

Effect of Matrix Properties on the Performance of a Counterflow Rotary Dehumidifier

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A finite difference model of a counterflow rotary dehumidifier is used to determine the effect of six matrix properties of dehumidifier performance. The matrix properties considered are the sorption isotherm shape, the maximum sorbent water content, the heat of sorption, the matrix thermal capacitance, matrix moisture diffusivity, and sorption isotherm hysteresis. The isotherm shapes and the sorption parameter values are selected to be representative of available insoluble desiccants. The results of the finite difference calculations show that the shape of the isotherm has a greater effect on dehumidification than the maximum water content. Large adsorption heat effects or matrix thermal capacitance has a detrimental impact on dehumidification. Hysteresis in the adsorption isotherm significantly impairs dehumidifier performance. The analysis shows that commercially available solid desiccants can result in nearly optimal dehumidifier performance.

Introduction

The performance characteristics of a rotary regenerator are largely determined by the physical properties of the porous matrix. Regenerative dehumidifiers, in which maximum moisture transfer is important, utilize a sorbent matrix with large moisture but small thermal capacity. Rotary dehumidifiers are used as industrial air driers [1] and in proposed residential desiccant cooling systems [2, 3].

The simultaneous heat and mass transfer in a rotary dehumidifier has been modeled by both finite difference techniques [4-6] and approximate analytic solutions [7, 8]. In all of these studies, the dehumidifier has been modeled using particular sets of matrix properties. To date, there has been no general study of the effect of matrix properties on the performance of the rotary dehumidifier.

In this paper, a finite difference solution [4, 9] is used to determine the effect of six matrix properties on the steady-state performance of a rotary dehumidifier. The matrix properties considered are the sorption isotherm shape, the maximum sorbent water content, the heat of sorption, the matrix thermal capacity, matrix moisture diffusivity, and sorption isotherm hysteresis. The range of property values was selected to be representative of available solid porous physical adsorbents, such as silica gels or molecular sieves. The results of this study are useful as guides for the selection and appraisal of matrix materials. The results of this study have also been applied to determine the influence of property dependent variations in dehumidifier performance on the performance of an open cycle desiccant cooling system [9].

The Dehumidifier Model

The rotary dehumidifier to be modeled is shown schematically in Fig. 1. The porous matrix of the dehumidifier can be either a packed bed of granular desiccant or a parallel passage wheel formed by spirally winding an adsorbent ribbon on a spoked hub [10]. The two air streams can pass through the matrix in either parallel flow or counterflow paths. A counterflow exchanger with uniform air temperature, humidity ratio, and velocity at the inlet of each period is considered in this study.

Several conventional [4, 5] assumptions are made to focus the model on the dominant flow and transfer processes occurring in the dehumidifier:

- 1 The air flow in each period is at constant pressure and velocity.
- 2 The interstitial air thermal and moisture storage capacities are negligible compared to the matrix capacities.
- 3 Axial heat and mass diffusion in both the air and matrix are negligible.
- 4 The combined solid diffusion-convective film resistance to heat or mass transfer can be described by composite coefficients.
- 5 There is no transfer flux coupling through thermal diffusion or Dufour effects.

Under these constraints, the equations of mass and energy conservation in period j of the dehumidifier, written with respect to a coordinate system moving with the rotating matrix, become [4, 5]

$$\begin{aligned} \frac{\partial w}{\partial x'} + \theta'_j (\mu\kappa)_j \frac{\partial W}{\partial \theta'} &= 0 \\ \frac{\partial i}{\partial x'} + \theta'_j (\mu\kappa)_j \frac{\partial I}{\partial \theta'} &= 0 \end{aligned} \quad j=1,2 \quad (1)$$

The mass and heat transfer rate equations are

$$\begin{aligned} \frac{\partial w}{\partial x'} &= \Lambda_{w,j} (w_m - w_f) \\ \frac{\partial i}{\partial x'} &= \Lambda_{w,j} (Le_o c_f (t_m - t_f) + i_{wu} (w_m - w_f)) \end{aligned} \quad j=1,2 \quad (2)$$

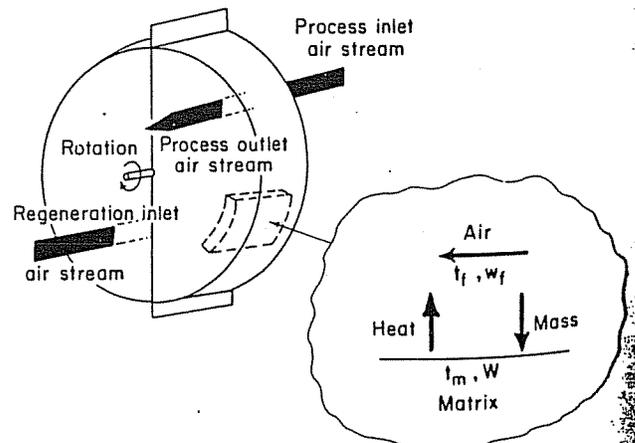


Fig. 1 Counterflow rotary dehumidifier

Contributed by the Heat Transfer Division and presented at the ASME Winter Annual Meeting, Phoenix, Arizona, November 14-19, 1982. Manuscript received by the Heat Transfer Division August 30, 1982.

The independent variables in equations (1, 2) are normalized axial position x' and normalized rotational time θ' (equivalent to circumferential position). The dependent variables are moist air humidity ratio and enthalpy (w, I), and matrix water content and enthalpy (W, I). Because the coordinate system is fixed with respect to the matrix, the rotary nature of the dehumidifier is introduced by imposing periodic boundary conditions. The counterflow condition is represented by a periodic reversal in flow direction. The bulk process outlet state ($t_{p,o}, w_{p,o}$) is the average with respect to θ' of the air state distributions at the matrix process period exit. The finite difference solution of equations (1, 2) utilized in this study employs a method developed by Maclaine-cross [4, 9]. The difference equations, which are of second order, are solved for three space-time grid sizes, and the solutions are quadratically extrapolated to zero grid size. The extrapolated solution is of fourth order. In most cases represented in this study, the lack of closure in the system moisture and energy balances is less than 0.01 percent [9]. The dehumidifier performance is characterized by a dehumidifier moisture efficiency, η_w , defined as

$$\eta_w = \frac{w_{p,o} - w_{p,i}}{w_{p,int} - w_{p,i}} \quad (3)$$

where $w_{p,int}$ is the humidity ratio at the intersection point of the line of constant adiabatic saturation temperature through the process inlet state and a relative humidity line through the regenerating inlet state, as shown in Fig. 2. The minimum potential humidity ratio would be $w_{p,int}$ if the dehumidification process were the reverse of an adiabatic saturation process with air exiting the dehumidifier at the relative humidity of the regenerating state. Because the dehumidification potential lines depend on the matrix properties as well as the moist air properties and are skewed away from wet bulb and relative humidity lines [11], $w_{p,int}$ is only a convenient normalizing parameter.

Physical Adsorption and Absorbents

Adsorption is the condensation of a vapor on a surface at a pressure below the normal saturation pressure of the vapor. Thorough discussions of the mechanisms and models of adsorption are found in [12-14]. This study is limited to consideration of the physical adsorption of water vapor on solid sorbents. The characteristics of various physical adsorbents are summarized here to provide perspective for the numerical simulations to be subsequently discussed. This brief

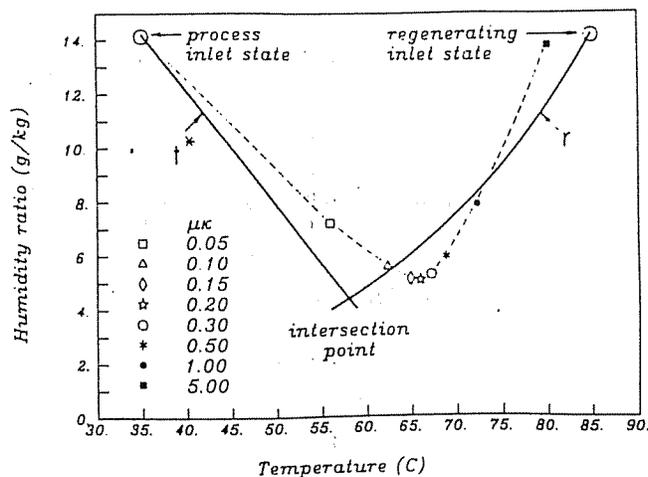


Fig. 2 Variation of the dehumidifier process stream outlet states with μ_k , superimposed on a wet bulb (t^*) line through the process inlet state and a relative humidity (r) through the regenerating inlet state

description relies heavily on vapor pressure lowering theory and does not mention other factors, such as desiccant surface area and electric field, in proper proportion to their importance [12-14].

Brunauer [13] classified experimentally observed isotherms into five types, illustrated in Fig. 3. The different shapes are generally characteristic of different adsorption mechanisms.

The type 1 isotherm is observed for porous adsorbents with pores that are approximately the size of the sorbate molecules. These ultra-micro pores are filled at low relative pressures, resulting in a plateau in the isotherm. Molecular sieves have a type 1 water adsorption isotherm [12, 15].

Type 2 and type 3 isotherms are associated with multilayer adsorption without capillary condensation. Wool and other biological materials have a type 2 water adsorption isotherm [16, 17]. Type 3 water vapor adsorption isotherms are rare; an example is adsorption on glass [13, 14]. Type 2 materials have a heat of adsorption larger than the heat of vaporization, while the type 3 materials have a heat of adsorption that is less than the heat of vaporization [13].

Types 4 and 5 result for porous materials in which capillary condensation occurs. Type 4 isotherms are characteristic of hydrophilic porous materials, such as silica gels. The plateau in water content at the low relative pressure region of the isotherm is associated with the filling of molecular dimension

Nomenclature

c_d = desiccant specific heat [energy/(dry mass-temp)]	$i_s = \left(\frac{\partial i}{\partial w} \right)_t - \left(\frac{\partial I}{\partial W} \right)_t$, isothermal differential heat of adsorption [energy/dry mass]	$J_{w,j} = 4h_w/(\rho' d_h)$, where h_w is the mass transfer coefficient, ρ' is the dry fluid density, and d_h is the hydraulic diameter. The lumped matrix-fluid mass transfer coefficient per unit mass of fluid [time ⁻¹]
c_f = moist air specific heat [energy/(dry mass-temp)]	i_v = heat of vaporization [energy/mass]	$Le_o = J_{i,j}/J_{w,j}$, overall Lewis number [dimensionless]
c_m = matrix thermal capacitance [energy/(dry desiccant mass-temp)], see equation (8)	i_{wv} = water vapor enthalpy [energy/mass]	p_{ws} = saturation pressure of water vapor [force/area]
c_w = liquid water specific heat [energy/(mass-temp)]	I = matrix enthalpy [energy/dry mass], see equation (7)	p_{wu} = equilibrium adsorbed water vapor pressure [force/area]
$G(W)$ = isotherm at some temperature t_0 [dimensionless]	$J_{i,j} = 4h/(\rho' d_h c_f)$, where h is the heat transfer coefficient, ρ' is the dry fluid density, and d_h is the hydraulic diameter. The lumped matrix-transfer coefficient per unit mass of fluid [time ⁻¹]	r = relative humidity (or pressure), ratio of vapor partial pressure to saturation pressure [dimensionless]
h^* = ratio of the isothermal differential heat of adsorption to the heat of vaporization [dimensionless], see equations (4) and (5)		t = temperature
i = moist air enthalpy [energy/dry mass]		

Characteristic Isotherms

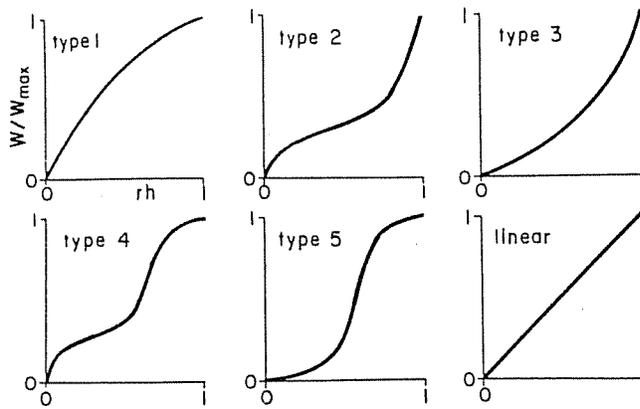


Fig. 3 Brunauer isotherm classification

pores (less than 10A dia), and the rise in water content at a higher relative pressure is due to the filling of capillary pores (10A-500A dia) [12, 13, 18]. The low relative pressure plateau in the type 4 isotherm can be very narrow and indistinct, resulting in an approximately type 1 isotherm. Several microporous (20A mean pore dia) silica gels exhibit approximately type 1 behavior [15, 18, 19]. The type 5 isotherm is characteristic of capillary porous materials in which the solid surface is hydrophobic, an example being the isotherm for water adsorption on activated charcoal [13, 20]. The heat of adsorption for the type 5 adsorbents can be less than the heat of vaporization [13].

The capillary-porous materials (types 4 and 5) frequently exhibit a hysteresis loop in the isotherm. Sorption hysteresis results from changes in the characteristic radii of the adsorbate meniscus in the capillary pores. Hysteresis behavior has been classified according to the irregularities in the pore shapes [21] and can be modeled [12, 22].

Continuum Thermodynamics of Adsorbents

The Clausius-Clapeyron equation relates the water vapor pressure and the saturation pressure to the ratio of the differential heat of sorption to the enthalpy of condensation:

$$\left(\frac{\partial \ln p_{wv}}{\partial \ln p_{ws}} \right)_w = \frac{i_s}{i_v} = h^* \quad (4)$$

Nomenclature (cont.)

t^* = thermodynamic wet-bulb temperature
 v_j = air velocity in period j [length/time]
 w = moist air humidity ratio [dimensionless]
 W = matrix water content [dimensionless]
 W^* = W/W_{mx} ratio of matrix water content to maximum water content [dimensionless]
 W_{mx} = maximum ($r=1$) matrix water content [dimensionless]
 x = axial displacement through matrix measured from period entrance [length]
 η_w = dehumidifier moisture efficiency [dimensionless], see equation (3)

θ = time from the beginning of period 1
 θ_j = duration of period j [time]
 θ' = θ/T , rotational time divided by the time for a complete matrix revolution [dimensionless]
 θ'_j = θ_j/T , normalized duration of period j [dimensionless]
 κ_j = $L/v_j\theta_j$, carry-over ratio [dimensionless]
 $\Lambda_{r,j}$ = $J_{r,j}L/v_j$, dimensionless heat transfer length
 $\Lambda_{w,j}$ = $J_{w,j}L/v_j$, dimensionless mass transfer length
 μ_j = dry period j matrix mass divided by dry fluid mass contained in matrix in period j [dimensionless]
 T = time required for a complete matrix rotation

Subscripts

f = evaluated at fluid state
 i = inlet state
 int = evaluated at the intersection point of a wet-bulb temperature line through the process inlet state and the relative humidity line through the regenerating inlet state
 j = period index
 m = evaluated at, or in equilibrium with, the matrix state
 o = spatial or rotational average outlet state
 p = process period
 r = regenerating period
 x = relating to maximum dehumidification

Brandemuehl [23] analyzed heat of wetting data for silica gel [24-26] and found that the ratio h^* can be expressed as an exponential function of desiccant water content. The following empirical form is used in this study

$$h^*(W^*) = 1 + \Delta h^* \frac{\exp(kW^*) - \exp(k)}{1 - \exp(k)} \quad (5)$$

where W^* is the water content W , normalized by the maximum water content W_{mx} , $1 + \Delta h^*$ is h^* at $W^* = 0$, and k is a constant.

If the ratio h^* is independent of temperature, equation (4) can be integrated to show that if the adsorption isotherm is a function $G(W)$ at temperature t_0 , then at any temperature t

$$r = G(W) (p_{ws}(t)/p_{ws}(t_0))^{h^*-1} \quad (6)$$

The form of equation (5) used in this study insures that isotherms given by equation (6) converge to the maximum water content W_{mx} at $r=1$. This allows W_{mx} to be used as a scaling parameter for the isotherms. The physical assumption implicit in this behavior of the isotherms is that at saturation ($r=1$), adsorption becomes normal condensation on the matrix.

The enthalpy of the matrix at any temperature and water content with respect to a dry matrix at 0°C is

$$I = c_m t + c_w W t + i_v \int_0^W (1 - h^*) dW \quad (7)$$

The dry matrix thermal capacitance, c_m , is related to the bulk desiccant specific heat, c_d , and the specific heats of the nonsorbing matrix materials, c_{Ni} , by

$$c_m = c_d + \sum_i (M_i c_{Ni}) / M_d \quad (8)$$

where M_i is the mass of nonsorbing component i and M_d is the mass of the desiccant in the matrix.

The moist air is taken to be an ideal binary mixture of dry air and water vapor, characterized by conventional psychrometric relationships [9, 27].

Matrix Parameters

The intent of this study is to indicate the effect of important matrix properties on the performance of a rotary dehumidifier. Because none of the mechanistic adsorption models is entirely satisfactory [12, 14, 16] and there is considerable scatter in experimental data for common desiccants [15, 19, 28], the approach followed in this work has been to

Table 1 Dehumidifier flow and matrix parameters

Dehumidifier flow parameters			
$\Lambda_w = 20, 0.05 \leq \mu\kappa \leq 5.0$			
Inlet states pair	Process	Regenerating	
1	(35°C, 14.23/kg)	(85°C, 14.2 g/kg)	
2	(30°C, 24.5 g/kg)	(100°C, 14.2 g/kg)	
Matrix properties			
Variation	Isotherm type (Eq.)	W_{mx} (kg/kg)	$\Delta h^*, k$ (Eq. (5))
Nominal	Linear (9.6)	0.5	0.3, -5.0
Isotherm shape	1 (9.1)	0.5	0.3, -5.0
	2 (9.2)	0.5	0.3, -5.0
	3 (9.3)	0.5	-0.3, -5.0
	4 (9.4)	0.5	0.3, -5.0
	5 (9.5)	0.5	-0.3, -7.5
Maximum W	Linear	0.25	-0.3, -5.0
	Linear	1.00	0.3, -5.0
	1a (9.1a)	0.25	0.0
	4a (9.4a)	1.125	0.0
Heat ads.	Linear	0.5	0.0
	Linear	0.5	1.0, -1.0
$C_m = 3350 \frac{J}{kg^\circ C}$	Linear	0.5	0.3, -5.0
	Linear	0.5	0.3, -5.0
$Le_o = 4, \Lambda_w = 5.0$	Linear	0.5	0.3, -5.0
	Linear-process	0.5	0.0
Hysteresis	Linear-regenerating	0.5	0.0
	Linear-regenerating	0.5	0.0

Table 2 Isotherm equations

Type	$r = G(W^*)$	Eq.
1	$r = 1 - (1 - W^*)^{1/2}$	(9.1)
1(a)	$r = W^* / (1 + 50(1 - W^*))$	(9.1a)
2	$r = 0.43194 + 0.43950 \tan^{-1}(5.0(W^* - 0.3))$	(9.2)
3	$r = W^* / (1 - 0.75(1 - W^*))$	(9.3)
4	$r = 0.29754 + 0.29437 \tan^{-1}(6.37959(W^* - 0.25))$	(9.4)
4(a)	$r = 0.65 + 0.06280 \tan^{-1}(3.98089(W^* - 0.65))$	(9.4a)
	$r = 0.35 + 0.30929 \tan^{-1}(42.5742(W^* - 0.05))$	
	$r = 0.85 + 0.06904 \tan^{-1}(3.052(W^* - 0.55))$	
5	$r = 0.50 + 0.10 \tan(2.7468(W^* - 0.5))$	(9.5)
linear	$r = W^*$	(9.6)

choose functional variations and ranges of parameter values that are qualitatively representative of a broad spectrum of solid physical adsorbents and matrix configurations. The constraints imposed by continuum thermodynamics are satisfied and the major adsorbent types are all represented.

The reference or base case desiccant is modeled with a simplified representation of Hubard's silica gel data [24]. The isotherm is linear at 60°C, has a maximum water content of 0.5 g/g, and a maximum h^* (at $W = 0.0$) of 1.3.

The counterflow dehumidifier modeled in this study has equal air mass flow rates and flow areas in each period. The reference matrix has a thermal capacitance equal to the bulk specific heat of silica gel ($c_m = 921 \text{ J/kg}^\circ\text{C}$) and an overall Lewis number of unity. These conditions are representative of a matrix with little nonadsorbent structural materials and in which convection governs the heat and mass transfer rates. The reference value of the dimensionless mass transfer length, Λ_w , is 20, which is representative of high-performance dehumidifiers. The dehumidifier outlet states are influenced by $\mu\kappa$, the ratio of matrix rotational mass flow rate to air mass flow rate, as shown in Fig. 2 for the reference linear isotherm. A range of relative rotational speeds is considered that results in both dehumidifier and enthalpy regenerator operation. The maximum dehumidifier efficiency η_{wx} and the optimum relative rotational speed for dehumidification $\mu\kappa_x$ depend on the matrix properties and the dehumidifier inlet states.

Two pairs of air inlet states relevant to air conditioning are used. One pair has a process inlet state of (35°C, 14.2 g/kg) and a regenerating state of (85°C, 14.2 g/kg). This corresponds to inlet relative humidities of 40 percent and 4 percent, respectively. The other inlet state pair is (30°C, 24.5 g/kg) and (100°C, 14.2 g/kg), with relative humidities of

approximately 90 percent and 2 percent, respectively. These inlet state pairs are subsequently referred to as 1 and 2.

The reference matrix properties and the principal variations considered in this study are summarized in Table 1. These variations and their effects on dehumidifier performance are described in the following section.

Results and Discussion

Adsorption Isotherm Shape. Functions $G(W)$ were chosen to qualitatively reproduce the features of the five generic Brunauer types and a linear isotherm. These equations are given as a function of $W^* = W/W_{mx}$ in Table 2. The isotherms qualitatively characterize available desiccants, as illustrated in Fig. 4, where the type 1 and 2 isotherms and normalized data for a microporous silica gel (Davison 03) [15] and wool [17] are shown. Similarly, the types 4, 5, 1(a) and 4(a) isotherms were chosen to be representative of activated alumina [29], charcoal [20], molecular sieve [15] and macroporous silica gel [15, 28].

The effect of temperature on the isotherm was determined using equations (6) and (5). The values of the constants Δh^* and k (equation (5) and Table 1) were selected on the basis of Brandemuehl's analysis of silica gel data [23]. A negative value of Δh^* is used for the type 3 and type 5 isotherms because the heat of sorption is less than the heat of water vaporization for these adsorbents. The temperature at which $r = G(W^*)$ is $t_0 = 60^\circ\text{C}$.

The dehumidifier efficiency was determined for the types 1-5 and linear isotherms with $W_{mx} = 0.5 \text{ g/g}$ as a function of rotational speed and inlet state. The optimum rotational speed ratio $\mu\kappa_x$, process outlet state, and maximum

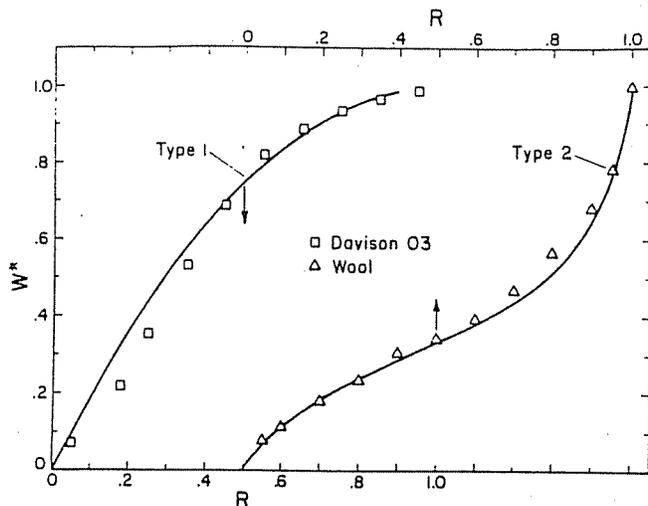


Fig. 4 Type 1 (equation (9.1)) compared to Davison O3 silica gel isotherm [15], and type 2 (equation (9.2)) compared to wool isotherm [17]

dehumidifier efficiency η_{wx} are given in Table 3. These results indicate that the isotherms can easily be classified in two groups, one favorable and the other unfavorable for dehumidification.

The types 1, 2, and 4 and linear isotherms have relatively high η_{wx} and can be considered favorable for dehumidification. The type 1 isotherm η_{wx} are about 5 percent greater than those of the other favorable isotherms. The values of η_{wx} for inlet state pair 1 are about 5 to 7 percent greater than those for inlet state pair 2.

The types 3 and 5 isotherms have η_{wx} that are about 20 percent lower than those for the first group and can be considered unfavorable for dehumidification. For these isotherms, the η_{wx} for inlet state 2 is slightly greater than for inlet state 1.

The results also show that the optimum rotational speed varies with matrix properties and dehumidifier inlet states. The favorable isotherms have a much lower $\mu\kappa_x$ than the unfavorable isotherms, corresponding to a lower optimum matrix rotational speed at a given air flow rate. However, $\mu\kappa_x$ varies more with the change in inlet state for the favorable isotherms than for the unfavorable types. For any of the favorable isotherms, $\mu\kappa_x$ for inlet state 2 is about twice $\mu\kappa_x$ for inlet state 1, representing a double in optimum matrix rotational speed as the inlet states change.

To indicate the effect of operating the dehumidifier at nonoptimal rotational speeds, Table 4 lists the values of $t_{p,o}$, $w_{p,o}$ and η_w at values of $\mu\kappa$ equal to $\mu\kappa_x$ for the alternate inlet state pair. Comparing the results given in Tables 3 and 4, it can be seen that operating at the nonoptimal $\mu\kappa$ results in an average drop in η_w of about 4 percent. This suggests that near optimum dehumidification is obtained over a reasonably broad range of $\mu\kappa$.

Except for the clear distinction between the high-performance favorable isotherms and the low-performance unfavorable isotherms, the variations in isotherms type $\mu\kappa$ and inlet state result in at most 5 to 7 percent variations in η_w . However, measuring these effects as proportional changes in η_w masks the fact that the changes in high-performance dehumidifier design required to offset a 5 percent variation in η_w with matrix properties can be large. For example, Table 5 lists the Λ_w required at optimum rotational speed for the various isotherms to have $\eta_w = 0.95$ for inlet state 1 and $\eta_w = 0.90$ for inlet state 2. The results show that the Λ_w required for a given η_w by the type 2, 4 and linear isotherm dehumidifiers is about twice that of a type 1 isotherm dehumidifier. The type 3 and 5 isotherm dehumidifiers cannot obtain the required η_w at Λ_w more than four times that of the type 1 dehumidifier. Thus other variables being equal, the volume of the type 1

Table 3 Effect of isotherm shape on optimum dehumidifier performance

Type	Inlet state 1			
	$\mu\kappa_x$	t_o (°C)	w_o (g/kg)	η_{wx}
1	0.12	63.84	4.729	0.965
2	0.17	65.65	5.154	0.922
3	0.50	66.36	6.678	0.766
4	0.17	65.58	5.124	0.925
5	0.55	67.63	7.096	0.727
linear	0.18	65.64	5.081	0.929
Type	Inlet state 2			
	$\mu\kappa_x$	t_o (°C)	w_o (g/kg)	η_{wx}
	0.22	82.03	6.918	0.911
	0.30	84.09	7.879	0.862
	0.60	82.35	9.080	0.799
	0.28	83.80	7.620	0.875
	0.70	83.88	10.252	0.739
	0.35	84.02	7.914	0.860

Table 4 Dehumidifier performance at $\mu\kappa$ away from the optimum

Type	Inlet state 1			
	$\mu\kappa$	t (°C)	w_o (g/kg)	η_w
1	0.22	65.26	5.053	0.932
2	0.30	67.34	5.441	0.892
3	0.60	67.99	6.904	0.743
4	0.28	66.99	5.408	0.896
5	0.70	69.85	7.341	0.699
linear	0.35	67.65	5.467	0.890
Type	Inlet state 2			
	$\mu\kappa$	t_o (°C)	w_o (g/kg)	η_w
	0.12	79.04	7.299	0.892
	0.17	80.67	8.380	0.836
	0.50	79.97	9.229	0.792
	0.17	81.17	7.968	0.857
	0.55	79.86	10.498	0.726
	0.18	79.85	8.413	0.834

Table 5 Λ_w required to obtain $\eta_{wx} = 0.95$ for inlet state 1 and $\eta_{wx} = 0.90$ for inlet state 2

Type	Inlet state 1		
	$\mu\kappa_x$	Λ_w	η_w
1	0.12	16.0	0.950
2	0.17	38.0	0.951
3	0.50	80.0	0.841
4	0.17	35.0	0.949
5	0.50	80.0	0.801
linear	0.18	30.0	0.951
Type	Inlet state 2		
	$\mu\kappa_x$	Λ_w	η_w
1	0.22	17.0	0.899
2	0.30	40.0	0.899
3	0.60	80.0	0.865
4	0.28	30.0	0.900
5	0.75	80.0	0.792
linear	0.35	40.0	0.899

dehumidifier will be at most half that of the alternative designs. The seemingly insignificant performance advantage of the type 1 isotherm dehumidifier and the importance of operating at optimum relative rotational speed are magnified when viewed in this perspective.

Maximum Water Content. The maximum water content W_{mx} of insoluble desiccants ranges considerably, from ~0.25 g/g for molecular sieves, to 0.35–0.50 g/g for silica gels and activated aluminas, to greater than 1.0 g/g for macroporous gels. A nominal value of $W_{mx} = 0.5$ g/g was used in deter-

Table 6 Effect of W_{mx} on optimum dehumidifier performance

Inlet state 1				
W_{mx}	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
0.25	0.30	67.69	5.591	0.877
0.50	0.18	65.64	5.081	0.929
1.00	0.10	64.20	4.792	0.958
Inlet state 2				
	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
	0.50	85.55	9.044	0.801
	0.35	84.02	7.914	0.860
	0.22	82.67	7.180	0.898

Table 7 Comparison of molecular sieve, microporous gel, and macroporous gel dehumidifier performance

Inlet state 1				
Desiccant type	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
Mole sieve	0.15	64.46	6.153	0.820
Micro gel	0.12	63.84	4.729	0.965
Macro gel	0.30	62.82	6.028	0.832
Inlet state 2				
	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
	0.30	84.89	9.694	0.767
	0.22	82.03	6.918	0.911
	0.50	84.97	8.814	0.813

Table 8 Effect of heat of adsorption on optimum dehumidifier performance

Inlet state 1				
Δh^*	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
0.0	0.18	62.53	5.188	0.918
0.3	0.18	65.64	5.081	0.929
1.0	0.20	72.14	6.217	0.813
Inlet state 2				
	$\mu\kappa_x$	t_o (°C)	w_o ($\frac{g}{kg}$)	η_{wx}
	0.30	80.58	7.229	0.895
	0.35	84.02	7.914	0.860
	0.50	89.44	11.306	0.684

mination of the effect of isotherm shape on dehumidifier performance.

The effect on optimum dehumidifier performance of varying W_{mx} of the linear isotherm from 0.25 g/g to 1.0 g/g is shown in Table 6. These data show that as W_{mx} increases, $\mu\kappa_x$ decreases while η_{wx} increases. Because the η_{wx} for $W_{mx} = 1.0$ are approximately 0.95 and 0.90 for inlet states 1 and 2, the results in Table 5 imply that use of the linear isotherm with $W_{mx} = 0.5$ would require the dehumidifier Λ_w to be doubled in order to achieve the same performance as obtained with the $W_{mx} = 1.0$ desiccant. It was determined that the $W_{mx} = 0.25$ isotherm requires the dehumidifier Λ_w to be increased to more than 80 to obtain the same η_{wx} as the $W_{mx} = 1.0$ isotherm dehumidifier with $\Lambda_w = 20$. For the linear isotherm, the Λ_w required for η_w in excess of 90 percent seems to be inversely proportional to W_{mx} .

Although increasing W_{mx} is beneficial to dehumidifier performance, the η_{wx} for the type 1 isotherm with $W_{mx} = 0.50$ (Table 3) are greater than the η_{wx} for the linear isotherm with $W_{mx} = 1.0$. Changing the isotherm shape from linear to

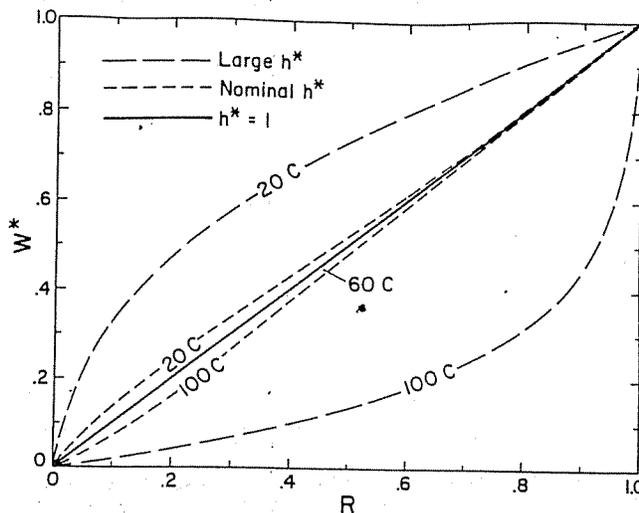


Fig. 5 Temperature variation of the linear isotherm for three different variations of the heat of adsorption

type 1 at $W_{mx} = 0.50$ has a greater beneficial effect on η_{wx} than increasing W_{mx} of the linear isotherm from 0.50 to 1.0.

Because variation in the isotherm shape can have as much effect on dehumidifier performances as doubling W_{mx} , the combined effect of isotherm shape and W_{mx} was considered by modeling three generic desiccants. Isotherm type 1(a) with $W_{mx} = 0.25$, type 1 with $W_{mx} = 0.50$, and type 4(a) with $W_{mx} = 1.125$ were used to represent molecular sieves, microporous adsorbents, and macroporous adsorbents. The η_{wx} shown in Table 7 indicates that the microporous adsorbent with the type 1 isotherm has by far the superior performance. The macroporous adsorbent performs slightly better than the molecular sieve, though W_{mx} for the macroporous desiccant is over four times that of the molecular sieve.

Heat of Adsorption. The effect of the heat of adsorption on dehumidifier performance was determined by considering extreme variations in $h^*(W^*)$ for the linear isotherm. The temperature response of the linear isotherm is shown in Fig. 5.

Table 8 shows that a large increase in the heat of adsorption has an adverse effect on dehumidifier performance. For $\mu\kappa$ between 0.10 and 0.50, the strongly temperature sensitive isotherm results in a 6°C to 10°C increase in process outlet temperature and a 10 percent to 25 percent decrease in η_w in comparison to the temperature-independent linear isotherm. The energy liberated on adsorption tends to increase the matrix and air temperatures, adversely affecting the absorptive capacity of the matrix.

The weakly temperature-dependent isotherm also results in dehumidifier process stream outlet temperatures above those obtained with the temperature independent isotherm. However, in this case, for inlet state 1, the outlet humidity ratios are slightly less than those resulting from the temperature-independent isotherm.

These results indicate that the small adsorption heat effects characteristic of common materials such as silica gels have a minor influence on dehumidifier performance. Large latent heat effects, on the other hand, are undesirable.

Matrix Thermal Capacitance. In common matrix configurations, a certain amount of nonadsorbing material is used in the matrix. The bulk specific heat of silica gel, 921 J/(kg-°C) [15], has been used as the reference value of matrix thermal capacitance. A value of $c_m = 3350$ J/(kg-°C), corresponding to a desiccant-substrate system that is 50 percent mylar by volume [10], was used to test the effect of matrix thermal capacitance on dehumidifier performance.

The numerical results show that increasing c_m results in significantly hotter and wetter process stream outlet states. For $\mu\kappa$ between 0.10 and 0.50, the process outlet temperatures

Table 9 Effect of matrix thermal capacitance on optimum dehumidifier performance

$\left(\frac{c_m}{\text{kg} \cdot ^\circ\text{C}}\right)$	$\mu\kappa_x$	Inlet state 1		
		$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_{wx}
921	0.18	65.64	5.081	0.929
3350	0.115	69.60	6.285	0.806
Inlet state 2				
	$\mu\kappa_x$	$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_{wx}
	0.35	84.02	7.914	0.860
	0.17	86.77	10.409	0.730

Table 10 Effect of Le_o on optimum dehumidifier performance

Λ_t/Le_o	$\mu\kappa_x$	Inlet state 1		
		$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_{wx}
20/1	0.18	65.64	5.081	0.929
20/4	0.17	63.64	5.836	0.852
Inlet state 2				
	$\mu\kappa_x$	$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_{wx}
	0.35	84.02	7.914	0.860
	0.28	80.34	9.193	0.793

and the η_w for the large c_m dehumidifier are, respectively, 5–7°C higher and 10–15 percent lower than for the base case. The data in Table 9 show that the increase in c_m results in a 15 percent decrease in η_{wx} and a reduction in $\mu\kappa_x$.

Comparison of the results for $c_m = 3350 \text{ J}/(\text{kg} \cdot ^\circ\text{C})$ in Table 9 to those for $\Delta h^* = 1$ in Table 8 shows that the increased sensible heat effects associated with large c_m cause roughly the same decrease in η_{wx} as the large latent heat effects associated with large Δh^* . Increasing c_m has a larger adverse effect on η_{wx} than does decreasing W_{mx} . These results indicate that large latent or sensible heat effects have a significant detrimental impact on the performance of the dehumidifier.

Matrix Moisture Diffusivity. The dehumidifier model is based in part on an assumption that the combined process of diffusion in the matrix and convection at the matrix surface can be described by composite or lumped transfer coefficients. If the resistance to diffusion into the matrix is small, the overall transfer coefficients are governed by the convective film resistances. The convective Lewis number for the air-water vapor system is nearly unity, and $Le_o = 1$ has been used to this point in this study. However, Banks [30] has estimated that Le_o is at least 2.0 for a parallel passage wheel and van Leersum's results [31] indicate that $Le_o = 4$ is a lower limit for typical packed bed dehumidifiers.

The results in Table 10 show the effect on the performance of a linear isotherm dehumidifier of increasing Le_o from 1.0 to 4.0 at constant $\Lambda_t = 20$, corresponding to an increase in the matrix resistance to water vapor diffusion at constant heat transfer length. Increasing Le_o to 4.0 decreased η_{wx} by about 8 percent. This performance can be obtained by an $Le_o = 1$ linear isotherm dehumidifier with $\Lambda_w = 9.0$. The volume of the $Le_o = 4$ dehumidifier is therefore about twice that of an $Le_o = 1$ dehumidifier with the same performance.

Adsorption Hysteresis. An example of the sorption-desorption hysteresis loop in an adsorbent is illustrated by an isotherm for Davison 03 silica gel [28] shown in Fig. 6. This loop was modeled by using the linear isotherm in the adsorbing (process) period of the dehumidifier and the type 1

Table 11 Effect of isotherm hysteresis on dehumidifier performance

Isotherms proc/reg	$\mu\kappa$	Inlet state 1		
		$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_w
lin/lin	0.10	58.89	5.793	0.857
lin/lin	0.15	61.60	5.260	0.911
lin/lin	0.20	62.99	5.195	0.917
lin/l	0.10	55.28	7.457	0.687
lin/l	0.15	56.70	7.557	0.677
lin/l	0.20	57.57	7.872	0.645
Inlet state 2				
	$\mu\kappa$	$t_o (^{\circ}\text{C})$	$w_o \left(\frac{\text{g}}{\text{kg}}\right)$	η_w
	0.20	77.58	7.616	0.875
	0.25	79.39	7.320	0.891
	0.30	80.58	7.229	0.895
	0.20	72.74	9.832	0.760
	0.25	73.78	10.011	0.751
	0.30	74.56	10.285	0.737

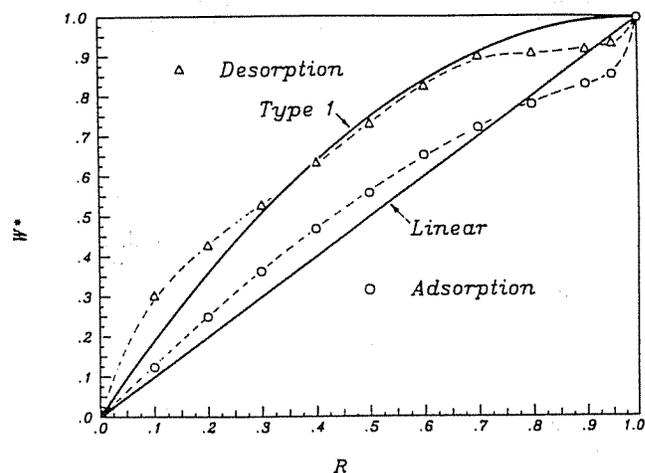


Fig. 6 Adsorption-desorption isotherm hysteresis for Davison 03 silica gel [28]

isotherm in the desorbing (regenerating) period. Because the Clausius-Clapeyron relation (equation (4)) cannot apply in this situation, $\Delta h^* = 0$ was used for both branches of the hysteresis isotherm so that the hysteresis loop is independent of temperature.

Modeling the sorption hysteresis isotherm by a simple superposition of two isotherms forces a discontinuous transition at constant W between the sorption and desorption branches of the isotherm and is only a first-order representation of the hysteresis phenomenon [21, 22]. However, this model should provide an upper bound estimate of the effect of adsorption hysteresis on dehumidifier performance.

The performance of a dehumidifier with a linear/type 1 hysteresis isotherm is compared to that with a reversible linear isotherm in Table 11 for values of $\mu\kappa$ that scan the optimum range for the reversible isotherm. The desorption hysteresis loop has a very pronounced adverse effect on the performance of the dehumidifier. The η_w for the hysteresis isotherm are between 15 and 30 percent less than the η_w for the reversible linear isotherm. This corresponds to a decrease in the apparent Λ_w of the dehumidifier from 20 to about 5; i.e., a linear isotherm dehumidifier with $\Lambda_w = 5$ ($Le_o = 1$) has roughly the same η_w as the hysteresis isotherm dehumidifier with $\Lambda_w = 20$.

Because an increase in Le_o at fixed Λ_t is equivalent to an increase in mass transfer resistance in the matrix, another way to interpret the effect of the hysteresis isotherm on dehumidifier performance is to determine the apparent Le_o of

Table 12 Le_o required to match the linear isotherm and hysteresis isotherm dehumidifier performance for inlet state 1

Hysteresis isotherm				
	μ_k	t_o ($^{\circ}\text{C}$)	w_o ($\frac{\text{g}}{\text{kg}}$)	η_w
	0.10	55.28	7.457	0.687
	0.15	56.70	7.557	0.677
	0.20	57.57	7.872	0.645
Linear isotherm				
Le_o	μ_k	t_o ($^{\circ}\text{C}$)	w_o ($\frac{\text{g}}{\text{kg}}$)	η_w
9.25	0.10	55.04	7.441	0.689
11.50	0.15	56.51	7.547	0.678
13.00	0.20	57.48	7.863	0.646

$Le_o = 20$ exchanger that results in the same performance as obtained using the hysteresis isotherm. As shown by the data in Table 12, the effect of the hysteresis isotherm is equivalent to Le_o , ranging from 9.0 to 13.0. Both the outlet temperatures and humidity ratios of the hysteresis isotherm dehumidifier can be closely matched using a single value of Le_o . This implies that if estimates of Le_o are to be obtained by matching predictions of a convective model with experimental data for the dehumidifier outlet states, care must be exercised to avoid confusing the effects of the matrix diffusion resistance and adsorption hysteresis.

Conclusions

The effect of six different matrix properties on the performance of a counterflow rotary dehumidifier has been investigated. The properties considered have been isotherm shape, maximum water content, heat of adsorption, matrix thermal capacitance, matrix moisture diffusivity, and adsorption hysteresis. Results have been obtained for the maximum dehumidification efficiency in each case.

The variation of matrix properties has a profound effect on the design requirements for high-performance dehumidifiers. For example, the dehumidifier Δ_w required for a given level of performance can vary by a factor greater than four as the shape of the adsorption isotherm changes.

The results of this investigation can be summarized in several rough guidelines. For maximum dehumidifier performance, an adsorbent with a near type 1 (weak type 4) isotherm similar to those characteristic of microporous adsorbents should be selected. If an alternate isotherm is considered, the maximum water content must be substantially greater than that of the type 1 adsorbent to realize equivalent dehumidifier performance. The heat of adsorption of the material should be low. It is preferable to design a matrix with low thermal capacitance and $Le_o < 4$ than to have high matrix thermal capacitance and $Le_o = 1$. Isotherms with a major hysteresis loop should be avoided.

Cumulatively these guidelines suggest that commercially available microporous silica gels are attractive materials for dehumidifier construction. Radical changes in desiccant properties would be required to significantly improve dehumidifier performance over that obtainable with these materials.

Acknowledgments

The authors wish to thank Dr. R. K. Collier and Mr. R. Barlow of SERI, who enthusiastically supported this project. Mr. Barlow suggested the tangent and arctangent functional forms used to model several of the isotherms. Dr. D. J. Close, Dr. P. J. Banks, and Dr. J. G. van Leersum of CSIRO, Division of Energy Technology were also very helpful in the early stages of this project. This work was funded by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U.S. Department of Energy.

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