Diffusion and Adsorption of Moisture in Desiccant Sheets

The simultaneous diffusion and adsorption of water vapor into specially prepared silica gel and activated carbon desiccants was experimentally studied for laminar flow through an isothermally maintained parallel-plate channel. The equilibrium characteristics and tortuosities of the various desiccant sheets used were experimentally determined.

The data were compared with a modified Rosen model. The Rosen model predicts outlet concentrations from the knowledge of adsorption equilibrium constants, diffusion, and mass transfer coefficients. A comparison of computed and measured concentrations as a function of sorption time shows that with independently measured equilibrium and effective diffusion coefficients, the modified Rosen model became completely predictive.

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SCOPE

Separation and purification of gases by adsorption are common unit operations. The sorbents are generally used in pellet or granular form. However, to minimize pressure drop and thus to increase the energy efficiency of separation, the adsorbents are sometimes formed into sheets. In the drying of air for air conditioning applications, such a design can give electrical coefficients of performance of 20 or 30. In such a concept the energy for regeneration of the sorbent can be waste heat or solar energy collected with inexpensive flat plate collectors when the desiccant used is a material such as silica gel or activated carbon that can be regenerated at low temperature. In the last few years this concept was acquired the name of desiccant cooling (Shelpuk, 1978). Air is dried by passing it over the desiccant material and the heat of sorption is removed by sensible cooling. The air is then further cooled by adiabatic humidification and is directed into the residence as cool, relatively dry air. In the system used at the Institute of Gas Technology (Rush and Macriss, 1969; Staats, 1977) the dehumidification is accomplished by means of a molecular sieve matrix wheel and the cooling is by means of a rotary heat exchanger. In 1980 to 1982 Australian investigators and a University of Wisconsin group resumed joint work on a cooling concept using an adiabatic wheel (Banks et al., 1970) for dehumidification.

The principal component of the IIT system (Gidaspow, et al., 1978) is a cross-cooled desiccant dehumidifier in which the process air is passed through channels containing the desiccant material and the cooling air is passed at right angles to the direction of the process air flow through intermittently arranged cooling channels. Commercially available silica gel powder was fabricated by a specially developed manufacturing procedure into porous, thin, paperlike sheets holding silica gel particles in a Teflon web. The unit shown in Figure 1 was completely tested (Worek, 1980) and modeled using an extension of the mass transfer coefficient model of Roy and Gidaspow (1974). A complete solar-powered cooling system consisting of two such dehumidifiers was also built and tested (Monnier, 1981). The thermal coefficient of performance was about 0.5; that is, half the energy collected with a solar collector could be converted into cooling.

To improve such cooling and dehumidification systems and to calculate their potential relative to competing systems, such as absorption air conditioning and vapor compression systems, it is necessary to have a valid mathematical model for dehumidification. The input to such a model preferably should be data—such as equilibrium characteristics of desiccants—that is already available in the literature, or data that can be estimated or measured easily, such as mass transfer coefficient or diffusivity data. As already reviewed by Ghezelayagh and Gidaspow (1982), the models available to date are inadequate for accurate design of a dehumidifier.

CONCLUSIONS AND SIGNIFICANCE

Accurate transient dehumidification data were obtained under well-controlled hydrodynamic and thermal conditions for several thicknesses and types of silica gel sheets and for a commercial activated carbon sheet. A parallel-plate, isothermally maintained channel with one active wall was used. Independent measurements of the equilibrium capacities and diffusivities of the desiccant sheets were made. Using these values, a predictive model for dehumidifications was developed. The model is a modification of a well-known Rosen model in the literature and is a limiting case of the micro-macropore model of Ghezelayagh and Gidaspow (1982).

We believe that given the thermal properties of the desiccants,

this model can now be used for making performance predictions of various desiccant cooling schemes. The technique should also be useful for gaining a better understanding of various other gaseous purification and separation processes.

EXPERIMENTAL

Sorbent Sheets

The desiccant sheet process involves blending micron-size silica gel with previously wet ground ammonium bicarbonate and about 5% by weight of DuPont Teflon powder in an adequate quantity of Shellsolv® 340. The resulting suspension was filtered to form a wet cake and then physically worked by roller-reduction to form a net structure of Teflon, (Raghavan, 1982).

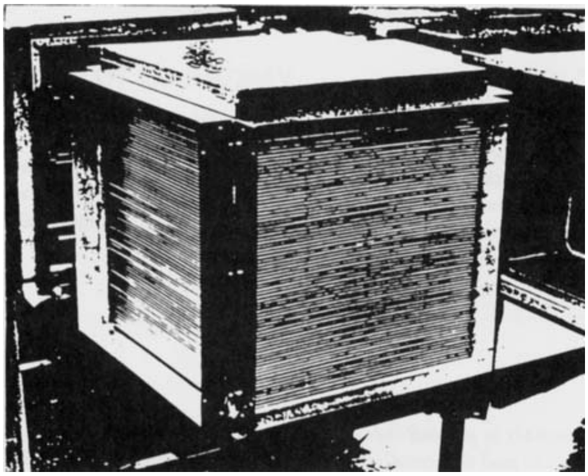

Figure 1. Desiccant dehumidifier prototype. Cube, 0.606 m high, containing 81 process and 80 cooling channels. Process channel width = 2.18 × 10^{-3} m. Cooling channel width = 1.4 × 10^{-3} m. Aluminum thickness = 2 × 10^{-4} m. Desiccant sheet thickness = 1.7 × 10^{-3} m.

Sorption Dynamics

The apparatus used in this investigation was a dynamic flowing-adsorbing rectangular channel constructed to satisfy the assumptions of the hydrodynamically well-defined Graetz problem. A schematic diagram of the apparatus is shown in Figure 2. The prepared desiccant sheet was held as a portion of one wall of the rectangular channel. Each experimental run was started with essentially zero moisture content with respect to that contained during each run. This was done by regenerating the desiccant. During this procedure, dry air (230 K dew point) was passed through the channel and the outlet dew point of the stream was continuously monitored with a dew point hygrometer until the outlet dew point matched that at the inlet. The dry air flow rate was maintained at a constant low value of 7 L/min for all regenerations for the first half-hour and at 15 L/min for a subsequent one-hour period. The low flow rate produced measurable outlet humidity of the air stream in the "best portion of the hygrometer's range. The first sorption run was not made until the desiccant and channel cooled to a constant temperature with dry air continually passing through the channel. After cooling, the dry air was switched to wet air. The dew point of the saturated air passing through the by-pass line was continuously recorded. When constant inlet conditions were obtained (30 min), the inlet moist air was switched into the channel by solenoid-operated valves. The dew point hygrometer responded 3 s after the stream switching due to a holdup slug of dry air in the channel; then, about 60 s after the switch, it tracked the slowly rising outlet humidity of air. Because of this, initial sorption rates could only be estimated. The sorption process was halted when the outlet dew point approached approximately 98% of the inlet dew point, because of the hygrometer's accuracy limitations. At this point, the inlet humidity was once again recorded for 15 min and the change, if any, was within the hygrometer's limitations. At the end of the

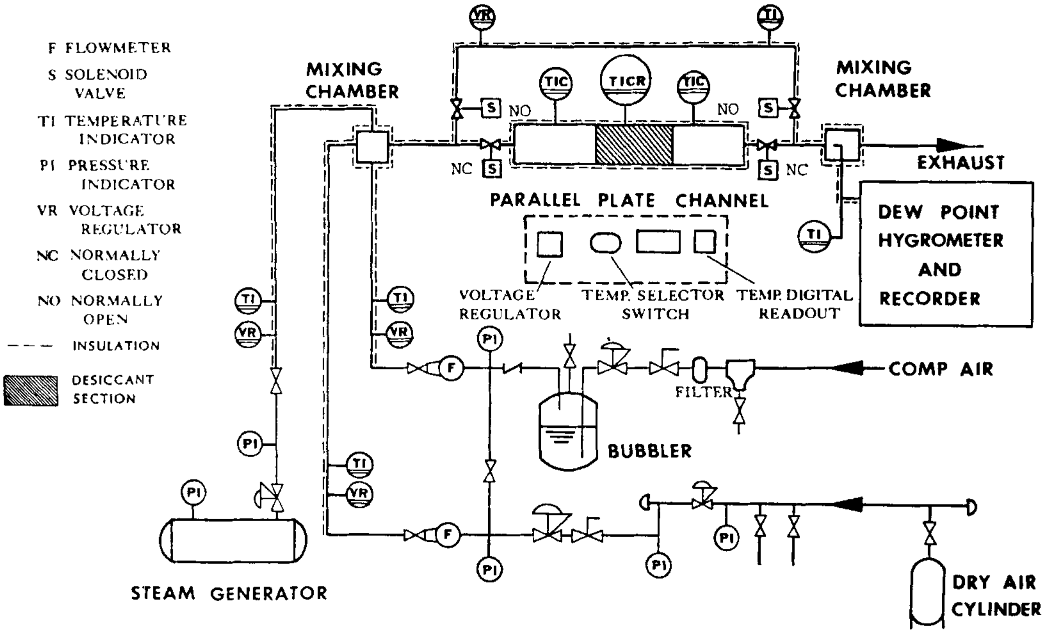

Figure 2. Schematic diagram of adsorber test set-up.

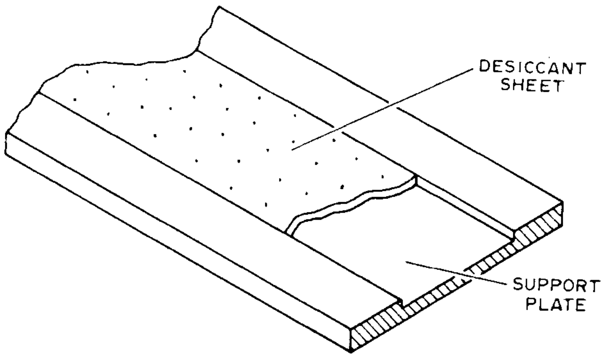

Figure 2A. Details of desiccant section.

run the inlet moist air was switched to dry air and regeneration heating began. Each experimental run was duplicated and the reproducibility was within 3%. Raghavan (1982) gives further details.

Table 1 lists the properties of desiccant sheets and the various materials used in our study.

Data Analysis

The adsorption data were analyzed using the overall mass balance of water. The adsorption section is represented as a system composed of a gas space of volume V and of a finite amount of silica gel desiccant. Air of certain moisture content flows into and out of the system. The following differential equation describes the process.

$$\rho V \frac{\partial \omega_a}{\partial t_A} + \frac{d\Gamma_{\text{total}}}{dt_A} = \rho v_{\text{in}} A \omega_{\text{in}} - \rho v_{\text{out}} A \omega_{\text{out}} \qquad (1)$$

The following simplifications apply to our study:

1. The maximum difference between inlet and outlet concentrations of water in the air streams in terms of weight is less than 1 or 2%. Hence the difference between the corresponding velocities is also less than 1 or 2%.

2. The residence time of a water molecule in the adsorption section is much less than the elapsed time of an experimental run. This enables the first term in Eq. 1, the rate of accumulation of water in the gas space, to be neglected. The water adsorbed per unit weight of desiccant can thus be expressed by

$$\Gamma_t = \frac{vAC_{\text{in}}}{\text{gm. of desiccant}} \int_o^{t_A} \left(1 - \frac{C_{\text{out}}}{C_{\text{in}}}\right) dt_A \qquad (2)$$

Equation 2 was integrated using Simpson's rule giving the total mass of water adsorbed per gram of silica gel present.

Diffusion Coefficients

To determine the effective diffusivity of each porous desiccant sheet used in our study, the desiccant sheet was mounted in a specially constructed cell so as to separate two gas flow systems. At one exposed face of the sheet, a stream of dry air passed, at the other, a stream of saturated air. As water vapor diffused through the sheet, the outlet dew point of the dry air stream was measured and recorded continuously. The diffusivity was determined from the concentration c_w, the dry air flow rate F_A, the water concentration difference Δc_w, and the sheet dimensions.

For desiccant sheets of silica gel and activated carbon, the effective diffusivity was determined by

$$D_{\text{eff}} = F_A C_w \frac{4a_w}{\pi d^2} \frac{1}{\Delta C_w} \qquad (3)$$

where a_w and d are the thickness and diameter of the sample respectively. Direct pen recording allowed visual observations of the time required to reach steady-state diffusion in each sample. This was a matter of a few minutes in samples having a diffusivity of the order of 10-$^{-6}$m^2/s. Table 2 lists the data for the diffusion coefficients and the tortuosities. The reproducibility of diffusivities was within 2.5%.

Equilibrium Characteristics

A thermogravimetric analysis (TGA) test system constructed by Dini (1981) was used to study the equilibrium adsorption capacity of various desiccant materials, particularly silica gel and activated carbon sheets at relative humidities ranging from 4 to 95%. Figure 3 shows the equilibrium moisture content of silica gel sheet containing 5 μm particles determined at the equilibrium temperature of 22.4°C. Similar data were obtained for 106 μm silica gel and activated carbon sheets.

Functional relations between relative humidity, RH, and equilibrium moisture content, Γ_{eq}, in the form of

$$\Gamma_{\text{eq}} = m \cdot RH \qquad (4)$$

were obtained for silica gel and activated carbon sheets using a linear regression program.

Γ_{eq} is related to the absolute humidity of air in equilibrium, Y_w, through the psychrometric relation. Thus

$$\Gamma_{\text{eq}} = KY_w \qquad (5)$$

Table 2 lists the values of the equilibrium constants, K, used in our study. Equation 5 is used in the mathematical model.

TABLE 1. SORPTION EXPERIMENTS WITH DESICCANT SHEETS*

No.	Sheet Thickness mm	Bulk Density g/cm^3
	5 μm Silica Gel	
1	0.76	0.4553
2	1.52	0.4457
3	3.18	0.4427
4	1.52	0.4037
5	1.52	0.5438
	106 μm Silica Gel	
6	1.22	0.4132
	Activated Carbon**	
7	2.54	0.1279

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* Flow rates ranged between 7.46 and 22.8 L/min.

** Regeneration temperature for carbon sheet, 120°C.

TABLE 2. EFFECTIVE DIFFUSIVITIES AND EQUILIBRIUM CONSTANTS OF DESICCANT SHEETS

No.*	Macroporosity ϵ_M	Effective Diffusivity, D_{eff} cm^2/s	Tortuosity, τ	Equil. Const.** K
		Silica Gel		
1	0.566	0.0302	4.6	18.8
2	0.576	0.0426	3.3	21.1
3	0.578	0.0565	2.5	17.7
4	0.616	0.0384	3.9	22.4
5	0.482	0.0440	2.7	23.8
6	0.607	0.0413	3.6	27.0
		Activated Carbon		
7	—	0.1628	—	17.7

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* Corresponding to sheet nos. in Table 1.

** At 23 to 28°C wall temperature (Raghavan, 1982).

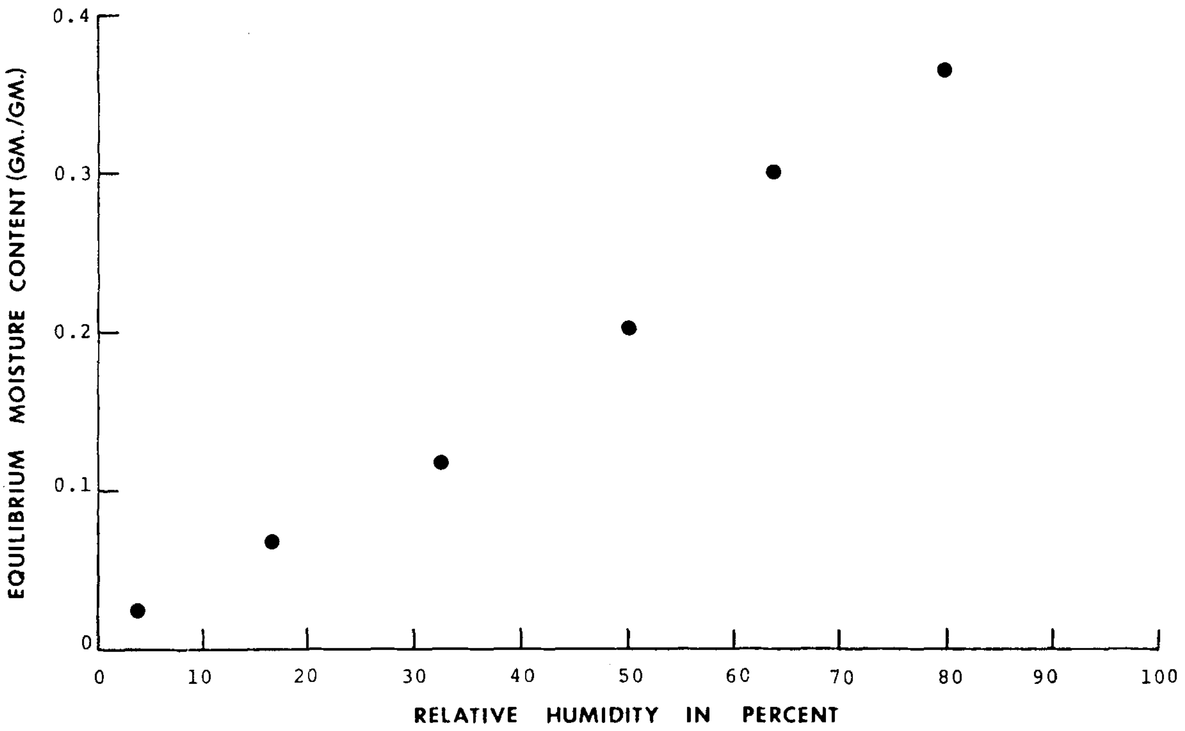

Figure 3. Equilibrium characteristic of silica gel sheet containing 5 μm particles for $T_w = 22.4°C$. $RH = -6.033 + 0.3298\,T_w + 211.8\,\Gamma_{eq}$.

DIFFUSION MODEL

Flow and diffusion of humidity in the channel and in the desiccant sheet can be shown to be given by the following differential equations, where U_1 is a dimensionless humidity in the channel and U_2 is a dimensionless humidity in the desiccant. See Figure 4.

Channel

$$(1 - y^2)\frac{\partial U_1}{\partial x} = \frac{\partial^2 U_1}{\partial y^2} \tag{6}$$

Inactive Wall

$$\frac{\partial U_1}{\partial y}(x,l,t) = 0 \tag{7}$$

Inlet

$$U_1(0,y,t) = 1 \tag{8}$$

Interface

$$\frac{\partial U_1}{\partial y}(x,-1,t) = \frac{1}{\gamma}\cdot\frac{\partial U_2}{\partial y}(x,-1,t) \tag{9}$$

$$U_1(x,-1,t) = U_2(x,-1,t) \tag{10}$$

Sheet

$$\gamma\frac{\partial U_2}{\partial t} = \frac{\partial^2 U_2}{\partial y^2} \tag{11}$$

Impermeable Wall

$$\frac{\partial U_2}{\partial y}(x,-\sigma,t) = 0 \tag{12}$$

Initially Dry Desiccant

$$U_2(x,y,0) = 0 \tag{13}$$

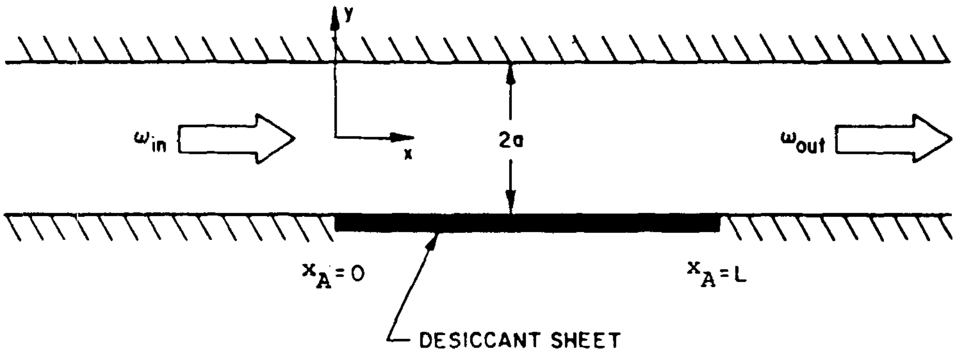

Figure 4. Adsorption section geometry. (Desiccant thickness is a_w).

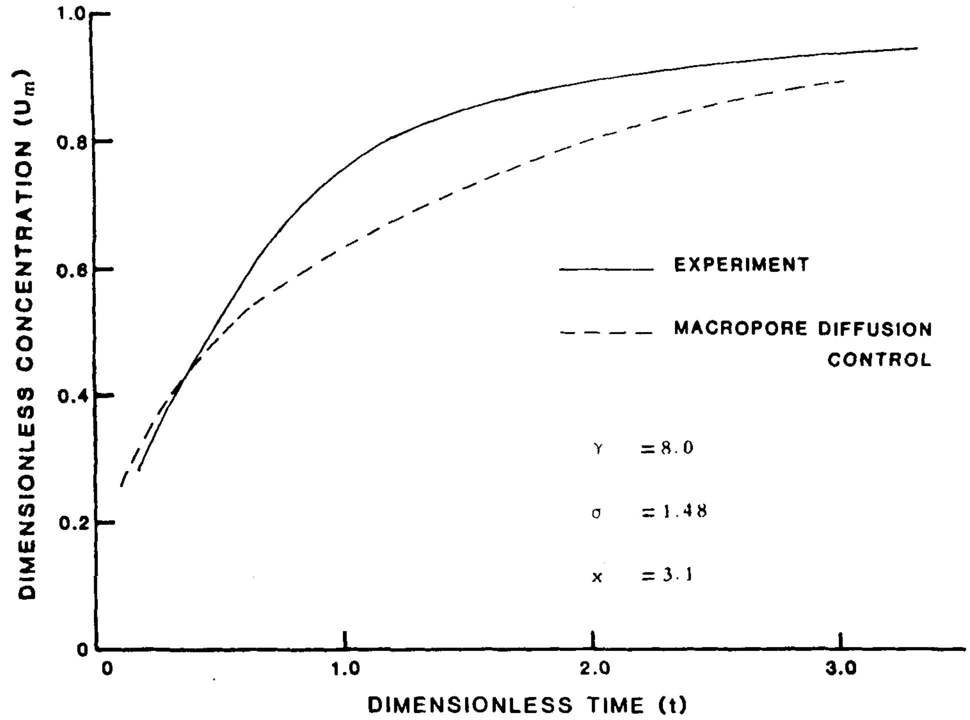

Figure 5. Dimensionless bulk concentration vs. dimensionless time for model compared to experimental data of 0.76 mm thick silica gel sheet at $x = 3.1$.

The dimensionless variables have the following meanings:

Concentration in the Channel

$$U_1 = C_1/C_{in} \tag{14}$$

Concentration in the Desiccant

$$U_2 = C_2/C_{in} \tag{15}$$

Dimensionless Contact Time

$$x = \frac{D_1 x_A}{3/2\bar{v}a^2} \tag{16}$$

Dimensionless Width

$$y = y_A/a \tag{17}$$

Dimensionless Sorption Time

$$t = \frac{D_1 \rho_{air} t_A}{\rho_b K a^2} \tag{18}$$

Gas to Desiccant Diffusivity Ratio

$$\gamma = \frac{D_1}{\epsilon_M D_M} \tag{19}$$

Total to Channel Width Ratio

$$\sigma = (a + a_w)/a \tag{20}$$

The dimensionless mixing cup concentration is given by the usual expression, as

$$U_m = \frac{Cm}{C_{in}} = 3/4 \int_{-1}^{+1} (1 - y^2) U_1(x,y)dy. \tag{21}$$

The dimensionless total uptake is scaled by the equilibrium value, Γ_{eq} as follows

$$\frac{\Gamma_t}{\Gamma_{eq}} = \frac{4}{3}\frac{1}{x(\sigma - 1)} \int_o^t 1 - U_m(t',x)dt' \tag{22}$$

This model is a limiting case of the micro-macropore model of Ghezelayagh and Gidaspow (1982) for the case when diffusion in the micropores is rapid. Physically this occurs when the particle size is small compared with the desiccant thickness and when the diffusivity in the micropores is not so small as to limit the rate of water uptake. Since the desiccant sheet is made of micron-size particles, one would normally assume the micropore resistance to be negligible. In the preliminary data of Perkari (1978) analyzed by Ghezelayagh and Gidaspow, this micropore resistance was included for generality.

The present mathematical model has only two parameters that have to be supplied from independent measurements on the desiccant. They are, first, the equilibrium capacity which enters into the dimensionless time in Eq. 18 through the value K. The second parameter is the diffusivity of the desiccant sheet which enters into γ, given by Eq. 19. Both values can be measured easily, as was done in this study. With these independent measurements, the model is completely predictive.

The model presented here is essentially Rosen's (1952) model. However, instead of using a mass transfer coefficient in the channel, we describe the diffusion process by means of the more rigorous Graetz formulation. This is done for greater accuracy in view of the fact that the local mass transfer coefficient is both time- and position-dependent, as already illustrated by Ghezelayagh and Gidaspow (1982). Rosen's model is commonly used in adsorption studies and has been extended to include resistances due to chemical reaction and heat effects due to nonisothermal operation (Chase et al., 1970). Hence it is pleasant to discover that it can describe transient operation of dehumidifiers when the relevant assumptions have been satisfied.

The assumptions made are as follows. We assume an isothermal operation. We know that the diluteness assumption is valid because we are always below 2% of water vapor in air. In Eqs. 6 and 11 we neglect the accumulation of water vapor in the gas space compared with that accumulated in the desiccant. This is a pseudosteady-state assumption that is valid here because the characteristic sorption

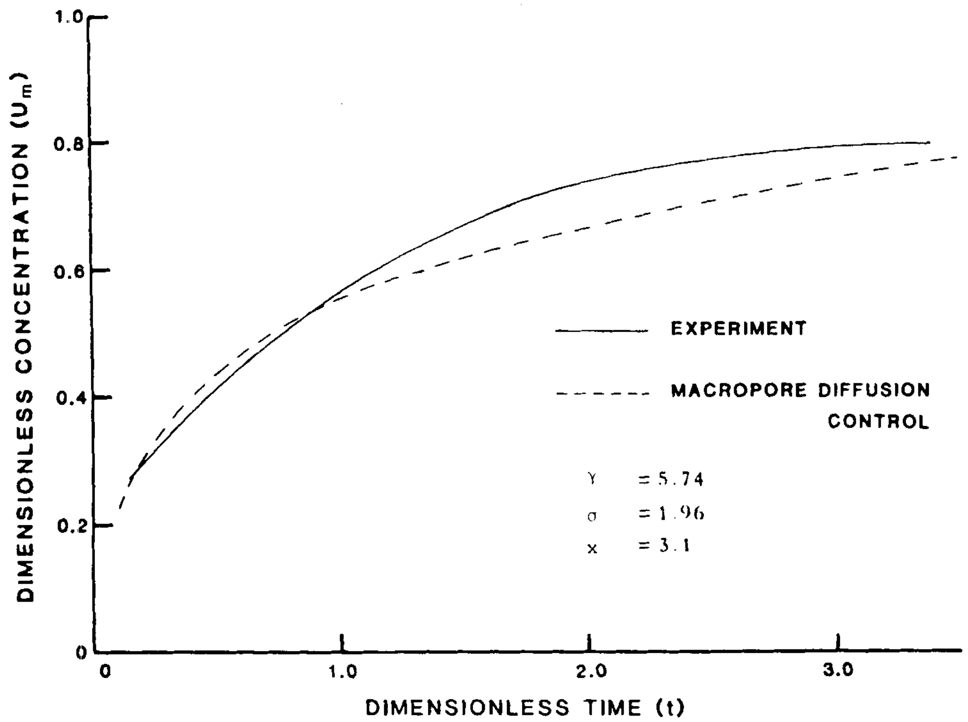

Figure 6. Dimensionless bulk concentration vs. dimensionless time for model compared to experimental data of 1.52 mm thick silica gel sheet at $x = 3.1$.

times are much larger than the time it takes the gas to flow through the channel. Differential Eq. 6 is thus the usual Graetz problem in the channel for laminar flow (Gidaspow, 1971). Equation 7 states that in our experiment we have desiccant at one wall only. Equation 8 is the statement that the inlet humidity is kept at its inlet value during the experiment. Equation 9 is a statement of the continuity of mass fluxes at the interface, that is, a mass balance. Equation 10 is a result of the fact that diffusion in the desiccant occurs in the pores between the micron-size particles. Thus the concentrations at the surface of the channel and in the pores right at the surface

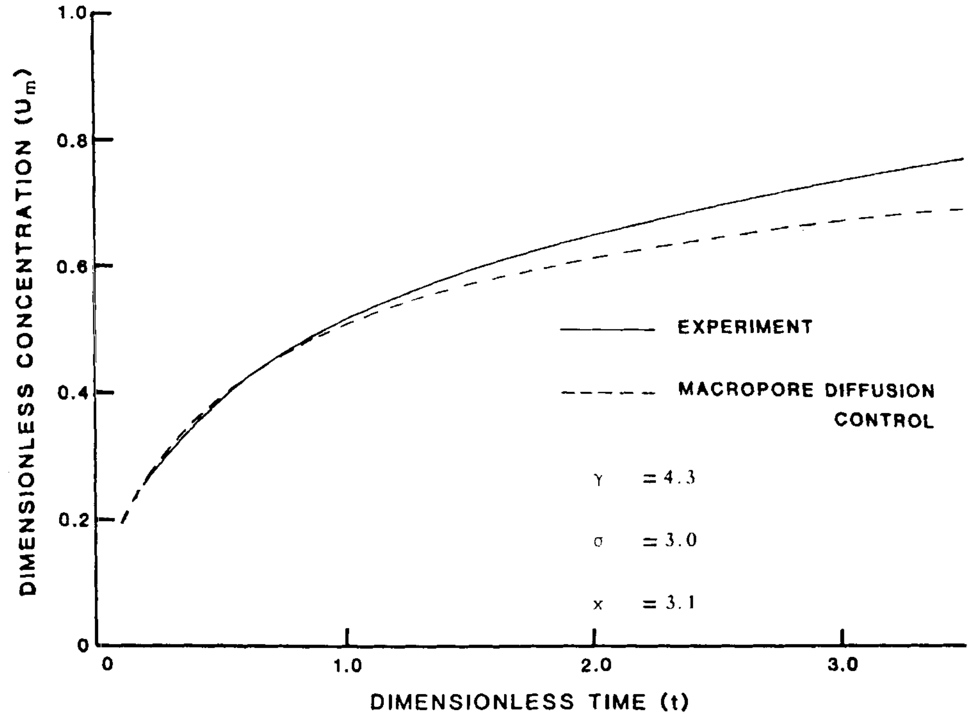

Figure 7. Dimensionless bulk concentration vs. dimensionless time for model compared to experimental data of 3.18 mm thick silica gel sheet at $x = 3.1$.

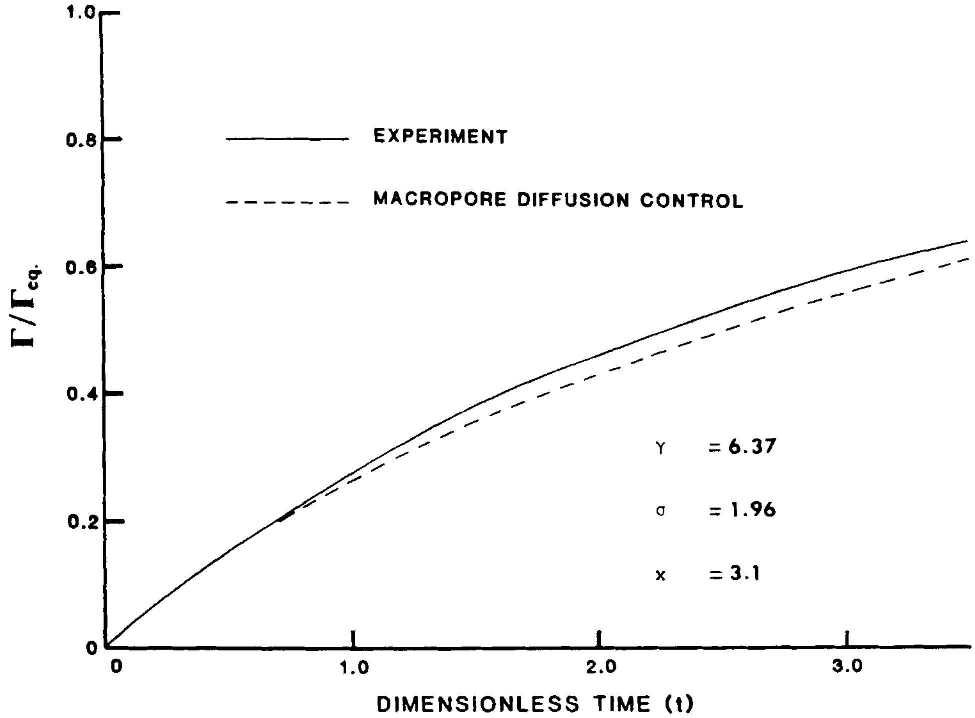

Figure 8. Amount adsorbed vs. dimensionless time for model compared to experimental data for low-density silica gel sheet (0.4037 g/cm^3) at $x = 3.1$.

are clearly identical. Equation 11 is the usual Fick's second law. As already stated, the accumulation in the pores in the desiccant was neglected compared with the huge value in the desiccant. Equation 12 states that the water vapor cannot diffuse out through the metal plate containing the desiccant sheet. Equation 13 is valid, because in each experiment we dried the desiccant to essentially zero moisture content with respect to that contained during each run. This transient boundary value problem was solved using the computer program and the method developed by Ghezelayagh and Gidaspow (1982).

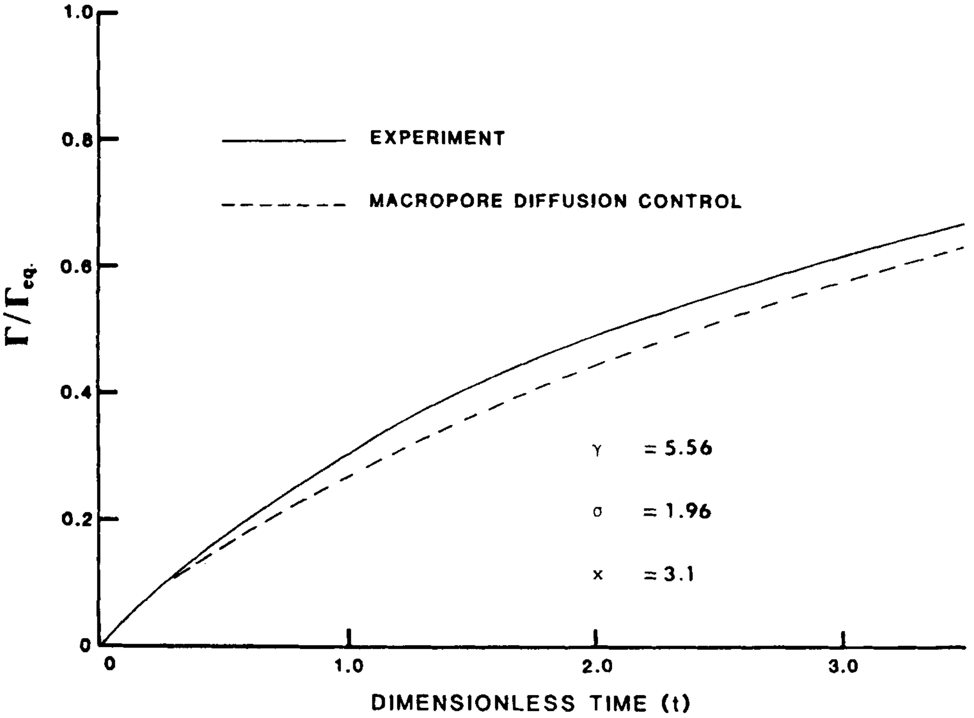

Figure 9. Amount adsorbed vs. dimensionless time for model compared to experimental data for high-density silica gel sheet (0.5438 g/cm^3) at $x = 3.1$.

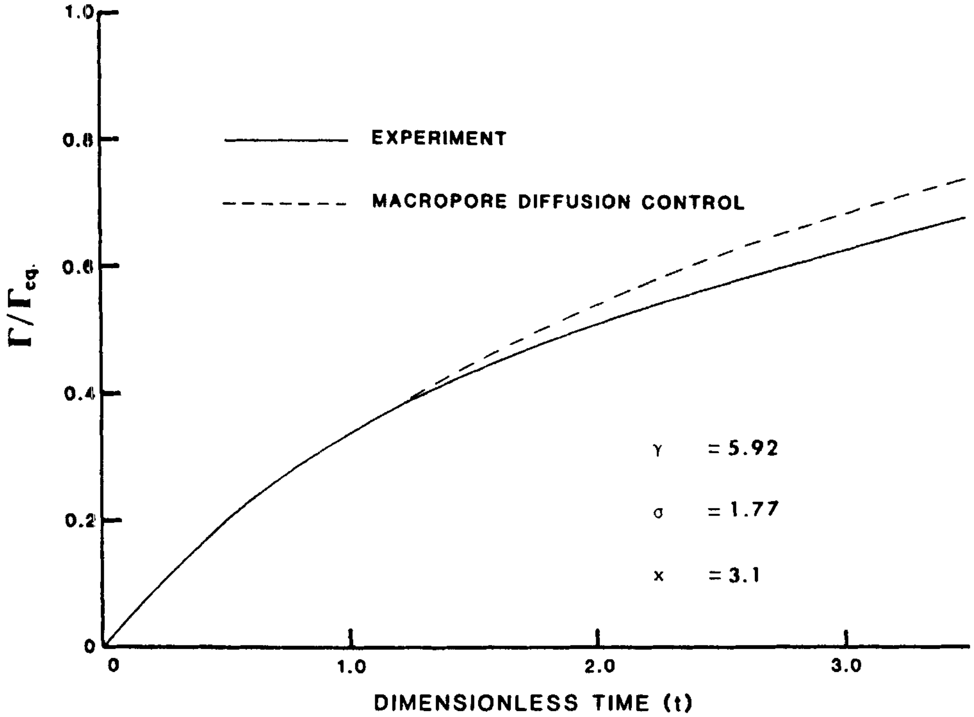

Figure 10. Amount adsorbed vs. dimensionless time for model compared to experimental data for silica gel sheet composed of 106 μm particles at $x = 3.1$.

RESULTS AND DISCUSSION

In order to have a valid comparison of our experiment to the mathematical model, the adsorption data should contain information at several different positions along the adsorbing test section of the channel. This was accomplished through an isothermal adsorption experiment carried out by varying inlet flow rates with the rest of the conditions remaining the same. Using Eq. 16, the dimensionless contact time, x, can be related to the flow rate of the humid air entering the channel. The data analyzed here are for

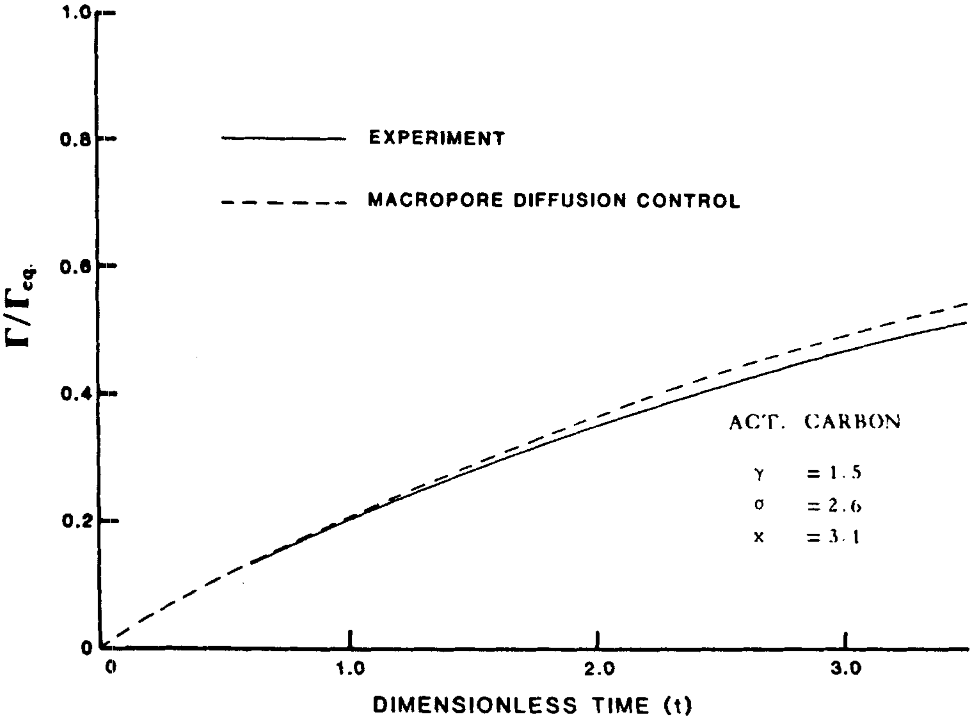

Figure 11. Amount adsorbed vs. dimensionless time for model compared to experimental data for activated carbon sheet supplied by Toyobo Co. at $x = 3.1$.

adsorption of water from humid air flowing through a rectangular channel with a porous sorbent sheet composed of 5 μm, 106 μm silica gel particls and activated carbon sheet at one wall. The reported data are a dynamic measurement of humidity at the channel exit for various flow rates with inlet humidity being kept constant at a dew point of 17.2°C.

Since the particles are sufficiently small, 5 μm compared with desiccant sheet thickness of the order of 1 mm, it is reasonable to assume that the particles should offer little resistance to diffusion of water. When the diffusion and adsorption in the macropores of the sorbent sheet is the only resistance to the transfer of water, the only two parameters needed to calculate the breakthrough curves of bulk concentration at different locations along the channel are γ and σ. The dimensionless length σ can be calculated from channel and sheet thicknesses. In an early attempt, Ghezelayagh (1982), in order to fit the limited data then available to him, conducted a parametric study with $\gamma = 2.0$, 5.0, and 20.0, corresponding to tortuosity factors of 1.4, 3.5, and 14.0. However, the fit was not good. He concluded that the experimental data cannot be explained by means of the macropore diffusion only, even with unreasonably high tortuosity factors.

Thus as a next step we obtained the effective macropore diffusion coefficient for each sheet. This eliminated the earlier need for a parameteric study of the macropore diffusion control model. The value of γ thus obtained varied between 4 and 8 for different silica gel sheets. This may be due to the variation in sheet-making procedure and the compaction pressure used during hand-rolling of the sheets.

Figures 5 through 7 show the calculated breakthrough curves of dimensionless bulk concentration compared with experimental channel data at $x = 3.1$ for 5 μm silica gel sheets of different thicknesses. Figures 8 and 9 show the sorption uptake compared with experimental channel data at $x = 3.1$ for 5 micron silica gel sheets of different bulk densities. Dimensionless contact time of 3.1 corresponds to the lowest flow rate in the data set. In Figures 10 and 11 similar plots for 106 μm silica gel sheet and activated carbon sheet are presented. A closer look at Figures 5 through 11 reveals that with the experimentally determined effective diffusivity and the equilibrium capacity, the modified Rosen model, as expected, does predict the initial sorption of up to at least 30% of the final capacity for both the silica gel and the activated carbon sheets.

From Figures 5 through 7 it is obvious that for thinner sheets the equilibrium capacity is attained much faster, and that in the long run the total amount of moisture adsorbed increases with increasing thickness. A comparison of Figures 8 and 9 shows that the denser sheet adsorbs more moisture due to its greater mass. In comparing sheets composed of 5 μm and 106 μm silica gel, Figures 8 and 10, we expected the sheet made of the smaller particles to adsorb moisture faster because of a smaller penetration time required for adsorbing phase to diffuse into the smaller particles. Surprisingly, this did not occur. In the particle size range investigated there is clearly no strong dependence on particle size.

ACKNOWLEDGMENT

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NOTATION

a = half-channel thickness, cm
a_w = sorbent sheet thickness, cm
A = area of the channel, cm^2
C_1 = sorbate concentration in the channel, g/cm^3
C_2 = sorbate concentration in the macropores, g/cm^3
C_{in} = inlet concentration in the channel, g/cm^3
C_{out} = outlet concentration in the channel, g/cm^3
C_m = mixing cup concentration, g/cm^3
C_w = water concentration, g/cm^3
d = diameter of the sheet, cm
D_1 = gas phase diffusion coefficient in the channel, cm^2/s
D_{eff} = effective macropore diffusivity, cm^2/s, $D_1\epsilon_M/\tau$
D_M = macropore diffusion coefficient, cm^2/s
D_m = micropore diffusion coefficient, cm^2/s
F_A = flow rate of air, cm^3/s
K = equilibrium constant defined in Eq. 5
m = slope defined in Eq. 4
RH = relative humidity
t = dimensionless time
t_A = actual time, s
T_w = equilibrium temperature, °C
U_1 = dimensionless concentration in the channel
U_2 = dimensionless concentration in the macropores
U_m = dimensionless bulk concentration in the channel
V = volume of the channel, cm^3
v_{in} = fluid velocity at the channel inlet, cm/s
v_{out} = fluid velocity at the channel outlet, cm/s
$\bar{v}$ = average fluid velocity in the channel, cm/s
x = dimensionless coordinate in the direction of flow
x_A = coordinate in the direction of gas flow, cm
Y_w = equilibrium humidity in the sorbent sheet
y = dimensionless lateral coordinate from the center of channel
y_A = lateral coordinate from the center of channel, cm

Greek Letters

γ = dimensionless group, $D_1/D_M\epsilon_M$
Γ_t = total amount adsorbed, g solute/g sorbent
Γ_{total} = total amount adsorbed, g solute
Γ_{eq} = amount adsorbed at equilibrium, g solute/g sorbent
ϵ_M = macropore porosity
κ = dimensionless group defined by Ghezelayagh (1982)

$$= \frac{\text{amount adsorbed by micropores at equilibrium}}{\text{amount adsorbed by macropores at equilibrium}}$$

ρ_{air} = density of air at STP, g/cm^3
ρ_b = bulk density of the sheet, g/cm^3
σ = dimensionless length, $1 + (a_w/a)$
τ = tortuosity factor
ω_a = weight fraction of water in gas space, g H$_2$O/g dry air
ω_{in} = inlet weight fraction of water, g H$_2$O/g dry air
ω_{out} = outlet weight fraction of water, g H$_2$O/g dry air

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