed increases, the sorption capacity of the desiccant decreases. This change causes an increase in the humidity ratio of the exit process air stream, and a reduced adsorption capacity for the desiccant bed. Therefore, many researchers are interested in finding new desiccant materials with improved thermal properties. In addition, searching for new design for the desiccant bed as well as bed particles is highly recommended. Many investigators have studied the heat and moisture transfer mechanisms in adsorbent packed bed using the silica gel as a desiccant [1,3–5]. Some others proposed new configurations of desiccant bed to improve the desiccant bed performance and make more utilization for the desiccant material [6,7]. Majumdar [8] investigated the performance of adsorption and desorption processes during a single blow operation in a dehumidifier made of a composite mixture of silica gel particles and inert particles with different compositions and thermophysical properties. It was observed that increasing the inert particles, the process air dehumidified is at lower temperature at exit, but in the regeneration process, the air stream at the exit has higher temperature and lower humidity ratio. Rady et al. [9] investigated the operation of a dehumidifying desiccant bed with macro-encapsulated phase change materials to decrease the effect of heat of adsorption. It was observed that, the air stream at exit had relatively lower temperature and slightly higher moisture content than from purely desiccant bed. Chang et al. [10] studied experimentally the effects of thickness of silica gel, which is formed as a layer on a metal substrate, as well as the particle size on the heat and mass transfer performance of the silica gel coated bed. It was concluded that the thinner consolidated layer made of larger silica gel particles show a better mass transfer performance of the system. Aristov et al. [11,12] developed a composite desiccant by impregnating silica gel with calcium chloride ($CaCl_2$), so that the adsorption capacity of silica gel increases. Chakraborty et al. [13] studied the thermo-physical properties of calcium chloride-silica gel as a composite desiccant for water vapor adsorption for desiccant cooling applications. Pesaran and Mills [1,14] have reported their experimental and theoretical studies on the moisture transport in silica gel packed bed as well as intra-particle water vapor diffusion. Part of their results showed that the entire portion of the silica gel particle was not being utilized fully as desiccant material. Moreover, it leads the bed to need more regeneration energy during the desorption process. The main idea of this study is to propose a composite silica gel particle, wherein a layer of silica gel is coated over an inert particle, with the primary intention that it will enhance the heat and mass transfer processes during the adsorption and desorption modes. Theoretical formulation of the heat and mass transfer governing equations for the vertical packed bed of composite silica gel particles is presented in detail. The performance of the packed bed during adsorption and desorption modes has been evaluated by varying various parameters like composite particle thickness ratio, inert material thermo-physical properties and bed configuration. A comparison study between the performance (i.e. the pressure drop, bed volume and total mass adsorbed or desorbed) of conventional silica gel bed and that of the composite silica gel bed is carried out in such a way that the mass of silica gel material is maintained equal.

2. Physical model

The physical model for the silica gel packed bed is illustrated in Fig. 1. In packed beds of adsorbing material, air loses a part of its moisture content to the particles in a transient heat and moisture transfer process. Fig. 1a shows the bed of desiccant material with the flow of humid air through the bed along the *z*-direction. In the same figure (Fig. 1b), the variation of air properties ($w_a(z,t)$ and $T_a(z,t)$) as it flows through a small increment d*z* of the bed under certain condition ($q(z,t)$ and $T_s(z,t)$) is shown. Also, a sketch for the new proposed silica gel particle versus the common particle design is presented in Fig. 2. The conventional silica gel spherical particle of diameter d_p is presented in Fig. 2a and the composite silica gel particle of diameter d_p with a layer of silica gel coated over the inert material of diameter d_m as shown in Fig. 2b. It is to be noted that in general the diameter of desiccant particle is d_p. Thus, it follows that the excess silica gel due to replacement of inert material is used to make more composite silica gel particles to keep the mass of desiccant in the bed constant. In this case, the increase in number of desiccant particles will increase the volume of the desiccant bed in comparison with a bed of conventional silica gel particles. This increased volume can be used to increase the bed diameter by keeping same height or increase bed height by keeping same diameter.

3. Governing equations for adsorption and desorption processes in a bed of composite silica gel particles

Adsorption/desorption processes in a bed of desiccant material involves a strong interaction between the heat and mass transfer due to the release of enthalpy of adsorption. In addition, the amount of the adsorbable species adsorbed in the bed depends on the temperature at the solid particle surface. Hence, heat transfer by convection between the solid adsorbent particles and the air could influence greatly the local equilibrium conditions and needs to be accounted for adequate description of the process. A theoretical model for combined heat and mass transfer in conjunction with adsorption/desorption in the vertical packed bed is presented as follows:

Consider a packed bed of spherical particles of silica gel, Fig. 1a, with a uniform temperature T_{s0} and initial average silica gel water content q_0. The bed is in equilibrium with the adjacent air layer having water content of w_{s0} and is suddenly exposed to humid air with water vapor mass fraction w_{ai} and a temperature T_{ai}. Water vapor is transferred from the bulk air stream to particles by convective mass transfer at volumetric mass transfer rate $\text{VMTR} = h_m a_s(w_{ai} - w_{s0})$. To calculate the humidity ratio of the air adjacent to the surface of silica gel particle w_s, the water vapor-silica gel isotherm is used. The water vapor - silica gel isotherm is a function of gel water content and silica gel surface temperature $w_s = f(q,T_s)$. The process of moisture adsorption on the surface of the silica gel particles releases an amount of heat called heat of adsorption (H_A), which results in bed temperature rise. This problem can be treated as a transient heat and mass transfer problem, and the following assumptions will be considered in the system analysis,

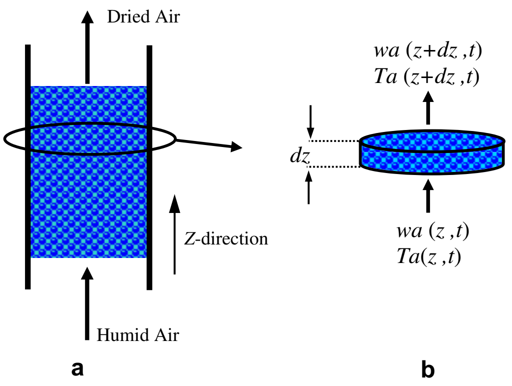

Fig. 1. (a) Physical model for adsorptive packed bed, (b) Air properties through an increment of the bed.

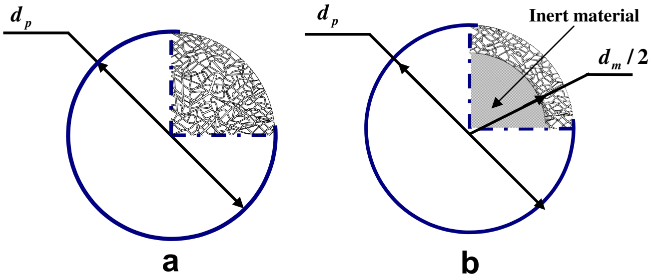

Fig. 2. a) Conventional silica gel particle. b) Proposed silica gel composite particle.

1. The bulk air stream contains only one adsorbable component i.e. water vapor.
2. The flow direction of air in the packed bed is in the *z*-direction only.
3. Heat of adsorption results from the condensation of water vapor in the internal pores of silica gel particles, so the heat of adsorption is assumed to be generated in the silica particles [15].
4. The pressure drop across the bed is small compared with ambient pressure.
5. The heat and mass transfer takes place only by forced convection to or from the flowing air through the bed.
6. The radial dispersion is regarded as unimportant, when the bed diameter is far greater than the particle diameter [16].
7. For relatively high air velocity the vertical dispersion can be neglected,

Governing equations for the adsorption and desorption processes in silica gel packed beds are as follows:

The species conservation equation in the gas phase:

$$-\frac{\partial(\dot{m}_a w_a)}{\partial z}\,dz + \text{VMTR} \times dv = \varepsilon_b dv\,\frac{\partial(\rho_a w_a)}{\partial t} \tag{1}$$

While, overall mass conservation requires that:

$$\varepsilon_b dv\,\frac{\partial \rho_a}{\partial t} + \frac{\partial \dot{m}_a}{\partial z}\,dz = \text{VMTR} \times dv \tag{2}$$

Combining Eqs. (1) and (2) it can be shown that

$$-\dot{m}_a \frac{\partial w_a}{\partial z}\,dz + h_m a_s(w_a - w_s)(1 - w_a) \times dv = \varepsilon_b \rho_a dv\,\frac{\partial w_a}{\partial t} \tag{3}$$

In Eq. (3), the first term in the left hand side represents the change in humidity of flowing air, second term is the net convective mass transfer to the bed, and the right hand side is the storage term in the inter-particle air. Table 1 lists the volumetric surface area a_s as referred from Satterfield and Sherwood [17]. Practically the storage term in Eq. (3) can be neglected [1,6,15] and Eq. (3) is reduced to

Table 1
Volumetric surface area of spheres in fixed beds [m^2/m^3] [17].

d_p [mm]	ε (bed porosity or void fraction)		
	0.3	0.4	0.5
7.63	$a_s = 550$	$a_s = 471$	$a_s = 393$
5.08	825	709	590
2.54	1650	1420	1180
1.27	3300	2830	2360

$$\dot{m}_a\frac{\partial w_a}{\partial z} = h_m a_s A(w_a - w_s)(1 - w_a) \tag{4}$$

For solid phase, using solid side resistance model (SSR) proposed by Pesaran and Mills [1], the species conservation equation for the desiccant particle can be presented as

$$\frac{\partial q}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_e r^2\frac{\partial q}{\partial r}\right) \tag{5}$$

The left hand side is the storage term in the desiccant particle, and the right hand side attributes effective diffusion rates. Eqs. (4) and (5) are coupled by the continuity at the particle surface

$$-D_e\rho_p\frac{\partial q}{\partial r}\bigg)_{r=d_p/2} = h_m(w_s - w_a) \tag{6-a}$$

The second boundary condition for Eq. (5) is as follows:

$$-D_e\rho_s\frac{\partial q}{\partial r}\bigg)_{r=d_m/2} = 0 \tag{6-b}$$

The diffusion coefficient has been calculated from the following equation (may be referred to Pesaran and Mills [1]):

$$D_e = D_{se} + \frac{D_{ke}}{\rho_p}\left(\frac{\partial w_s}{\partial q}\right)_T \tag{6-c}$$

Applying the method of lumped capacitance (LC) for composite silica gel particles, Eqs. (5), (6-a) and (6-b) can be replaced by

$$\beta_s(1 - \varepsilon_b)\rho_s\frac{\partial q}{\partial t} = h_m a_s(w_a - w_s) \tag{7}$$

where, β_s is the silica gel volume fraction of the particle. Eq. (7) has the initial condition as

$$q(z, t = 0) = q_0 \tag{8}$$

The energy balance for gas phase gives

$$\varepsilon_b\rho_a C_a\frac{\partial T_a}{\partial t}dv = C_v\text{VMTR} \times (T_a - T_s)dv + h a_s(T_s - T_a)dv \tag{9}$$

where, the left hand side is the storage term and can be neglected. Rearranging Eq. (9)

$$\frac{\partial T_a}{\partial z} = (C_v h_m(w_a - w_s) - h)\frac{a_s A}{\dot{m}_a C_a}(T_a - T_s) \tag{10}$$

The desiccant particle was assumed isothermal by Pesaran and Mills [1]. In this work the history of the intra-particle temperature gradient in composite as well as conventional silica gel particle is studied using the energy conservation equation

$$\frac{k_{s/m}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T_{s/m}}{\partial r}\right) = \rho_{s/m}C_{s/m}\frac{\partial T_{s/m}}{\partial t} \tag{11}$$

In Eq. (11), air temperature inside pores is assumed same as desiccant temperature, Eq. (11) would be the modification for the SSR model. Eqs. (10) and (11) are coupled by the continuity at the particle surface as follows:

$$k_s\frac{\partial T_s}{\partial r}\bigg)_{r=d_p/2} = h_c(T_a - T_s) + H_s\rho_s\frac{\partial q}{\partial t} \tag{12-a}$$

At the interface of the entire particle and the silica gel, the energy balance gives

$$\rho_{av}C_{av}\frac{\partial T}{\partial t} = \left(k_m\frac{\partial T_m}{\partial r} - k_s\frac{\partial T_s}{\partial r}\right)_{r=d_m/2} \tag{12-b}$$

In addition, the second boundary condition is

$$k_m\frac{\partial T_m}{\partial r}\bigg)_{r=0} = 0 \tag{12-c}$$

For the isothermal particle the LC method is adopted for the energy balance in the bed, the inert material as well as silica gel properties are combined in average properties based on the particle weight composition.

$$C_{av}\rho_b\frac{\partial T_s}{\partial t} = H_A h_m a_s(w_a - w_s) - h a_s(T_s - T_a) \tag{13}$$

where, the storage term is presented on the left hand side and on the right hand side the heat generated due to adsorption (or absorbed due to desorption processes) and convection heat transfer to or from flowing air stream are presented respectively. This equation, Eq. (13) has the initial condition as:

$$T_s(z, t = 0) = T_m(z, t = 0) = T_{s0} = T_{m0} \tag{14}$$

Finally, for the gas phase side Eqs. (4) and (10), initial and boundary conditions are as follows:

$$\begin{aligned} T_a(z, t = 0) &= T_{a0},\ \ w_a(z, t = 0) = w_{a0},\ \ T_a(z = 0, t) \\ &= T_{ai},\ \ \text{and}\ \ w_a(z = 0, t) = w_{ai} \end{aligned} \tag{15}$$

Eqs. (1–15) are the mathematical model for the heat and mass transfer through adsorption as well as desorption processes for the composite silica gel particle packed bed. A summary of LC, SSR and modified SSR models is listed in in Table 2.

The pressure drop (PD) in Pascal through a packed bed of spherical particles can be obtained from the friction factor relation given by Taylor et al. [18] as,

$$\frac{150}{\text{Re}} + 1.75 = \frac{\text{PD}d_p\varepsilon_b^3}{\rho_a V^2 L(1 - \varepsilon_b)} \tag{16}$$

To consider the change in air properties through the bed, the above Eq. (16) has been modified approximately. Accordingly, the pressure drop (PD) is calculated for bed increments individually as follows:

Table 2
Summary of the mathematical model.

Equation	MSSR model of the present study	LC model	SSR model [1]
Gas phase species eq.	Eqs. (4) and (15)	Eqs. (4) and (15)	Eqs. (4) and (15)
Gas phase energy eq.	Eqs. (10) and (15)	Eqs. (10) and (15)	Eqs. (10) and (15)
Solid phase species eq.	Eqs. (5), (6-a) and (6-b)	Eqs. (7) and (8)	Eqs. (5), (6-a) and (6-b)
Solid phase energy eq.	Eqs. (11), (12-a), (12-b) and (12-c)	Eqs. (13) and (14)	Eqs. (13) and (14)

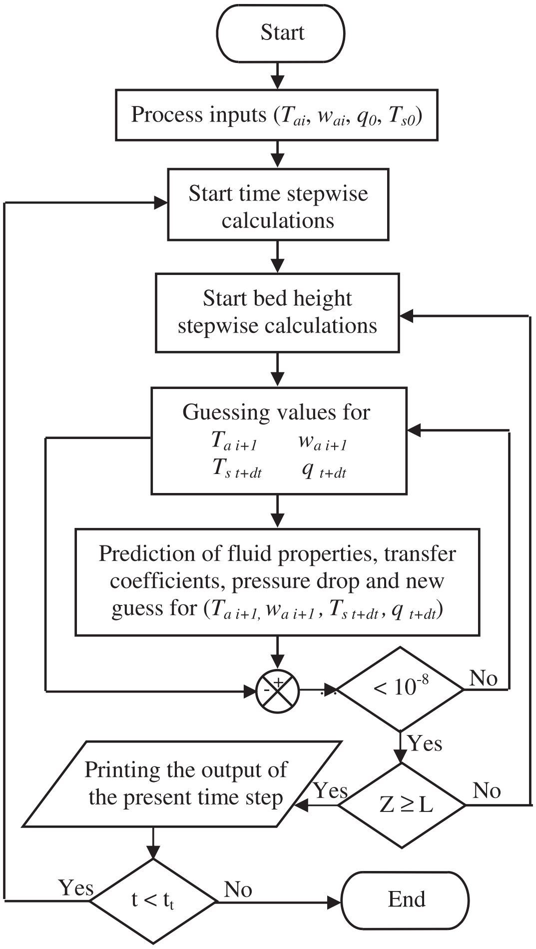

Fig. 3. The flow chart for solving the LC, SSR and MSSR models.

$$\mathrm{PD} = \sum_{i=1}^{n}\mathrm{PD}_i = \sum_{i=1}^{n}\left(\left(\frac{150}{\mathrm{Re}_i}+1.75\right)\left(\frac{\rho_i V^2(1-\varepsilon_\mathrm{b})(z_i-z_{i-1})}{d_\mathrm{p}\varepsilon_\mathrm{b}^3}\right)\right) \tag{17}$$

4. Improvement expected

The new design of silica gel is a composite comprising silica gel and sand as shown in Fig. 2b. The study focuses such that, the mass of silica gel in the conventional bed and the mass of silica gel in the bed of composite silica gel particles is the same. However, due to composite silica gel construction, the volume of the bed and mass will be more due to the presence of sand particles. Due to this, the size of bed made of composite silica gel is larger. This increase in bed size is accommodated in two ways, increasing only the bed height (case (a)), or by increasing only the bed diameter (case (b)).

Case (a): In this case, as the superficial velocity of the flowing air is not changed, heat and mass transfer coefficients are not changed as well. However, the heat and mass transfer area is increased because of increasing bed height $L_\mathrm{new} = Ld_\mathrm{p}^3/(d_\mathrm{p}^3 - d_\mathrm{m}^3)$. For this case, more dehumidification as well as pressure drop is expected for a specified time of operation.

Case (b): In this case, the diameter of desiccant bed is increased according to $d_\mathrm{b\,new} = \sqrt{d_\mathrm{b}^2(d_\mathrm{p}^3/(d_\mathrm{p}^3 - d_\mathrm{m}^3))}$. Moreover, for the same air flow rate, the superficial velocity is decreased, subsequently, pressure drop as well as blowing power through the bed are decreased. On the other hand, heat and mass transfer coefficients are decreased, but the increase in exposed area to heat and mass transfer processes will compensate this decrease. By simple calculations, it can be shown that:

$$\begin{aligned}\mathrm{MTR}_\mathrm{new} &= \mathrm{MTR}\left(\frac{d_\mathrm{b\,new}}{d_\mathrm{b}}\right)^{1.02} \quad \text{and}\\ \mathrm{HTR}_\mathrm{new} &= \mathrm{HTR}\left(\frac{d_\mathrm{b\,new}}{d_\mathrm{b}}\right)^{1.02}\end{aligned} \tag{18}$$

$$\mathrm{MTR} \propto \left(\frac{d_\mathrm{p}^3}{d_\mathrm{p}^3 - d_\mathrm{m}^3}\right)^{0.51} \tag{19}$$

and so is HTR also.

$$\mathrm{PD} \propto \left(1 - \frac{d_\mathrm{m}^3}{d_\mathrm{p}^3}\right)^2 \tag{20}$$

From Eq. (19), it can be observed that mass transfer rate during specified period of operation is inversely proportional to the

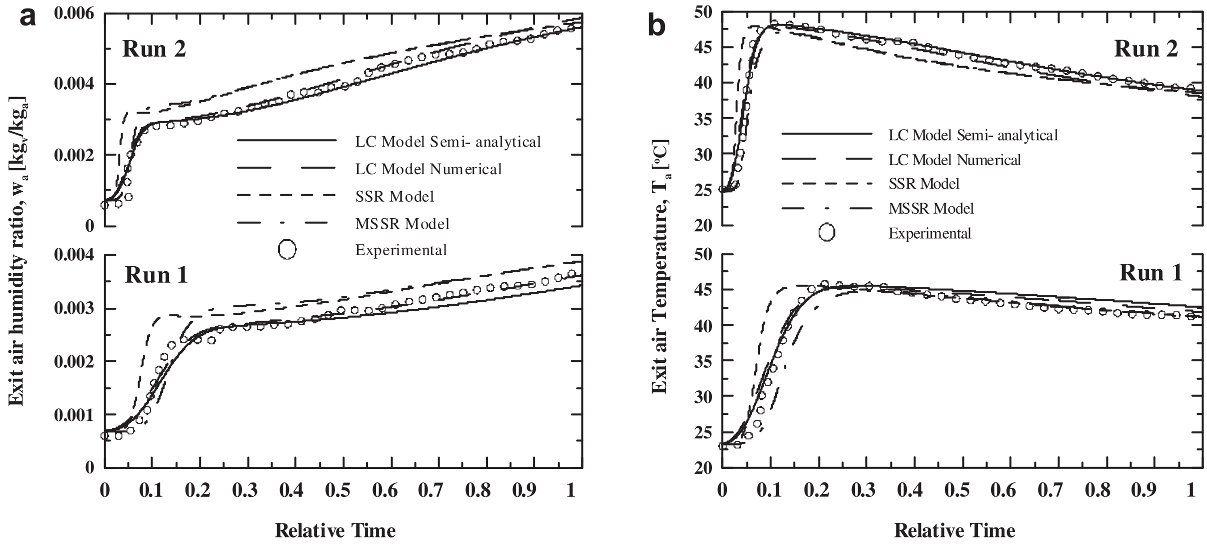

Fig. 4. Theoretical results for adsorption processes of present study and experimental data [14]. a) Exit air humidity ratio b) Exit air temperature versus relative time.

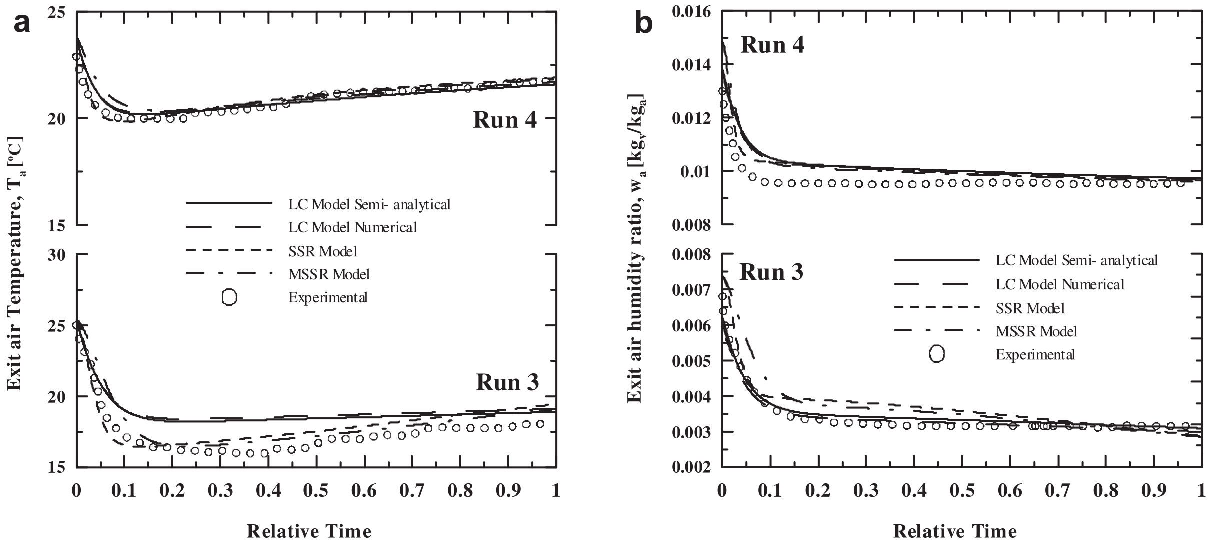

Fig. 5. Theoretical results for desorption processes of present study and experimental data [14]. a) Exit air humidity ratio b) Exit air temperature versus relative time.

thickness of the silica gel in the composite particle. In addition, pressure drop is directly proportional to this thickness (Eq. (20)). Therefore, it is stated here that redesigning the desiccant particle in this way will enhance both heat and mass transfer through the desiccant bed and reduces the required air blowing power. In addition, for comparison purposes the bed effectiveness is defined as $(w_{ai} - w_{ao})/(w_{ai} - w_{s0})$. So, when air is dehumidified until its humidity and the bed equilibrium air humidity at the zero time are the same, in this case, the effectiveness is 1.0 and if the air is coming out without humidity change then the bed has effectiveness of 0.0.

5. Computation procedures

LC model solution: Semi-analytical solution for the LC model has been implemented for thin desiccant bed [19], and the same is implemented for the composite particle packed bed. The LC model is solved using Runge Kutta Fehlberg method [20] for gas phase Eqs. (4) and (10), and using finite difference method for solid phase Eqs. (7) and (13). Eqs. (21)–(24) are the summary of the semi-analytical solution for this model.

$$w_{ao} = \frac{w_s(1 - w_{ai}) + (w_{ai} - w_s)\exp(-\mathrm{NTU_m}(1 - w_s))}{(1 - w_{ai}) + (w_{ai} - w_s)\exp(-\mathrm{NTU_m}(1 - w_s))} \tag{21}$$

$$\frac{T_{ao} - T_s}{T_{ai} - T_s} = \left(\frac{1 - w_{ao}}{1 - w_{ai}}\right)^{-C_v/C_a} \exp(-\zeta \Delta z) \tag{22}$$

$$q_t - q_0 = \varphi_1(w_a - w_s)\Delta t \tag{23}$$

$$T_{st} - T_{s0} = \frac{\varphi_3(w_a - w_s)}{\varphi_2} + \left((T_{s0} - T_a) - \frac{\varphi_3(w_a - w_s)}{\varphi_2}\right)\exp(-\varphi_2 \Delta t) \tag{24}$$

MSSR and SSR model solutions: The gas phase equations are solved using Runge Kutta Fehlberg method. For the solid phase balance equations, namely Eqs. (5) and (11), Crank–Nicholson method is applied. For Eq. (13), the finite difference method is used. The flow chart for developing the computer program for SSR and MSSR models is given in Fig. 3. Following the same, a computer code is developed using Turbo-C compiler.

6. Results and discussion

6.1. Model validation

In the following discussion, the results for adsorption and desorption processes for packed bed of regular density silica gel are presented. A comparison between the experimental data of Refs. [14] and [21] and the results of LC, SSR and MSSR models is evaluated and presented graphically. Fig. 4a shows the exit air humidity ratio versus the relative time. It can be observed that for runs 1 and 2 the humidity is minimum at the start time and sharply increases, the same holds true for exit air temperature, Fig. 4b, until the exit air attains a maximum temperature. Because of high adsorption rates during the initial times, the adsorption heat generated increases the bed temperature sharply, and consequently the flowing air is heated by means of convective heat transfer. With this increase in the system temperature, the ability of the bed to adsorb moisture decreases, and the system continues adsorption at a rate limited by heat and mass transfer rates. For the remaining period of the process, water vapor adsorption from air continues and increases the water content of the bed, which gradually decreases the bed ability for adsorption. Therefore, the adsorption rate decreases gradually, and the dehumidified air acts as a cooling fluid which gradually has lower temperature.

Table 3
Bed and flow conditions for experiments conducted by Refs. [14] and [21].

Run	Ref.	d_b [m]	Process kind	d_p [mm]	L [cm]	q_0 [kg$_w$/kg$_s$]	T_{s0} [°C]	T_{ai} [°C]	w_{ai} [kg$_v$/kg$_a$]	v_a [m/s]	t [h]
1	[11]	0.13	Ads	3.88	7.75	0.0417	23.3	23.3	0.01	0.21	0.5
2	[11]	0.13	Ads	2.54	6.5	0.041	24.7	24.7	0.0106	0.39	0.5
3	[11]	0.13	Des	5.2	5.0	0.26	25.4	25.4	0.0007	0.67	0.33
4	[11]	0.13	Des	5.2	5.0	0.37	23.8	23.5	0.009	0.65	0.33
5	[21]	0.1026	Ads	1.0	8.0	0.004	22.0	22.0	0.01157	0.0708	10

Ads: adsorption, Des: desorption, Ref: reference.

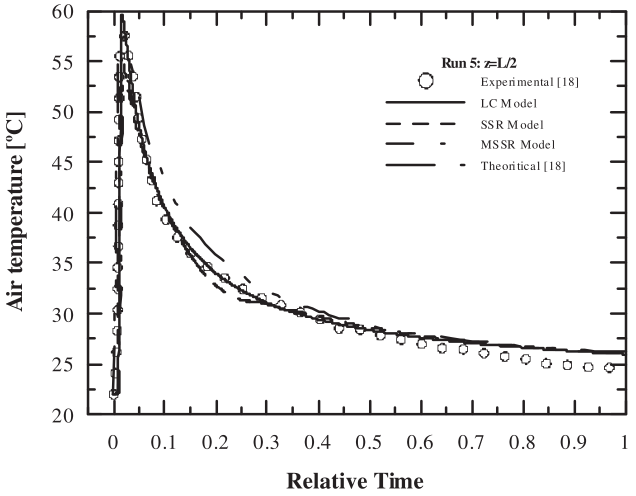

Fig. 6. Theoretical results of present study and experimental data of [21]. Air temperature at $z = L/2.0$ versus the relative time.

Fig. 5 (runs 3 and 4) is the variation of exit air humidity and exit air temperature for the desorption process and the necessary data for calculations are given in Table 3. During desorption process the heat required for the water molecules to transfer from liquid phase inside the pores to vapor in the air is extracted from the bed particles. In runs 3 and 4 very dry air is used for regeneration (pressure sewing process).

As the particles have high water content in the beginning of the desorption process, desorption rate is maximum. With progressing in time, the bed temperature decreases sharply, and consequently the desorption rate decreases. The regeneration air loses its heat to the bed by convection and takes the moisture off, this operation results in the high humidity ratio and low temperature at the exit (Fig. 5a). The desorption process afterwards is limited by the heat transfer from the regeneration air to the bed and the bed water content which is gradually decreasing, then the air temperature is gradually increasing to its inlet temperature and the humidity ratio is decreasing to its inlet value. Fig. 6 shows the experimental results of Ref. [21] as well as the theoretical results of this study for a long period of adsorption process. It can be seen that the adsorption process is continuing for long time but with very low rates.

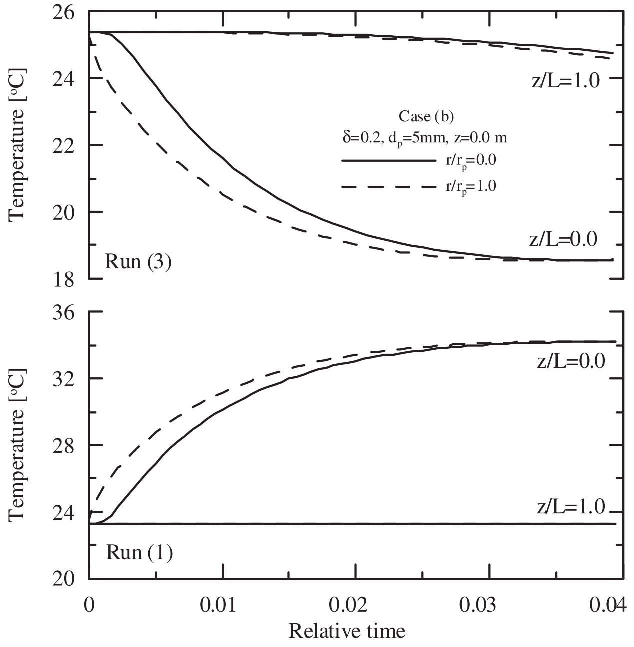

Fig. 7. Variation of intra-particle temperature with relative time (RT).

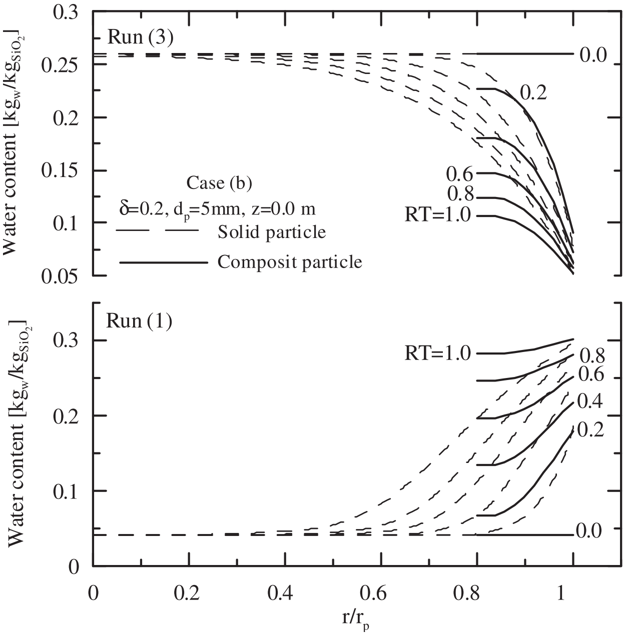

Fig. 8. Variation of intra-particle water content at various relative time (RT).

From this discussion, it can be noted that the adsorption as well as desorption rates are mainly dependent on the heat and mass transfer rates between the air and bed particles. So, increasing the area of heat and mass transfer for a given fixed mass of desiccant can result in a good improvement in the system operation. It can be observed from Figs. 4, 5 and 6 that the theoretical models predict the system dynamic parameters during the bed operation for the case of short time processes and long time processes as well. SSR model and the proposed MSSR model give good agreement with the experimental data. The advantage of the MSSR model over the SSR model is to give the ability to investigate the effects of heat transfer properties of the desiccant on the system operation. Also, both models give the ability of predicting the water content distribution inside the desiccant particle, which is difficult to measure experimentally. In addition, the main purpose of MSSR model is to investigate the proposed design of the silica gel particles.

6.2. Numerical investigation on composite silica gel bed

a) *Intra-particle moisture and temperature profiles.* The intra-particle temperature distributions for a silica gel–sand composite particle at $z/L = 0.0$ and 1.0 are shown in Fig. 7. It can be seen that maximum temperature difference through the particle radius is about 2.5 K, for the operating conditions of run 1 and run 3 as shown in Fig. 7. However, it is expected that the temperature difference through the particle will be more for composite particle with larger diameter. In addition, it is found that maximum intra-particle temperature difference takes place during the period of high adsorption/desorption rate then the particle tends to be isothermal until completion of the adsorption/desorption process as shown in Fig. 7. Also, this difference does exist in the leading layer of the bed because in this layer the particle is suddenly exposed to high amount of the generated/extracted heat of adsorption/desorption respectively. On the other hand the other layers are first affected by the air stream

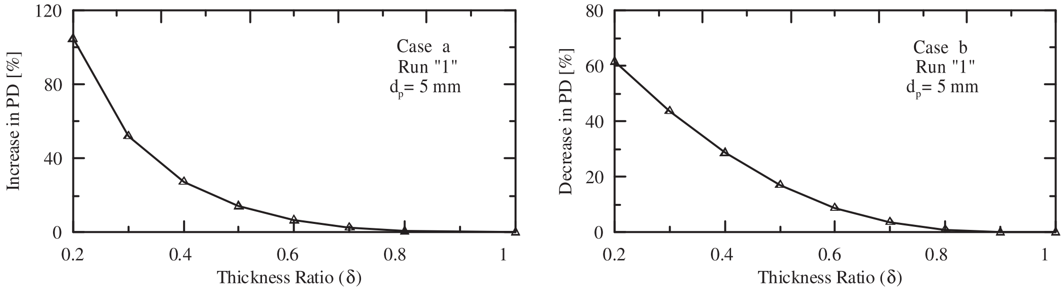

Fig. 9. Effect of thickness ratio on pressure drop for cases a and b.

temperature then after some time by the heat of adsorption/desorption. It can be seen from Fig. 7 that the particle can be assumed isothermal at a position of $z/L = 1.0$. Fig. 8 shows the intra-particle water content distribution in an ordinary as well as composite silica gel–sand particle at $z = 0.0$. It can be seen that for the case of ordinary particle, there is high difference in the water content with in the particle during the whole period of adsorption/desorption operation. It is also observed from Fig. 8 that the entire portion of the desiccant particle, $r/r_p = 0.0–0.6$, can be considered as unutilized desiccant material. On the other hand, all amount of desiccant material can be considered active and highly utilized for adsorption/desorption in case of composite particle. This means that in composite silica gel, effect of mass transfer by diffusion is reduced and the mass transfer by convection is increased.

b) *Pressure drop across the bed of composite silica gel particles*: As mentioned earlier the new bed using composite silica gel particles contains the same mass of silica gel as that of conventional silica gel bed. Hence the new bed can be either of increased height (case a) or with lrger diameter (case b). The effect of the new configurations of the bed on the pressure drop is illustrated in Fig. 9 for case a and case b. From Fig. 9-case (a), it can be seen that pressure drop through the bed is increasing dramatically with the decrease of thickness ratio and for the same mass flow rate. The increase in total mass adsorbed (TMA), when compared with this increase in pressure drop, becomes negligible. For a thickness ratio of 0.2 the percent increase in pressure drop is 90% for the operating conditions of Run 1 and particle diameter of 5 mm.

On the other hand, Fig. 9-case (b) shows the decrease of pressure drop with decreasing thickness ratio. It can be seen that the pressure drop through the bed is decreasing when the thickness ratio decreases. This is due to the lower velocity of air through the bed for the same mass flow rate of air. For thickness ratio of 0.2, pressure drop decreases by about 60% for the same operating conditions. Therefore, it can be concluded that case (b) is more preferable than case (a) with regards to savings in air blowing power.

c) *The performance of desiccant bed using composite silica gel particles*: Exit air condition is plotted in Fig. 10 for operating conditions of run 1 and for various thickness ratios of composite silica gel particle. The inert material chosen is sand particles with specific heat of 800 J/kg.K, particle density of 1515 kg/m^3 and conductivity of 0.27 W/m K. From Fig. 10 it can be observed that the decrease in the thickness ratio decreases the exit air humidity ratio during the adsorption mode operation. For bed operation under conditions for case (b), it is found that for thickness ratio of 0.2, the exit air humidity at the end of adsorption process is reduced by 23.9% when compared to thickness ratio of 1.0. The exit air temperature is shown in Fig. 10

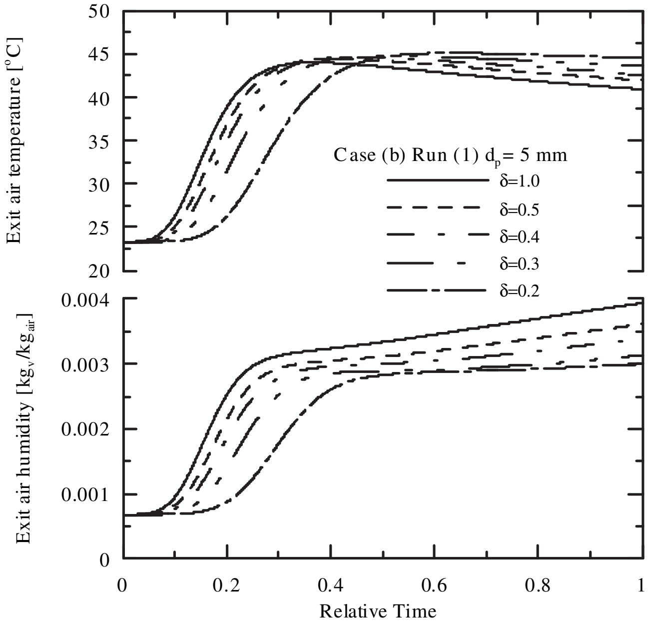

Fig. 10. Exit air conditions for various thickness.

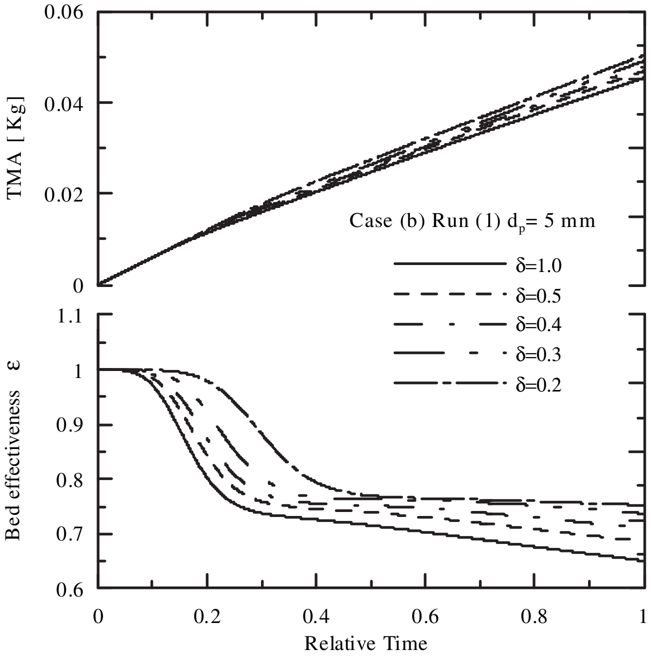

Fig. 11. Bed effectiveness and TMA for various thickness ratios.

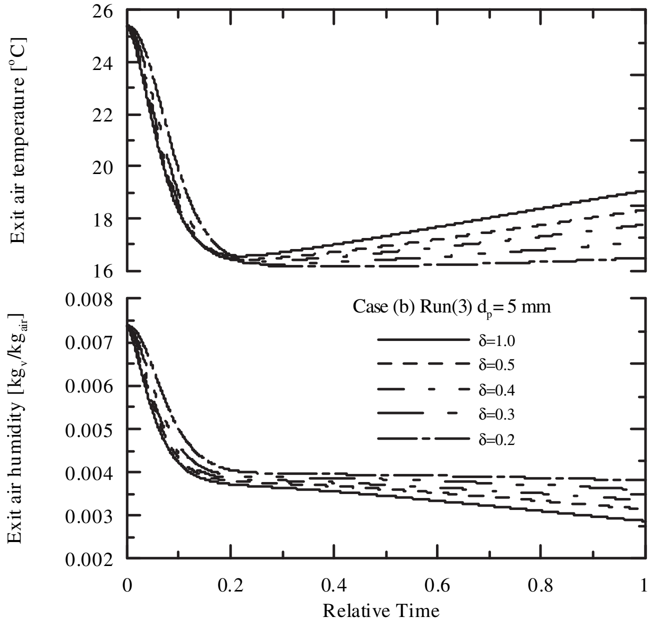

Fig. 12. Exit air conditions for various thickness ratios (desorption mode).

for various thickness ratios. The exit air temperature is lower for lower thickness ratios during relative times of 0.0–0.3 and for relative times beyond this, the exit air temperature is higher for lower thickness ratio. It can be explained as follows, at the start of adsorption process, say, relative time between 0–0.3, decreasing the thickness ratio provides more heat transfer area as well as bed heat capacity, so, most of adsorption heat is removed and its effect is delayed. For relative time after 0.3, the lower thickness ratio leads to more adsorption rate in this period and consequently more adsorption heat is generated. The effect of thickness ratio on the TMA and bed effectiveness is shown in Fig. 11. It can be seen that for lower thickness ratios, the bed is more effective and more humidity can be adsorbed from the process air stream. The sharp decrease in the bed effectiveness is due to the effect of heat of adsorption. With progressing time it decreases gradually because of increase in bed water content. Fig. 11 shows total mass adsorbed and bed effectiveness with time for different thickness ratios. It can be observed that higher bed effectiveness and total mass adsorbed are expected for lower thickness ratio particles. For example, for thickness ratio of 0.2 and at the end of adsorption mode operation, total mass adsorbed is increased by 11.07% and the effectiveness of the adsorption process is higher by 15.5%. Figs. 12 and 13 show the operation of a composite particle packed bed during desorption process, Run 3, for various thickness ratios. From the numerical experiments it is found that for thickness ratios between 1.0 and 0.5 the regeneration process for the bed has no much significant difference. The decrease in the thickness ratio increases the exit air humidity ratio during the desorption mode, which implies faster regeneration rate is taking place. Fig. 13 shows the comparison between the total mass desorbed (TMD) during the desorption operation for different thickness ratios. It can be seen that decreasing the thickness ratio increases total mass desorbed. For a thickness ratio of 0.2 the increase in total mass desorbed is 20.46% of that when bed of conventional particles is used for the operating condition of run 3.

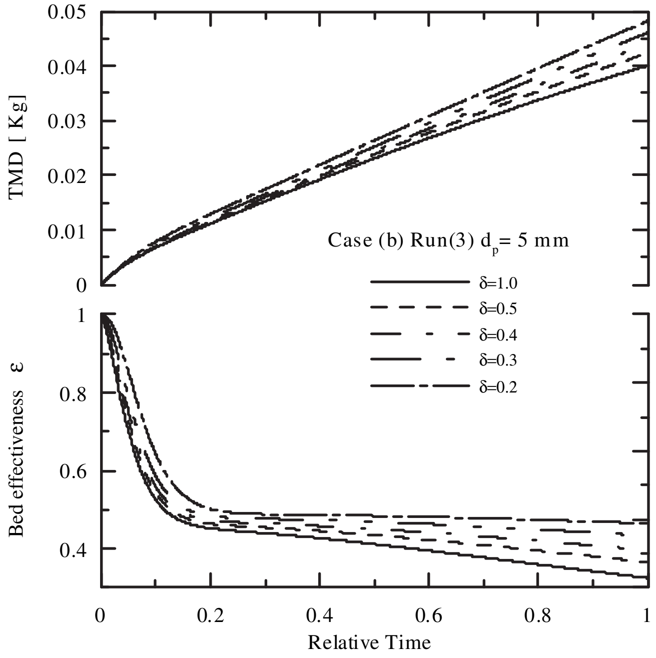

Fig. 13. Bed effectiveness and TMD for various thickness ratios.

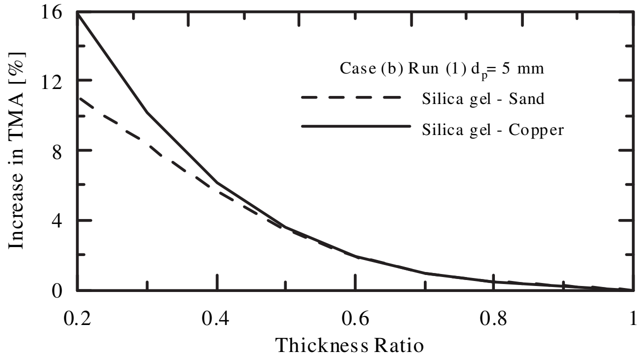

Fig. 14. Variation of percent increase in TMA with the thickness ratio.

The effect of the thermo-physical properties of the inert particle material on the bed operation is studied by comparing the bed operation using silica gel-sand composite particle bed with another bed using silica gel–copper composite particle. Fig. 14 shows total mass adsorbed during Run 1 for both kinds of composite particles. It can be observed that using the inert material with advanced heat transfer properties increases the total mass adsorbed for the same

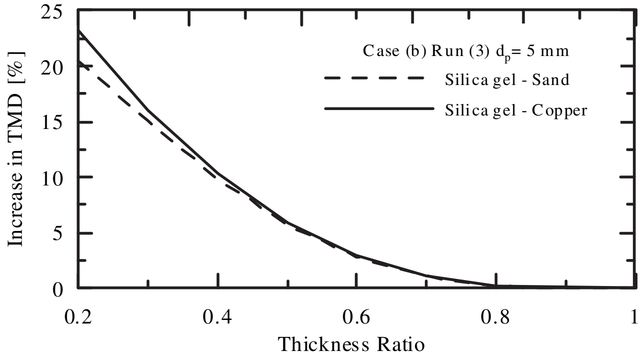

Fig. 15. Variation of percent increase in TMD and TMD with the thickness ratio.

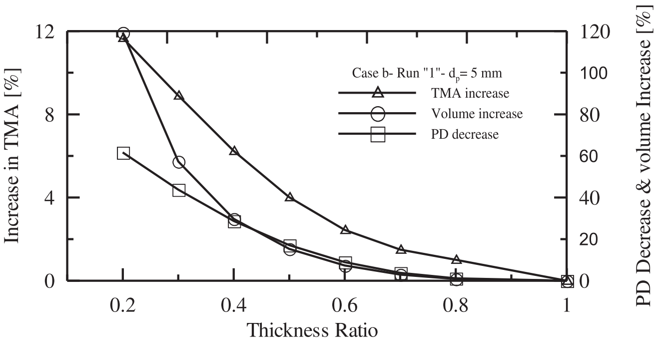

Fig. 16. Variation of TMA, decrease in PD and increase in bed volume with composite particle thickness ratio.

operating conditions of run 1. From Fig. 14 it can be seen that the difference in the increase in total mass adsorbed, when different inert materials are used, is very small for thickness ratios of 1–0.5 and decreasing the thickness ratio less than 0.5, the difference in the increase in total mass adsorbed becomes more significant. Fig. 15 shows total mass desorbed during Run 3 for both silica gel-sand and silica gel copper composite particles. It can be seen that the inert material has similar influence on the increase in total mass desorbed as in adsorption process. For full comparison, the mass of the bed should be considered as a comparing parameter in case of lightweight dehumidifier is required. A concluding result due to the effect of thickness ratio on total mass adsorbed, bed volume and pressure drop is plotted in Fig. 16. These results can be used to select the most suitable particle design for specific operating conditions. In some cases, it is the objective to maximize the bed dehumidification capacity. On the other hand, there may be some instances when the system will be operated so that minimum power consumption in air blowing is intended. In addition sometimes there is a limitation for the bed volume according to the application of the system.

7. Conclusions

A new composite particle of desiccant (spherical particle of inert material coated with silica gel) is proposed and investigated. The lumped capacitance, solid side resistance model and the modified solid side resistance model have been used for the transient analysis of heat/mass transfer during adsorption/desorption processes in a desiccant bed of composite silica gel particles. The intra-particle temperature and water content profiles for conventional and composite silica gel particles have been analyzed. The composite particle bed operation during adsorption and desorption processes has been investigated and the effect of thickness ratio on the bed operation as well. Based on the results obtained, the following conclusions can be drawn:

- Comparison between theoretical results of the MSSR model and experimental and theoretical results from literature tells that MSSR model can be used for predicting heat and mass transfer rates during adsorption and desorption processes in the conventional silica gel packed bed.
- The intra-particle water content profiles are evaluated and it is found that more utilization for the desiccant material is obtained when ordinary silica gel particles are replaced by composite silica gel particles.
- Using the proposed composite particle of 0.2 thickness ratio, pressure drop decreases by about 60% (Fig. 16). Consequently, it is expected to reduce the required blowing power for the same mass flow rate of air.
- Increase of 20.46% and 11.07% in the total mass desorbed and adsorbed respectively, and 15.5% in the bed effectiveness are obtained, for a specified bed operating parameters, using the new proposed silica gel-sand composite particles, for the same amount of desiccant material, with thickness ratio of $\delta = 0.2$ (Figs. 13 and 14).
- The expected improvement in total mass adsorbed/desorbed is observed to be dependent on the inert material thermo-physical properties for thickness ratio less than 0.5 (Figs. 13 and 14).

Appendix

Mass transfer coefficients [11]	For LC model: $h_m = 0.704 G_a \mathrm{Re}^{-0.51}$ For SSR and MSSR model: $h_m = 1.7 G_a \mathrm{Re}^{-0.42}$
Heat transfer coefficient [11]	For LC model: $h = 0.683 G_a C_a \mathrm{Re}^{-0.51}$ For SSR and MSSR model: $h = 1.6 G_a C_a \mathrm{Re}^{-0.42}$
Effective diffusion coefficients [11]	$D_{se} = 1.6 \times 10^{-6} \exp\left(\frac{-0.947 \times 10^{-3} H_A}{T_s + 273.15}\right)$ $D_{ke} = \frac{22.86 \times \varepsilon_p d_{pe}}{\tau}(T_s + 273.15)^{1/2}$
Specific heat of silica gel [4,11]	$C_s = 4.178 \times q + 0.921$
The specific heat of moist air	$C_a = 1.884 \times w_a + 1.005(1 - w_a)$
Heat of adsorption [11]: regular density silica gel.	$H_A = 3500.0 - 13400.0 \times q;\ q \le 0.05$ $H_A = 2950.0 - 1400.0 \times q;\ q > 0.05$
Adsorption isotherm [11]: RH [%] $= 100 \times (0.0078 - 0.05759q + 24.16554q^2 - 124.478q^3 + 204.226q^4)$	
Fitting the experimental data from [17], the adsorption isotherm equation is obtained as follows: RH [%]$=100 \times (-0.02833 + 8.18612q - 41.7964q^2 + 82.9974q^3)$	

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