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CROSS-COOLED DEHUMIDIFIER MODEL TEST RESULTS AND
COMPUTER SIMULATIONS

MASTER

By
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November 1979

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Solar Energy

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CROSS-COOLED DEHUMIDIFIER MODEL
TEST RESULTS AND COMPUTER SIMULATIONS

BY

V. Mei

Z. Lavan

IIT, MMAE DEPARTMENT

FOR

DEPARTMENT OF ENERGY

CONTRACT NO. EG-77-C-03-1589

DEVELOPMENT OF SOLAR DESICCANT DEHUMIDIFIER

November 1979

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ABSTRACT

A 15 cm x 15 cm x 15 cm (6" x 6" x 6") cross-cooled silica gel desiccant dehumidifier model was designed, built and tested. The process of producing the silica gel sheets, the design and construction of the unit, the test setup and the test procedures are described in detail. A total of twenty tests were performed to determine the effect of inlet process stream dew point, process stream and cooling stream flowrates and regeneration stream temperature and dew point, on the performance of the unit.

The test results show that the unit performance improves with increasing regeneration temperature, process stream flowrate and process air inlet dew point. The unit performance decreases with increase of the regeneration stream dew point. The results clearly show that the process stream inlet dew point is the dominating factor and that the concept of cross-cooling works very well. With moderate cross-cooling, the unit performance can increase over 50%. All tests were simulated by a computer program. The experimental and theoretical results are in very good agreement.

I. INTRODUCTION

A desiccant is a solid sorbent which has the property of adsorbing moisture from, or adding moisture to a gas, such as a water vapor and air mixture. During the adsorption process, a considerable amount of heat is generated and the air will become dry and hot. If we remove part of the sensible heat from the dry air and then spray cool it, the air can be used for air-conditioning purposes.

A desiccant dehumidifier air-conditioning system if operated by solar energy, can have a very high EER (energy efficiency rating) value. The development of such systems, both theoretically and for practical applications has been under way for some time. Remington [1] and Dunkle [2] have developed a rotary type dehumidifier for air-conditioning purpose. A Solar-Mec system [3] was developed at the Institute of Gas Technology. It uses molecular sieve as desiccant in a wheel type arrangement. Molecular sieve has to be regenerated at relatively high temperatures (about 400°F or 200°C). Bank, Close and MacLaine-Cross [4] have theoretically analyzed the performance of an adiabatic silica gel dehumidifier. The heat generated during the adsorption process raises the temperature of the desiccant which in turn reduces the moisture adsorption capacity. Lunde [5] has built a rotary type silica gel packed wheel with stage intercooling and developed a computer simulation to predict the cyclic performance of the dehumidifier. Roy [6] theoretically analyzed a cross-cooled desiccant dehumidifier.

The cross-cooling keeps the desiccant temperature low, thus maintaining a high rate of moisture transfer. Also, since the cross-cooled dehumidifier is of a fixed bed configuration, its construction is simpler than that of a rotary type unit.

This report, describes work performed by the Illinois Institute of Technology under a DOE contract to develop a solar operated cross-cooled desiccant cooling system. Silica gel is used as the desiccant because of its low regeneration temperature (about 65°C or 150°F). As part of the contract work, this study describes the design, construction and testing of a scaled down cross-flow desiccant dehumidifier model. The purpose of this study is to learn as much as possible from the model test results before a full scale unit is constructed. A total of twenty tests under different operating conditions were performed. Each test was then simulated by computer calculations so that the mathematical model used in the calculation [9] could be carefully validated.

In Appendix A, the process to manufacture the silica gel sheets used in the dehumidifier model is described in detail.

II. DESICCANT DEHUMIDIFIER MODEL

A. DESIGN AND CONSTRUCTION OF THE MODEL

The dehumidifier model shown in figure 1 is 15 cm x 15 cm x 15 cm (6" x 6" x 6"). The design is based on the concept that the process stream, cooling stream and silica gel sheets each occupies 1/3 of the volume of the unit (excluding the space occupied by structural material). The unit is composed mainly of 16 channels and two end plates with 16 slots each to fit the channels. Each channel is made of two pieces 15.88 cm x 19 cm x 0.079 cm (6.25" x 7.5" x 0.032") aluminum sheet metal and two bronze square rods 0.32 cm x 0.32 cm x 19 cm long (0.125" x 0.125" x 7.5"). They were glued together by five minute epoxy. Each channel has an opening of 15 cm x 0.32 cm (6" x 0.125") and is carefully checked for leaks before the unit is assembled.

Two pieces of silica gel sheets were bonded to the two outside surfaces of each channel with 3M77 spray glue. Along the edges of the sheets, GE RTV rubber was used to strengthen the bond.

The channels were then assembled with the two end plates. The spaces between the channels form the process stream passage.

The gaps between the end plates and channels were sealed with clear silicon caulking compound to prevent leaks.

Two end caps formed from 0.079 cm (0.032") aluminum sheet were fastened to the top and bottom of the unit to complete the assembly. Flanges around the 4 sides of the unit were added

for ductwork connections. This design is aimed at preventing internal leaks. Since each channel was built and checked separately, leaks between the channels are unlikely to happen. Any leaks in other places can be easily sealed off without taking the unit apart.

B. TEST SET-UP AND PROCEDURES

Figure 2 shows the schematic of the test setup. Room air was used as the process stream and compressed air was used as the cooling stream. The reason for using room air as the process stream, is that residual oil particles in the compressed air may contaminate the silica gel sheets. The test setup consists of:

1. Process Stream

A steam generator (a regular steam humidifier with a capacity around one pound per hour) provides steam to be mixed with the room air to boost the inlet process stream dew point. Valve A (VA) shown in figure 2 controls the amount of steam and Valve B (VB) regulates the amount of room air. Valve C (VC) should be closed during the adsorption cycle. Valve D (VD) is used to make the fine adjustment of the process stream flowrate. A perforated plate with about 40% opening was installed just at the inlet process stream ductwork to reduce the jet effect of the stream. Valves A, B, C and D are 5.08 cm (2") butterfly ball valves. They are connected to 5.08 cm (2") O.D. copper tubing. The copper tubing is then connected to the ductwork. The process stream ductwork is composed of two 17.5 cm x 18.42 cm x 73.66 cm x 0.081 cm

thick (6.89" x 7.25" x 29" x 0.032") galvanized steel sheet metal ducts. A Dayton model 4C446, 0.03 kw (1/25 HP), 110V AC blower is used to provide the process stream. It can deliver up to 0.227 m³/min (8 CFM) flowrate. The process stream flowrate is measured by a cylindrical nozzle 5.08 cm to 1.27 cm (2" to 0.5") diameter throat, and the installation is based on ASHRAE standard ANSI B198-1977. The nozzle was calibrated by measuring the pressure drop across it at known air flowrates. An inclined manometer is used to measure the pressure difference across the nozzle. The stream inlet and outlet temperatures are measured by 4 copper-constantan thermocouples. (The inlet temperature was corrected by remeasuring the temperature with a nine-thermocouple pile). The inlet process stream dew point is measured by a General Easter 1100 AP hygrometer and the outlet dew point is measured by a General Easter 1200 AP hygrometer. The outputs of the hygrometers are connected to a Hewlett-Packard dual channel chart recorder so that the change of the dew points can be recorded simultaneously.

2. Regeneration Air Stream

Room air heated by four electrical heaters is used as the regeneration stream. During the regeneration cycle, valves A and B should be closed and valve C is open. The four 55V, 250W electrical heaters are connected in such a way that 110V power source can be applied. The heaters are plugged into a YSI model 74 proportional temperature control unit with a

temperature sensor located just upstream of the process air inlet to the cross-cooling unit. The regeneration air temperature can then be controlled by setting the proper temperature on the temperature control unit. The flowrate of the regeneration air is controlled by adjusting valve C.

3. Cooling Stream

Compressed air is used as the cooling stream. A pressure regulator is connected to the compressed air system to reduce the inlet pressure. A rotameter with $0.286 \text{ m}^3/\text{min}$ (10.1 CFM) capacity (the measured flowrate is adjusted when operating at inlet pressures other than 0.101 MPa or 14.7 psi). A perforated plate with about 40% openings is located at the stream inlet ductwork to reduce the jet effect of the stream. The inlet and outlet of the cooling stream temperatures are measured by two copper-constantan thermocouples. The cooling air inlet ductwork is 21.59 cm x 22.23 cm x 61 cm long and 0.081 cm thick (8.5" x 8.75" x 24" x 0.032"). The outlet duct has the same cross-section area and is 35 cm (13.78") shorter. All the connections between the ductwork and the cross-cooling unit and the copper pipes are sealed with silicon rubber caulking compound to prevent leaks. All the thermocouple wires are connected to a selector switch with the output connected to a Hewlett-Packard single channel chart recorder.

For tests performed at very humid room conditions, some compressed air was introduced into the process air stream in order to reduce the process stream inlet dew point.

A vacuum pump (not shown in the setup schematic) is used to suck air through the hygrometer sensors so that the hygrometers can have accurate readings of the process air dew point with a reasonable time response.

4. Test Variables

The experimental test setup permits control of the process air dew point and flowrate, the cooling stream flowrate and the regeneration air temperature. In addition to the above variables, tests were also performed at very humid room conditions so that the effect of the regenerating air dew point on the performance of the unit could be studied.

During the tests, typically one variable was allowed to vary while the others were kept constant. The analysis of the results was based on the above five variables.

5. Test Procedures

The following test procedures were closely followed during the tests.

- (a) Turn on the electrical heater 5 minutes before regeneration starts.
- (b) Valve C should be open and valves A and B closed.
- (c) Regenerate the unit for 30 minutes with the temperature setting on the proportional temperature control unit set at a desired regeneration temperature. Cooling stream should not be turned on.
- (d) Turn off the heater and blower. Valve C is closed.

- (e) Turn on the cooling stream at desired flowrate for 5 minutes.
- (f) Valve A and B are adjusted to have the desired process air dew point and flowrate. The blower is turned on while the cooling air is still flowing. The adsorption lasts 30 minutes.
- (g) Five minutes before the adsorption cycle ends, the electrical heater should be turned on.

The above procedures were repeated until a steady state periodic operation was reached. It usually took 5 to 7 cycles. Since the dew point outputs were sensed by two hygrometers and since the two unit time responses were not necessarily the same, the two hygrometers were calibrated dynamically for every test. The two hygrometers were provided with the same air sample from the inlet section of the process air for one cycle and then the sample air is switched to the process air outlet section for one cycle. With the information, the output of one hygrometer can be interpreted in term of the output of the other unit. Thus the difference in time responses can be eliminated.

C. TEST RESULTS AND DISCUSSION

A total of 20 tests were completed. The test results can be divided into five groups where each group represents the effect on the dehumidifier model performance of a specific variable.

1. Effect of Process Stream Dew Point on the Unit Performance

Figures 5 to 9 show the test results with regeneration

air at around 1.67°C (35°F) dew point 62.7°C (145°F) dry bulb. With the cross-cooling and process air flowrate kept constant at $0.227 \text{ m}^3/\text{min}$ (8 CFM), the effect of process air inlet dew point was studied. Figure 5 shows the test performed at 3.50°C (38.3°F) process air dew point. It was only able to cycle 5.4% of the moisture. Figure 6 shows the test results for 4.9°C (40.9°F) inlet process stream dew point. The total moisture cycled improved to close to 6%. With further increase of the process stream dew point to 8.7°C , 10.4°C , 14°C (47.57°F , 50.63°F and 57.33°F), the total moisture cycled improved to 6.9%, 7.8%, and 8.25% respectively. Test results from figures 5 to 9 are also plotted in figure 27.

2. Effect of Regenerating Air Dew Point

Figures 10 to 12 show the test results at high regeneration stream dew points. Since room air was used for regeneration purpose, these tests were performed under very humid room conditions. Since the room air was also used as the process stream, tests for low inlet process stream dew point were achieved by mixing the humid room air with dry compressed air. Figure 10 shows the test performed at 17.2°C (63°F) regeneration stream dew point while the process stream inlet dew point is only 6°C (42.85°F). From the figure, it can be seen that the total moisture cycled is less than 4% of the silica gel sheet by weight. One apparent reason for this poor performance

is that with very humid regeneration air, the silica gel sheets are not regenerated dry enough to provide efficient moisture cyclings. It can also be seen that for the first 12 minutes of the regeneration cycle, the total moisture regenerated is zero. Figure 11 shows similar test results as in figure 8 except that the process air inlet dew point is raised to 9.5°C (49.1°F). As is expected, the unit performs slightly better, but for the first 10 minutes of the regeneration cycle, no moisture is desorbed. Figure 12 shows the test performed at 15.4°C (59.69°F) process air inlet dew point and regeneration at 15.6°C (60°F) dew point. While it did manage to cycle 7.85% of moisture, it was expected to perform better at such high process stream inlet dew point, but poor regeneration lowers the overall unit performance. Figure 13 shows the test results performed at process stream inlet dew point of 16.3°C (61.4°F) dew point. The total moisture cycled is over 8% silica gel sheet by weight. The above four test results are also plotted on figure 27.

Figure 27 shows the effect of the inlet process stream dew point on the performance of the unit. Two sets of data are plotted. One for regeneration air at relatively dry room conditions (1.7°C or 35°F average dew point) and the other for regeneration air at very humid room conditions (15.6°C or 60°F average dew point). It can be seen that although the unit performance drops with increasing humidity of the regeneration stream, the influence of the inlet process stream dew

point in both cases is almost the same, i.e., the two straight lines are almost parallel. The upper line shows that at 3.5°C (38.3°F) process stream dew point, the total moisture cycled is 5.4% and that at 14.2°C (57.5°F) dew point, the reading increases to 9.25%. This means that for every 5.5°C (10°F) increase in dew point, the performance of the unit will improve by cycling close to 2% more moisture. If it is assumed that the average moisture cycled in a normal run is 8%, then, 2% represents a 25% improvement in the capacity of the unit. At 10°C (50°F) dew point, the upper line gives a 7.75% total moisture cycled and the lower line shows 5.3%. The average difference between the regeneration stream dew points in the two cases is 13.9°C (25°F). If we assume that the performance of the unit is proportional to the regeneration stream dew point difference, then the above results show that at an average of 5.5°C (10°F) increase in regeneration stream dew point, the unit performance drops by almost 1% of the total moisture cycled. Again, if 8% is the total moisture cycling at normal operation, then 1% represents a 12.5% reduction in the unit performance. This shows that the regeneration stream inlet dew point is a very important factor in determining the performance of the unit.

3. Effect of Cooling Stream on the Unit Performance

Figures 14 to 16 together with figure 8 show the test results representing the effect of the cooling stream on the unit performance. Figure 14 shows the unit operate at 0.227 m³/min (8 CFM) process stream but with no cooling stream.

It cycles close to 5% of the moisture (5% of silica gel sheet by weight). Figure 15 shows the results of the same test except with $0.1134 \text{ m}^3/\text{min}$ (4 CFM) cooling stream. It shows that the total moisture cycled is increased to 7.4%. Figures 8 and 16 show that at $0.227 \text{ m}^3/\text{min}$ (8 CFM) and $0.34 \text{ m}^3/\text{min}$ (12 CFM) cooling stream, the total moisture cycled increased to 7.85% and 8.3% respectively. These results are plotted in figure 28. Figure 28 shows that a little cross-cooling will increase the performance of the unit rapidly. The figure indicates that moderate cross-cooling can increase the performance of the silica gel sheets by over 50%. However, the unit performance seems to approach an asymptotic value with further increase of the cross-cooling stream.

4. Effect of Regeneration Stream Temperature on the Unit Performance

Figures 17 to 20 show the results of the unit performance at different regeneration temperatures. The average regeneration temperature was at 44.6°C , 51.3°C , 53.6°C , 61.3°C (112.3°F , 124.3°F , 128.5°F , 142.4°F). Figure 17 shows the test results at 44.6°C (112.3°F) regeneration temperature. Here, 5.65% of moisture is cycled. With the regeneration temperature increased to 51.3°C (124.3°F), the performance of the unit increased to 5.85% as shown in figure 18. Further increase of the regeneration air temperatures to 53.6°C and 61.3°C (128.5°F and 142.4°F), increased the moisture cycle to 6.3% and 6.9% (figures 19 and 20).

The four test results are plotted in figure 29. The results show that the moisture cycled increases uniformly with increasing regeneration temperatures.

5. Effect of the Process Air Flowrate on the Unit Performance

Figures 21 to 24 and figure 8 show the test results at different process air flowrates. The tests were performed at 0.11, 0.14, 0.17, 0.20 and 0.227 m³/min (3.9, 5, 6, 7 and 8 CFM). As expected, the higher the flowrate, the better the performance. When the process stream was less than 8 CFM, the inlet dew point starts to fluctuate (possibly due to the uneven distribution of the velocity profile caused by the change of the valve openings). At 0.11 m³/min (3.9 CFM), the total moisture cycled is 5.7% of silica gel sheet by weight and at 0.227 m³/min (8 CFM) it is 7.85%. This shows that the moisture cycled is not directly proportional to the process stream flowrate. This can be explained by the fact that at low flowrate, the air velocity passing over the surface of the silica gel sheets is also lower, which in turn, provides a longer contact time between the moisture particles and the silica gel surface and thus resulted in better adsorption. The test data do show that the moisture adsorbed per pound of dry air at lower process air flowrate is higher than at higher flowrate. Figure 30 shows the results for the five tests. From this figure, it can be easily seen that with each CFM (or 0.028 m³/min) reduction in flowrate, the unit performance is reduced by 6.5%.

6. Temperature Variation During the Periodic Operation

Figure 25 shows typical process air inlet and outlet temperature variations for the desorption and adsorption cycles. As is expected, the outlet temperature for the adsorption cycle rises at the beginning of the operation due to the heat generated by silica gel moisture adsorption. The fact that the inlet temperature in the adsorption cycle is much higher at the beginning, is due to the heat capacity of the duct. The inlet temperature in the desorption cycle did not level off until 16 minutes after starting because the ducts were cooled down in the adsorption cycle, thus part of the heat in the desorbing air was heating the ducts. The outlet temperature in the desorption cycle, in the specific run shown, can be approximated as a straight line.

Figure 26 shows the temperature variations of the inlet and outlet of the cooling stream. The sudden change of the outlet temperature at the 5 minute point is because at that time the purging was just completed and the adsorption cycle begins. The heat generated by moisture adsorption slows down the outlet temperature drop immediately. As is expected, the cooling stream inlet temperature is not affected by the adsorption heat penetration at all. The reason the inlet temperature is initially much higher is because the cross-cooling ductwork was heated up during the desorption cycle.

III. COMPUTER SIMULATION OF THE DEHUMIDIFIER MODEL TEST RESULTS

A. INTRODUCTION

The desiccant dehumidifier model has been analyzed both experimentally and theoretically. The calculated and tested results under the same dehumidifier operating conditions are then compared. The mathematical model first used in the dehumidifier performance calculation is the Schumann model [7] modified by Roy [6] for regenerative type desiccant dehumidifiers. In this model, it is assumed that since the silica gel sheets are very thin 0.16 cm (1/16"), in this case, the sheet resistance to moisture penetration can be neglected so that the moisture distribution across the sheet thickness is uniform. However, figure 3 shows that the calculated results with this mathematical model predict a much lower desorption rate than the test indicates at the beginning of the regeneration cycle and then the rate increases. The total moisture can be matched by the computer simulation by simply changing $1/Le$ (reciprocal of Lewis number) from 1.0 to 0.25 (see Figure 4). However, the matching of the other parts is even worse. Because of this discrepancy, an extensive effort was made to check the test equipment and procedures. Also, a thorough examination of the mathematical model was made to ensure that all the test data were correctly modeled in the simulation. After extensive studies, it was concluded that the assumption that the moisture in the silica gel sheet is uniformly distributed across its thickness was incorrect. In other words, the resistance of the silica gel sheets to the moisture penetration is high and

must be accounted for. Thus the moisture variation on the surface of the silica gel sheets varies in a much wider range than the mathematical model has predicted. At the beginning of the desorption cycle, the moisture content on the surface of the silica gel sheet should be very high so that initial desorption should be very efficient. At the end of the desorption cycle, the moisture content on the silica gel sheets is lower than that predicted by the model, resulting in lower desorption rates. With this concept, B. Mathiprakasam and Z. Lavan*, made a correction to the model assuming that the moisture distribution across the silica gel sheets is linearly distributed with height.

B. COMPARISON BETWEEN THE EXPERIMENTAL RESULTS AND COMPUTER SIMULATION

A total of twenty comparisons between experiments and the improved mathematical model were made. Figures 5 to 24 show the tests and calculated results at different operating conditions. The matchings for the first 15 minutes of operation are generally very good. The theoretical calculations constantly predicts a better unit performance than the test after 15 minutes of operation. However, the analytical and experimental results show the same trend throughout the 20 cases with the exception of the adiabatic test (Fig. 14) which shows that the test results are better than the calculated ones. The reason for this discrepancy is that, it is very difficult to have an adiabatic operation in the experiment

*Technical Report DES-79-3, "Theoretical Design for Cross-cooled Desiccant Dehumidifier," December 1979.

due to heat leaks through the aluminum metal frame of the unit and its ductwork, while the mathematical model operates under ideal adiabatic conditions.

It can be seen that the agreement of the adsorption cycles are better than those of the desorption cycles. This means that the mathematical model predicts the silica gel sheet surface moisture variation very well during the adsorption while it constantly over predicts the surface moisture content during the desorption.

It is interesting to note that the computer model is not very sensitive to the assumed moisture content at the bottom of the silica gel sheets. It is also observed that the agreement at operation with high percentage of moisture cycled is better than for those cycling less moisture. The computer model also predicts correctly the various test trends. When most of the test results show that there is an intersection point along the adsorption and desorption moisture cycling paths, the computer model also predicts an intersection point. When some of the test results show negative desorption (adsorption) at the beginning of the desorption cycle, the computer model for the corresponding operation also predicts negative desorption at the beginning of the desorbing cycle.

Figures 27 to 30 also show the computer simulations of the parametric analysis of the unit performance. Figure 27 shows that the calculated results for the effect of the inlet process air dew point match very well with the test results. The calculated and the test results have almost the same slopes except the calculated ones show higher unit performance.

Figure 28 shows that theoretically the cross-cooling should be even more effective than the test results have indicated. The computer simulations show that a moderate cross-cooling can increase the total moisture cycled by over 60% over the adiabatic operation.

Figure 29 shows that the computer results have a flatter slope, which means the matching is better when the total moisture cycled increases. Figure 30 shows the effect of the process air flowrate. The calculated results are scattered widely. One reason for that could be due to the unstable reading of the flowrate caused by the partial valve openings.

From these comparisons, it can be seen that the new mathematical model works very well, even though they do not match perfectly.

Figure 8, 10 and 14 show the experimental error bounds for the adsorption cycle. Since the experimental error grows with the total moisture adsorbed, the highest error occurs at the end of adsorption. The error analysis is based on $\pm 0.2^{\circ}\text{F}$ dew point and ± 0.2 CFM variations. The less moisture cycled, the higher the percent of error.

IV. CONCLUSION

The following conclusions can be made.

- 1) The process air inlet dew point is the dominating factor in the unit performance.
- 2) Regeneration air inlet dew point is also very important in determining the unit performance. Very humid regeneration air will result in poor unit performance.
- 3) The cross-cooling concept works very well. A moderate cross-cooling can increase the silica gel performance by about 50% as compared with adiabatic operation.
- 4) The higher the regeneration air temperature, the better the performance, but to a much less dominating degree than the process air inlet dew point.
- 5) The higher the process stream flowrate, the better the unit performs, although at lower flowrate, the moisture cycled per pound of dry air increases.
- 6) The experimental results prove that the silica gel sheet resistance to the moisture penetration is high and that the moisture distribution across the sheet thickness is not uniform. An improved mathematical model based on this finding is used for the computer simulation.
- 7) The new computer model matches the experimental results very well even though the calculated results are consistantly somewhat higher than the test results.
- 8) The mathematical model is not very sensitive to the assumed moisture concentration value at the bottom of sheet.

9) The computer calculations and test results match better at high moisture cycling operation.

10) The theoretical calculations predict a slightly higher desorption rate than the experimental results.

Since we do not know how the moisture moves in the silica gel sheets, the improved computer model for the desiccant desumidifier is not perfect yet. In order to further improve the computer model, the basic mechanism of the moisture movement in the silica gel sheet, the equilibrium data at different temperatures and humidities, the reaction of moisture and silica gel, the temperature distribution across the sheets thickness, etc., would have to be understood. However, with the improved computer model for the dehumidifier, it is very encouraging to see that the experimental and calculated results are matched well. We are, therefore, confident that the improved mathematical model predicts the performance of the desiccant dehumidifier accurately.

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APPENDIX

PREPARATION OF SILICA GEL SHEETS

The silica gel sheets used in the unit were hand made at the IGT laboratory. The procedure for producing the sheets is as follows:

1. Pour 300 gm (0.66 lb.) of ammonium bicarbonate into a jar with twenty 1.27 cm ($\frac{1}{2}$ ") diameter cylindrical alumina "balls" and fill the jar with shell solvent to 75% full.
2. Mill the ammonium bicarbonate for approximate 5-7 hours.
3. Empty the milled ammonium bicarbonate into a blender.
4. Sprinkle 100 gm (0.22 lb.) of silica gel powder (W.R. Grace Company) and hand mix them lightly.
5. Add 5 gm (.011 lb) of teflon powder to the mixture.
6. Blend the mixture at low speed for 5 seconds three times, then at high speed for 30 seconds.
7. Empty the contents of the blender into a filter funnel (Note: The filter paper has to be wetted first with shell solvent). The filter funnel drains out most of the shell solvent from the mixture.
8. Cover the top of the funnel with plastic wrap so that the aspirator can create a pressure on the mixture by the plastic seal.
9. Turn on the aspirator for 5-7 minutes or more. Now most of the solvent has been filtered and the mixture is in a "cake" form.
10. Put the "cake" on a piece of clean glass (glass should be cleaned by shell solvent).

11. Roll the cake slowly into a piece of sheet with a roller. Wrap up the sheet and roll it again. The rolling process is repeated until the sheet surface is very smooth. Each cake can be rolled into 4 to 5 pieces of 15.2 cm x 15.2 cm x 0.16 cm (6" x 6" x 1/16") silica gel sheet.
 12. Leave the sheets under room condition over night.
 13. Bake the sheets in an oven with an air vent for 1 hour 45 minutes. The temperature of the oven should be raised slowly from ambient condition to 93.3°C (200°F) in at least 45 minutes.
 14. The sheets are now ready for application.
- The density of the sheets is 0.282 gm/cm³ (17.6 lb/ft³).

Figure 1. 6" x 6" x 6" Cross-Cooled Desiccant Dehumidifier Model

Figure 2. Schematic of Test Setup

Figure 3. Comparison of Experimental and Analytical Results. (Gas Film Resistance Only, $\lambda_s = 1.05$)

Figure 4. Comparison of Experimental and Analytical Results.
(Increased Overall Resistance, $\lambda_3 = 0.25$)

Figure 5. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 6. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 7. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 8. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 9. Comparison of Experimental and Analytical Results.
($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 10. Comparison of Experimental and Analytical Results.
 ($\lambda_s = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 11. Comparison of Experimental and Analytical Results.
 $(\lambda_3 = 1.05, \text{Linear Moisture Distribution in Desiccant}).$

Figure 12. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 13. Comparison of Experimental and Analytical Results.
($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 14. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 15. Comparison of Experimental and Analytical Results.
 $(\lambda_3 = 1.05, \text{Linear Moisture Distribution in Desiccant})$.

Figure 16. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 17 . Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 18. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 19. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 20. Comparison of Experimental and Analytical Results.
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Figure 22. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 23. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 24. Comparison of Experimental and Analytical Results.
 ($\lambda_3 = 1.05$, Linear Moisture Distribution in Desiccant).

Figure 25. Temperature Variations at Inlet and Outlet Process Stream and Regeneration Stream

Figure 26. Temperature Variations at Inlet and Outlet of Cooling Stream

Figure 27. Effect of Inlet Process Air Dew Point on Total Moisture Sorbed.

Figure 28. Effect of Cross-Cooling Flowrate
On Total Moisture Sorbed.

Figure 29. Effect of Regeneration Temperature on Total Moisture Sorbed.

Figure 30. Effect of Process Air Flowrate on Total Moisture Sorbed.