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DYNAMIC PERFORMANCE CHARACTERISTICS OF BOUND POROUS
SILICA GEL DESICCANT

MASTER

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FOR

DEPARTMENT OF ENERGY

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DEVELOPMENT OF SOLAR DESICCANT DEHUMIDIFIER

October 1979

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ABSTRACT

Dynamic dehumidification performance was investigated for a silica gel desiccant fabricated in bound, porous paper-like sheets. Sheets of various thicknesses (0.7 to 3 mm) were fabricated and tested under several dynamic flow conditions in a flat rectangular channel apparatus. During each experiment conditions of inlet moisture, air flowrate, and sheet temperature were maintained constant. Comparisons were also made with conventional silica gel pellets and with other forms of bound silica gel. The sheets show superior utilization of silica gel in short times (30 minutes or less). Tests were also made to examine the sheet structure in order to explore the effect of temperature on the porous structure, and to obtain pore size distributions.

A. INTRODUCTION

Drying of air with silica gel is a well established procedure. However, for the specific use of silica gel in a novel desiccant air conditioning system, which continually cools the silica gel and utilizes solar energy for silica gel regeneration, conventional packed bed devices are not suitable. For this system to operate effectively the silica gel must not rise in its temperature or its capacity will be greatly diminished. In this direction, commercial fine powder silica gel was fabricated into bound, porous paper-like sheets suitable for construction of a layered, cross-cooled dehumidifier as shown in Figure 1. Process air would be dehumidified by passing through channels between silica gel layers while the adsorption heat would be removed by the cross-flowing cooling air stream.

The fabrication of the silica gel into thin, porous sheets and the evaluation of the performance of this pliable structure for the dehumidification of air under dynamic flow conditions was the purpose of this study. The silica gel desiccant sheet material is composed of 95 percent by weight silica gel. The remainder is inert binder.

Experimentally determined information is necessary to establish water removal characteristics and design options. Information is needed about water removal rate and capacity over a wide range of inlet air humidities, flowrates, and adsorption temperatures. Additionally, the effects on performance due to sheet thickness, porosity, and structure stability must be known for effective design.

FIGURE 1. SCHEMATIC OF CROSS-COOLED DEHUMIDIFIER

B. SILICA GEL SHEET PREPARATION PROCESS

The silica gel bound sheet structure were prepared by blending micro-sized silica gel powder with 5 percent by weight of DuPont Teflon in an adequate quantity of petroleum solvent (Shellsol^R 340). Ammonium bicarbonate was added in 200 percent by weight excess.

Davison Chemicals Syloid^R 63 was used as the silica gel material given as average particle size of about 9 microns.

The suspension was filtered to form a wet cake which was then suitable to be rolled into the sheet form. The thickness was controlled by rolling between shim strips. The wet sheet was dried overnight then the ammonium bicarbonate was decomposed by heating the sheet to about 80°C for approximately one hour.

It was easy to control the thickness of the sheets with the shim strips, but the control over the amount of silica gel present in a given thickness sheet was difficult.

The dimensions of the first sheet tested were 30.5 cm by 7.3 cm by 1.52 mm thick. The weight of the sheet was 25.1 grams and it contained 4.7% Teflon. An electron microscopic examination of the sheet showed that the nine micron silica gel particles were held by means of thin Teflon strands forming a net-like structure.

Figures 2(a) and 2(b) show the micron size silica gel powder and the manufactured sheet at a magnification of 1000X. The appearance of the silica gel particles is identical in both cases. The size distribution is fairly wide. At this

a) Silica Gel Powder 1000X

b) Silica Gel Sheet 1000X

c) Silica Gel and Teflon Before
Rolling 5000X

d) Silica Gel Sheet 5000X

Figure 2. Electron Microscope Photographs of the Desiccant

magnification the Teflon binder is almost indiscernible.

Figure 2(c) shows the "cake" (wet mixture of silica gel and Teflon powder) before rolling and the final sheet at a magnification of 5000X in Figure 2(d). The Teflon web can be clearly seen in 2(d). It is not present in the "cake" since the web is formed by the rolling process.

Silica gel from several manufactures and several grades from Davison Chemical Co. were used in initial desiccant sheet preparation. The Davison Chemical's Syloid 63 grade was selected on the basis of best equilibrium capacity and particle size characteristics for sheet fabrication.

C. EXPERIMENTAL APPARATUS

The apparatus used in this investigation permits the measurement of sorption performance under dynamic isothermal flowing-adsorbing conditions. The silica gel desiccant is held as a portion of one wall of the narrow flat rectangular channel. Isothermal rate data facilitates the determination of controlling mechanisms of the adsorption process.

Previously, Onischak and Gidaspow used such an apparatus to study adsorption of water by lithium chloride⁽¹⁾ and the kinetics of the removal of carbon dioxide⁽²⁾. This was constructed to satisfy the assumptions of the hydrodynamically well-defined Graetz problem. Isothermal, laminar flow, and constant inlet concentrations can be maintained.

A schematic diagram of the apparatus is shown in Figure 3. The rectangular channel consists of three sections: entrance, adsorption, and exit section. The overall length of the channel was 2.13 meters (7 feet). The internal dimensions

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Figure 3. Schematic Diagram of Adsorber Test Set-Up

were 7.62 cm (3 inches) by 3.18 mm (0.125 inch). The ends of the rectangular channel were joined with mixing chambers whose other ends were suitable for tube fittings. General Electric's "RTV 600" silicone rubber adhesive sealant was used as a gasket and as a leak sealant for the channel. This material can withstand temperatures up to 600°F for short periods.

The entrance section of the channel consisted of the initial two-thirds of the channel length. This was wrapped with resistance tape heaters to keep the temperature above the dew point of the entering air. The heating tape was controlled by a SCR voltage controller. The surface temperature of the channel at this section was measured using a chromel-alumel thermocouple. In addition, the section was covered with a low thermal conductivity insulating material to reduce heat losses.

The adsorption section was 39.69 cm (15.625 inches) in total length. Sorbent material of dimensions 7.62 cm by up to 39.6 cm can be placed in the sorption section. Various sorbent thicknesses can be accommodated by using copper holding pans machined to different depths.

The exit section of the channel was about 0.76 meters (2.5 feet) in length. This portion was also wrapped with a resistance tape heater and insulation. A heater for this portion prevented severe temperature gradients along the length of the channel and also prevented moisture from condensing on the interior surface especially during thermal regeneration. A continuous gas sample flows from a mixing chamber to the hygrometer as shown in Figure 3.

Various inlet moisture conditions can be obtained by mixing saturated air from the Institute's compressed air with bone dry air (-40°C dew point temperature) from cylinders. The Institute's air was filtered, then saturated by passing through a bubbler fabricated from a 44 liter (11-gallon) stainless steel tank. The tank was wrapped with coil heaters and was insulated to achieve dew points above ambient temperature. Air of dew point of 29.4°C (85°F) was obtained by carefully controlling the heat supplied to the tank. The water temperature in the tank was measured by a thermocouple and was maintained at constant temperature during the run. Dew point temperatures did not vary more than 0.5°C and were measured before and after each run. A porous polyethylene gas dispersion tube was used to produce small air bubbles. To achieve dew points below the ambient temperature, air exiting from the bubbler was mixed with a dry air stream and passed through a mixer.

Flowrates were measured with calibrated rotameters. Two different rotameters were used to cover the range of flowrates from 0-2.25 standard liters per minute to 0-25 standard liters/min. The rotameters were calibrated with a "laminar flow element" manufactured and calibrated by the Meriam Instrument Company and with a wet test meter. The calibration meters' accuracy was within 0.5% certified.

The moisture content of the total air stream was monitored with a continuously measuring dew point hygrometer. A provision was installed to allow dry air to slowly flow through the channel when a run was not in progress or while

the inlet moisture level was being established to maintain the regenerated or initial state of the desiccant. Solenoid valves were located prior to the total air stream entrance to the channel and at the exit sampling section permitting simultaneous switching of the established inlet moisture stream through the channel.

C-1. Adsorption Section (Desiccant Sheet Section)

The water removal performance of various silica gel sheet forms was studied in the parallel plate channel apparatus. The sheet was held in a pan machined into a massive (6.35 mm thick) copper plate that was bolted to an opening in the channel and sealed. This aided the isothermal operating condition. The copper plate's outside dimensions were 10.16 cm (4.0 inches) by 40.64 cm (16.0 inches) by 6.35 mm (0.25 inch). A pan of 7.62 cm by 39.69 cm by the thickness of the test sheet was milled out of the plate so when the sheet was inserted, it formed a smooth, parallel extension of the channel wall. Thermocouple holes were drilled perpendicularly to the sheet in the copper plate at each edge of the plate (5 cm from the end) and at the center of the plate. Chromel-alumel thermocouples were inserted in the holes such that they just touched the sheet or entered the sheet slightly.

The adsorption section was always maintained above the inlet dew point temperature of the air. This was achieved by using flat ceramic plate heaters that were primarily used for regeneration of the silica gel at about 100°C to insure complete regeneration.

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Figure 4. Adsorption Section Geometry

C-2. Sampling System and Hygrometer

The moisture content of the inlet air and outlet air streams were measured with a dew point hygrometer manufactured by General Eastern Company (Model #1200AP). This instrument was well suited for this application because of its very low response time which was 1.67°C (3°F) dew point per second and its accuracy which was 0.28°C ($\pm 0.50^{\circ}\text{F}$) dew point. In addition, the sample flowrate need not be known accurately or be steady.

The hygrometer's sensor unit was placed as close as possible to the outlet air stream mixing chamber minimizing the length of the outlet air sampling line. The sensor and tubing was wrapped with flexible heating tape to maintain the sampling line and the sensor at a higher temperature than the dew point of the stream. The sampling system was constructed with stainless steel tubing and valves with teflon packing and seals.

D. FLOWING CHANNEL DATA CONVERSION

The adsorption data can be analyzed in several ways. The most fundamental method is an overall mass balance of water in the adsorption system. The one-dimensional mass balance method of Anzelius ⁽³⁾ or the regenerator type of Schuman ⁽⁴⁾ using a constant mass transfer coefficient could be applied. Another method is the use of the solution of the convective diffusion problem in the rectangular duct with one catalytic wall as obtained by Solberg and Gidaspow. ^(5, 6, 7) Their solution, presented as mixing cup concentration charts for laminar and turbulent flow were applied to study adsorp-

tion of water by anhydrous lithium chloride by Onischak and Gidaspow.⁽¹⁾

The formulation of the overall mass balance of water approach considers the adsorption section to be represented as a system composed of a gas space of volume V , and of a finite amount of silica gel desiccant as represented in Figure 4. Air, of certain moisture content, flows into and out of the system. An overall mass balance of the water in this system is stated as the rate of accumulation of water in the air streams. This statement is represented symbolically by Equation 1.

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

The quantity of interest in this work is the term $(d\Gamma_{total}/dt)$, which is the rate of adsorption of water in the desiccant. An expression for this term is obtained from Equation 1 with certain simplifications applicable to this study. One simplifying condition made is that since the maximum difference between inlet and outlet concentrations of water in the air streams in terms of weight is less than 1 or 2 percent, the difference between inlet and outlet air stream velocities is also less than 1 or 2 percent.

The second simplification applicable to this study is that 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, the "rate of accumulation of water in the gas space" in Equation 1 to be neglected.

To justify the above statement, consider Equation 1 rewritten in the following form with equal inlet and outlet air velocities.

$$\frac{1}{\rho v A} \frac{d\Gamma_{\text{total}}}{dt_A} = (\omega_{\text{in}} - \omega_{\text{out}}) - \frac{v}{v A} \frac{\partial \omega_a}{\partial t_A} \quad (2)$$

An order of magnitude analysis can be performed on the right-hand side of Equation 2. The orders of magnitude of ω_{in} , ω_{out} , and ω_a are of the same order, since the maximum difference between inlet and outlet concentration of water is 1 to 2 percent weight. The order of magnitude of the coefficient of the "rate of accumulation of water in the gas space" term is found to be of the order of .2 to 1.0 second from the adsorption section geometry and inlet air velocities of the experimental runs. Now the time variable in the accumulation term represents real elapsed time of an experimental run. Its order of magnitude is of the order of 2000 seconds. Therefore, the second term on the right-hand side of Equation 2 is about 10^{-3} or less of the magnitude of the first term; hence it is neglected. The result is expressed as

$$\text{Total rate of adsorption} = \frac{d\Gamma_{\text{total}}}{dt} = \rho v A (\omega_{\text{in}} - \omega_{\text{out}}) \quad (3)$$

Conceptually, the coefficient of the second term of the right-hand side of Equation 2 can be described as a maximum residence time of a water molecule in the system. The real time variable in the accumulation term represents the elapsed time in which all the water molecules pass through the system.

It should be observed that at very slow flows and short run times this "rate of accumulation of water in the gas space" term could not be neglected. However, this never occurs in this study.

Equation 3 can be integrated to obtain the total amount of water adsorbed over the time period.

$$\int_0^{\Gamma_{\text{total}}} d\Gamma_{\text{total}} = \int_0^{t_A} \rho vA (\omega_{\text{in}} - \omega_{\text{out}}) dt_A$$

or

$$\Gamma_{\text{total}} = \rho Q \int_0^{t_A} (\omega_{\text{in}} - \omega_{\text{out}}) dt_A$$

where $Q = vA$ = volume flowrate of air at standard conditions of 21.1°C and 1 atm. Expressing the total amount of water adsorbed per unit mass of desiccant we obtain.

$$\frac{\Gamma_{\text{(total)}}}{\text{gr.of S.G.}} = \frac{Q\omega_{\text{in}}}{\text{gr.of S.G.}} \int_0^{t_A} \left(1 - \frac{\omega_{\text{out}}}{\omega_{\text{in}}}\right) dt_A \quad (4)$$

In an experimental run, air of constant dew point temperature is passed through the channel over the desiccant sheet. The outlet mixing cup dew point temperature of the air is measured and recorded continuously. The dew point temperatures are converted to dimensionless outlet concentration as a function of time. With computer-aided computations, the right hand side of Equation (4) is integrated by using Simpson's rule giving the total mass of water adsorbed

per gram of silica gel present.

Two quantities of interest were calculated from the outlet concentration data. One was the total grams of water adsorbed vs. run time, and the other was a dimensionless outlet concentration vs. time. These are calculated for example, at intervals of one minute of a 30 to 45 minute run.

Due to the response delay of the hygrometer used in this experiment, a small error was present in the first minute of each run. The response of this instrument was $3^{\circ}\text{F}/\text{second}$, which translated into a 60 to 90 seconds lag for the humidity depression. Therefore, readings of the hygrometer do not show exact dew point temperatures in the first minute of the run. In order to compensate for this error, the following method was used. Figure 5 shows a typical reading of the hygrometer as obtained with the 3.17 mm sheet at 77°F inlet humidity and 5 liter/min flowrate. Areas A plus B are the probable true value for the integral in Equation 5. Area B alone is the value based on the hygrometer reading which has a lag in the first minute. We have chosen a consistent operating procedure to take the $t=0$ dew point value as the $t=1$ value for data integration. Probable area-difference calculations show that for 30 minute run durations for the cases with the greatest dew point depressions, the error is about 1% of the total area.

E. RESULTS AND DISCUSSION

The experimental test program proceeded in two phases. In the first phase, the thin porous silica gel sheet-form

Figure 5. Initial Hygrometer Reading for 3.17 mm Thickness Sheet at 77°F Inlet Humidity and 5 Liter/min Flow Rate

desiccant was prepared and tested for water removal performance under dynamic sorption conditions. Two thicknesses of the sheets were made (1.52 and 0.71 mm, see Table 1) and tested under a variety of inlet humidities, air flowrates, and sorbent temperatures to broadly define the performance of the silica gel in the sheet-form, and define additional areas for testing.

The second phase of the test program was carried out to obtain additional information comparing the performance of a thicker sheet and three other different forms of silica gel, namely, standard silica gel pellets, a densely bound plate-form from Davison Chemicals Company, and a 1.37 mm thick sheet supplied by Energy Research Corp. This last sheet was manufactured in large quantities for testing in the prototype.

E-1. Performance of Silica Gel Sheet Desiccant in Phase I Testing

Two thicknesses of the same composition silica gel sheets were studied. Inlet humidity, air flowrate, and sheet temperature were varied widely to establish the performance bounds and trends.

Table 1. Summary of Phase I Test Conditions

SHEET THICKNESS (mm)	SILICA GEL WEIGHT (gram)	FLOWRATE (liter/min)	INLET DEW POINT (°C)	SORPTION TEMPERATURE (°C)
1.52	23.9	5, 10, 20	16.7	24, 37, 40
0.71	8.7	5, 10, 20	15.6, 29.4	27.8, 35, 43.3

Sheet Width = 7.3 cm

Sheet Length = 30.5 cm

For the first sheet (1.52 mm thick) the performance was studied for three velocities of air at a constant 16.7°C (62°F) inlet dew point. Data are presented in Figures 6-9. The three test velocities at this dew point were 1.343 meters per second, 0.696 meters per second and 0.338 meters per second at 24°C sorbent temperature. The corresponding flowrates are 20, 10 and 5 standard liters per minute, respectively. Inlet humidity and temperature of the sorbent were also systematically varied. Sorbent temperatures were varied and held at 24°C, 37°C and 40°C while maintaining the air velocity at 0.696 meters per second with 16.7°C inlet dew point air humidity. For the same air velocity, an additional run was made with a lower inlet dew point air humidity of 4.4°C and at 24°C sorbent temperature.

For the second thinner sheet (0.71 mm thick) the performance was studied with several air velocities in the channel at a constant inlet dew point temperature of 15.6°C for comparison with the previous sheet. In addition, the sheet was also tested at a higher inlet dew point of 29.4°C and three sorbent sheet temperatures of 27.8°C, 35°C, and 43.3°C. Data from the thinner sheet (0.71 mm) are given in Figures 10-14.

Figure 6 presents the measured outlet humidity from the channel sorption section for an inlet dew point of 16.7°C for several air velocities with sorption occurring at room temperature. A thermocouple imbedded in the sheet showed only a

Figure 6. Outlet Concentration and Dew Point Vs. Time for 1.52 mm Thick Sheet

small rise in temperature (about 3°C in 30 minutes) due to the large heat capacity of the copper plate. The dimensionless outlet concentration presented in Figure 6 is simply the outlet absolute humidity divided by the inlet humidity. Data of the type shown in Figure 6 are needed for a systematic analysis of the sheet performance. These types of calculations for related systems were illustrated by Gidaspow⁽⁸⁾ for analysis of reaction rate data in channels and in greater detail by Onischak and Gidaspow.^(1,2) This data upon comparison to model predictions allow controlling mechanisms to be determined which is necessary for rational design of dehumidifier units and scale-up to large sizes. Channel gas space above the sheet, desiccant sheet thicknesses and porosities are important variables that need to be optimized because they are related to pressure drops and desiccant sheet areas (hence amount of desiccant) for a given dehumidification load.

Note, that the operation of the single desiccant sheet channel apparatus at low flowrates of air, that is, those flows between sheets which could be representative of a possible large unit, has an important design advantage in that very meaningful performance data at constant temperature is obtained which is suitable for nearly direct scale-up purposes.

Figure 6 shows this at low air velocities where nearly dry air leaves the channel for a long time. There is only a slow rise in the humidity at an air velocity of 0.338 m/sec . At the intermediate flowrate, a characteristic sigmoid type

Figure 7. Water Removed Vs. Time for 1.52 mm Thick Sheet at Different Flowrates

curve is obtained and more moist air leaves the channel. Duplicate runs were made at each flowrate showing repeatability within 10 percent. Figure 7 shows the cumulative water removed during the run as a function of run time. The final amount of water removed is 0.325 g water/g silica gel. This value is only 21% lower than the manufacturer reported value for the silica gel nine micron particles at a relative humidity of 77%. It is felt that the loss (based on the reported value) in equilibrium capacity is small and that this sheet appears to be a practical candidate for use in the construction of a dehumidification unit.

Figure 8 shows the measurement of water sorbed or removed as a function of sorbent sheet surface temperature. There is the expected drop in capacity with temperature. Figure 9 compares the dimensionless outlet humidity as a function of time for two different inlet humidities. As expected, at the lower inlet dew point less water is removed.

Figures 10 and 11 show data for the thinner (0.71 mm) silica gel sheet for an expanded range of inlet air velocities. Figure 10 gives the outlet concentration as a function of time and Figure 11 shows the amount of water removed versus time. Every run is duplicated and it can be observed that at high velocities, a convergence to the equilibrium value is evident.

Additional runs were made to examine the effect of higher inlet dew point. Figure 12 shows the dimensionless outlet dew point temperature as a function of time for inlet dew points of 15.6°C (60°F) and 29.4°C (85°F) at several flows.

Figure 8. Water Removed Vs. Time for 1.52 mm Thick Sheet at Different Temperatures

Figure 9. Outlet Concentration and Dew Point Vs. Time for 1.52 mm Thick Sheet at Two Different Inlet Dew Points

Figure 10. Dimensionless Outlet Concentration and Dew Point Vs. Time at Several Air Flow Rates for 0.71 mm Thick Sheet

Figure 11. Water Removed Vs. Time for 0.71 mm Thick Sheet for Several Air Flow Rates

Figure 12. Dimensionless Outlet Concentration Vs. Time for Two Different Inlet Dew Point Temperatures for 0.71 mm Sheet

Figure 13. Water Removed Vs. Time for Two Inlet Dew Point Temperatures for 0.71 Thick Sheet

Figure 13 shows the amount of water adsorbed per gram of silica gel as a function of time. Though the desiccant temperatures are not the same, the desiccant removed more water for the higher inlet moisture runs for the same flow and same time. It is conceivable that at the same sorption temperature for these two inlet dew points of 29.4°C and 15.6°C the difference in water adsorbed will be even greater.

Figure 14 shows a plot of water removed as a function of sorbent sheet surface temperature of the thin sheet. Three sorbent temperatures were selected for each flowrate. For the lowest air velocity of 12.34 cm/sec there is a little variation in the amount of water removed during the period of the run for each sorbent temperature of 27.8°C (82°F), 35°C (95°F) and 43.3°C (110°F). For the velocity of 30.17 cm/sec , divergence from the room temperature performance begins to occur after 10-15 minutes into the run. However, at the highest velocity the effect of temperature on sorption performance is clearly seen. These temperatures were measured at the center of the sorbent sheet with a thermocouple imbedded in the 0.71 mm thickness via a small hole drilled perpendicularly through the copper holding plate.

Figure 14. Water Removed Vs. Time at Different Sorption Temperatures for 0.71 mm Thick Sheet

E-2. Performance of Silica Gel Desiccant Forms in
Phase II Testing

Further experimentation was carried out to obtain the comparative performance of three different types of silica gel sorption materials and to compare the performance of a much thicker 3.17 mm (1/8 inch) sheet with the previous thinner sheets (0.71 mm, 1.52 mm). The other silica gel forms tested in the channel apparatus for dynamic sorption performance were:

1.37 mm thickness sheet supplied by Energy Research Corp. and a 1.37 mm thickness sheet subjected to excessive regeneration heat; silica gel pellets manufactured by Davison Chemicals Company; and a densely bound plate-form (4.06 mm thickness) of silica gel supplied by Davison Chemicals Company.

The performance of the 3.17 mm (1/8 inch) thickness sheet was measured for various inlet humidities of 0, 18.9, 25 and 30°C dew point (32, 66, 77, 86°F, resp.) and various channel flowrates of 2.5, 5.0 and 10.0 liters per minute. The velocities in the channel apparatus corresponding to the above flowrates are 0.169, 0.338 and 0.696 meters per second respectively. Table 2 presents all the operating conditions for the experiments.

The test of a very thick sheet was attempted to investigate the effect of sheet thickness upon the rate of water removal. Obviously, if the rate is not affected much by

thickness as a mass transfer resistance than a practical device design option could require fewer thicker sheets (hence fewer flow channels) to obtain the same mass loading of silica gel to remove the moisture.

E-3. Performance of 3.17 mm Sheet

Figures 15 and 16 present the dimensionless outlet humidity from the channel test section for the 3.17 mm (1/8 inch) sheet containing 19.6 grams of silica gel corresponding to four different inlet humidities and three flowrates. Figure 17 shows the amount of water removed per unit weight of silica gel for the above conditions.

Table 2. Tests of Sorption Performance of Various Silica Gel Materials at 25°C Sorption Temperature

Experiment No.	Flowrate (liter/min)	Thickness and Type of Silica Gel Structure	Silica Gel Weight (gram)	Inlet Dew Point (°C)
1	2.5.	3.17 mm sheet	19.57	25 (77°F)
2	5.0			
3	10.0			
4	2.5	Pellets	34.50	
5	5.0			
6	2.5	1.37 mm sheet	13.78	
7	5.0			
8	2.5	1.37 mm sheet (heated)	13.49	
9	5.0			
10	2.5	4.06 mm plate	54.63	18.9 (60°F)
11	5.0			
12	10.0			
13	2.5	3.17 mm sheet	19.57	
14	5.0			
15	10.0			
16	2.5	Pellets	34.50	0 (32°F)
17	5.0			
18	10.0 .			
19	2.5	1.37 mm sheet	13.78	
20	5.0			
21	2.5	4.06 mm sheet	54.63	30 (86°C)
22	5.0			
23	2.5	3.17 mm sheet	19.57	
24	5.0			
25	2.5			
26	5.0			
27	10.0

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Figure 15A. Dimensionless Concentration Vs. Time at 86°F Inlet Dew Point for 3.17 mm Thickness Sheet

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Figure 15B. Dimensionless Concentration Vs. Time at 77°F Inlet Dew Point for 3.17 mm Thickness Sheet

Figure 16A. Dimensionless Concentration Vs. Time at 66°F Inlet Dew Point for 3.17 mm Thickness Sheet

Figure 16B. Dimensionless Concentration Vs. Time at 32°F Inlet Dew Point for 3.17 mm Thickness Sheet

Figure 17A. Water Removed Vs. Time for 3.17mm Thickness Sheet at 86°F Inlet Dew Point

Figure 17B. Water Removed Vs. Time for 3.17 mm Thickness Sheet at 77°F Inlet Dew Point

Figure 17C. Water Removed Vs. Time for 3.17 mm Thickness Sheet at 66°F Inlet Dew Point

Figure 17D. Water Removed Vs. Time for 3.17 mm Thickness Sheet at 32°F Inlet Dew Point

Figures 18 and 19 present the outlet humidity and water removed, respectively for the 3.17 mm sheet at various inlet humidities and the two lowest flows to show the effect of inlet humidity. The removal of water is greater and the outlet humidity is higher with an increase in the inlet humidity and flowrate. A design flowrate value for a given inlet humidity can thus be obtained, from these figures, for example such that a design value of outlet humidity is always maintained. That flowrate value would have to comply with the design pressure drops in the flow channels of any practical device.

Figure 20 presents a comparison of the adsorption performance in terms of the water removed per gram of silica gel present between the 3.17 mm sheet and the thinner sheets tested earlier for inlet humidities in the range of 60-66°F dew point. The thinner sheets have bulk densities slightly more than twice that of the 3.17 mm sheet. The length and width of each sheet was identical. The bulk densities of the 0.71, 1.52 and 3.17 mm sheets were 0.57, 0.74 and 0.28 grams per cm³ respectively.

Although the thickness and bulk density are different in the comparison made in Figure 20, the overall performance of the 3.17 and 1.52 mm sheet are nearly equivalent. An analysis of a multi-channel silica gel desiccant dehumidifier with simultaneous cross-cooling, by Roy and Gidaspo⁽⁹⁾ indicate that the dehumidification performance would be the same if the desiccant thickness times bulk density is constant.

This is true for the 1.52 and 3.17 mm thickness sheets within 79 percent, which reflects the 18 percent difference in total silica gel present in those two sheets.

Figure 18. Dimensionless Concentration Vs. Time at Low Flow Rates and Various Inlet Dew Points for 3.17 mm Thickness Sheets

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Figure 19. Water Removed Vs. Time at Low Flow Rates and Various Inlet Dew Points for 3.17 mm Thickness Sheet

Figure 20. A Comparison of Adsorption Performance Between 3.17mm Sheet and Thinner Sheets

The practical conclusion between these two sheet performances that can be made is that since they contain roughly the same mass of silica gel (within 18%) their equivalent performance identifies a design choice between thickness and bulk density; that is, how to distribute the active silica gel sheets in a practical device given that the performances of each sheet is satisfactory. Thicker sheets would require a greater volume for the device, but could aid practical engineering construction features such as sealing of edges.

E-4. Performance Comparison with Other Silica Gel Forms

Figures 21-24 show a comparison between three different silica gel forms tested in the channel apparatus in terms of control of outlet humidity and the amount of water removed per gram of silica gel. The three forms compared were the 3.17 mm (1/8 inch) sheet, silica gel pellets of approximately plus 50 minus 14 mesh, and a densely bound plate-form of silica gel fabricated and provided for testing by W.R. Grace Company in Baltimore, Maryland.

The pellets were put in the channel holding plate as a monolayer about 3 mm (1/8 inch) deep. Silica gel pellets held in monolayer channels, say between screens, could possibly be used in place of the bound sheet form in a practical device, if their performance were equivalent. The form provided by W. R. Grace Company was manufactured with their process to bind powders. The plate was 4.06 mm thick and 7.62 cm (3 inches) wide. A section 25.4 cm (10 inches) was cut and placed in the channel apparatus. 54.6 grams of silica gel were estimated to be in the form.

As shown in Figures 21 and 24, the outlet humidity remains lowest for the pellets for 77°F and 32°F inlet dew point. This is because of the greater amount of silica gel mass held in the channel by the pellets over the 3.17 mm sheet (about 2.8 times). The pellets also must have more surface area than the plate form, which was the most dense material.

However, the 3.17 mm sheet has a much better adsorption performance per unit weight of silica gel present as is indicated in Figures 23 and 24. The much higher porosity (i.e., lower bulk density) of the sheet structure with finely powdered silica gel makes more silica gel available in the sheet to remove water faster than the relatively dense pellet form or the form fabricated by W. R. Grace. For long times the equilibrium amount of water held per weight of silica gel would be equal.

Mercury porosimeter tests were performed on all the test materials except the W. R. Grace plate to examine the size of pores present and are discussed and shown later. The silica gel pellets' pore size distribution shows a different pore size distribution compared to the sheets. The sheets clearly remove more water in a shorter time than the pellets per unit weight of silica gel. In a cycle operating dehumidifier device, this is an advantage where the adsorption time is short.

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Figure 21. A Comparison of Outlet Concentration between 3.17 mm Sheet and Pellets for 77°F Inlet Dew Point

Figure 22. A Comparison of Outlet Concentration Between 3.17 mm Sheet and Pellets for 32°F Inlet Dew Point

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Figure 23. A Comparison of Water Removed Between 3.17 mm Sheet and Pellets for 77°F Inlet Dew Point

Figure 24. A Comparison of Water Removed Between 3.17 mm Sheet and Pellets for 32°F Inlet Dew Point

This suggests that the multi-sheet type dehumidifier will provide a better response in adsorbing water rather than silica gel pellets in some monolayer-type. Packed silica gel beds have not been considered because of the much higher pressure drops through the bed, and difficulty in controlling the temperature rise during sorption.

E-5. Effect of Excessive Regeneration Heat

Figures 25 and 26 present the dimensionless outlet concentration and the amount of water adsorbed per unit weight of silica gel for two identically prepared 1.37 mm sheets by Energy Research Corporation. One was freshly prepared and the other was subjected to elevated temperatures. Heating was carried out up to 275°C for one hour, much above the normal 80-100°C regeneration temperatures. The excessive heating did not destroy the performance totally.

Complete regeneration is always obtained at or below 100°C but it is possible that a sheet could be accidentally subjected to higher temperatures, and this effect on structure and performance would be useful information about durability. Silica gel itself would not be harmed by the high temperature, but the Teflon binder could restructure at this temperature.

The performance of the severely heated sheet is affected for sorption times greater than 12 minutes of the typical 30 minute test run. If 30 minutes would be close to an operating cycle sorption time, then control of the outlet humidity after 12 minutes is affected by the severe heating. If the cycle time is shorter, the effect is not as great.

It is felt that excessive regeneration temperatures up to 150 to 170°C do not affect the structure. More investigation of repeated sorption and heating cycles is necessary, but preliminary durability appears promising.

Porosity and pore size distributions were measured with a mercury penetration porosimeter on samples of the 3.17 mm sheet, silica gel pellets, and heated and unheated sheets. These measurements of pore size distribution are presented in Figure 27.

Among these samples the bound sheets show similar pore size distributions, however, the pellets show a quite different distribution. About 50% of the pellets pore sizes are greater than 30 microns. Most of the sheet pore sizes are in the 0.5 to 3 micron range.

This could be related to the better initial performance of the silica gel sheets compared to the silica gel pellets. A further study of optimization of particle size, pore size and distribution and sheet thickness would be useful. Experience in fabrication indicates that the pore size variation would be limited by the silica gel material in use. But, the particle size could be evaluated for optimum sorption performance. Also obtaining a constant particle size would be useful for interpretation of sorption mechanisms.

The powder used in this study was non-uniform in size as supplied directly by the manufacturer. The average size was specified as 9 microns, but the photo-micrographs show that

0.1 to 50 micron particles are present.

The differences between the unheated sheet (made in large quantities by Energy Research Corp) and the severely heated sheet are not as great as between the 3.17 mm sheet and pellets. However, the heated sheet lost some performance with respect to the unheated sheet suggesting that the small differences in pore size distributions shown are significant. Well controlled experiments could show the effect of the size and number of pores upon the rapid, initial water removal ability of the bound sheets of silica gel.

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Figure 25. A Comparison of Outlet Concentration Between the Excessively Heated Sheet and the Unheated Sheet for 77°F Inlet Dew Point

Figure 26. A Comparison of Water Removed Between the Excessively Heated Sheet and the Unheated Sheet for 77°F Inlet Dew Point

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Figure 27. Pore Size Distribution

F. CONCLUSIONS

A thin porous sheet-form of silica gel, composed of about 95 percent by weight silica gel was tested for performance under a variety of inlet air humidities, flowrates, and silica gel temperatures. In addition, the testing in the isothermal, flowing adsorbing channel apparatus produced very meaningful information for application to prototype and practical cross-flow dehumidifier units.

Various sheet thicknesses and porosities were evaluated for performance under dynamic test conditions. On an equal mass basis of silica gel, sheets of thicknesses of 1.52 and 3.17 mm performed nearly equivalently.

Sheet structure durability was found to be excellent in multiple sorption-regeneration cycles during testing. Excessive heating of the sheet to 275°C showed that the sheet structure is not destroyed. Performance was reduced by 50 percent only after a time of 10-12 minutes of a typical 30 minute sorption test run. Normal regeneration temperatures are in the 82-100°C range and should not affect sheet structure.

The short time performance of the sheet-form of silica gel was much better than that of silica gel pellets and of plate form supplied by Davidson Chemical Company, although equilibrium capacity is expected to be identical.

Additional experimentation with uniform particle size silica gel bound into sheets would be useful as would be the study of the effect of pore size distribution, overall porosity and thickness upon performance.

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