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SERI/TP-631-1157
UC CATEGORY: UC-59
PREPRINT
CONF-810509--28

OPTIMIZING THE PERFORMANCE OF DESICCANT BEDS FOR SOLAR-REGENERATED COOLING

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MARCH 1981

TO BE PRESENTED AT
INTERNATIONAL SOLAR ENERGY SOCIETY
AMERICAN SECTION ANNUAL CONFERENCE
26-30 MAY 1981
PHILADELPHIA, PENNSYLVANIA

PREPARED UNDER TASK NO. 1131.00

Solar Energy Research Institute
A Division of Midwest Research Institute

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Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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5285 Port Royal Road
Springfield, VA 22161
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NOTICE

OPTIMIZING THE PERFORMANCE OF DESICCANT BEDS FOR SOLAR-REGENERATED COOLING

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ABSTRACT

Detailed computer simulations as well as a simplified psychrometric analysis are used to determine the increase in cooling system performance that can be realized through the use of nonhomogeneous or staged desiccant beds. A staged bed of four hypothetical desiccants is shown to give a 10% higher cooling capacity than a silica gel bed of the same thickness. Alternatively, the same cooling capacity is produced by a staged bed 37% thinner than the silica gel bed. These effects could be employed to reduce the parasitic power requirements of desiccant cooling systems.

1. INTRODUCTION

Previous studies (1,2) have shown how the thermodynamics of the desiccant bed itself affects the performance of desiccant cooling systems. They have demonstrated that tradeoffs between capacity, thermal COP, and parasitic power are determined by the heat and mass transfer within the desiccant bed. It has also been demonstrated (3) that the dynamic moisture cycling capacity of silica gel for typical operating conditions is only 3% to 5% by weight, which is only a fraction of the change in equilibrium moisture capacity between the same operating conditions. This is due primarily to the fact that the theoretical length of the mass transfer zone (MTZ) during adsorption is several times greater than the length of desiccant beds used in cooling systems. This is especially true during adiabatic adsorption, when the heat of adsorption increases the bed temperature, reduces the moisture capacity of the silica gel, and lengthens the MTZ. As the amount of moisture cycled per unit mass of desiccant decreases, one must either increase the thickness of the bed or increase the flow rate of process air to maintain a give cooling capacity. In both cases the parasitic power requirement of the machine increases. Lavan and Lunde have recognized this problem and have advocated nonadiabatic drying of the air; Lavan (4) investigating a cross-cooled desiccant bed, and Lunde (5) proposing a series of desiccant beds and heat exchangers. The purpose in both concepts is to keep the temperature of the silica gel low during adsorption so that the moisture capacity remains high.

An alternative approach would be to use a nonhomogeneous or staged desiccant bed. Figure 1 shows typical process lines between the states of the air entering and leaving a desiccant bed during adsorption and regeneration. To simplify the explanation of the staging concept, it is postulated that for the thin beds used in cooling machines, the ends of the bed are in equilibrium with the inlet and outlet air states and that the moisture gradient is nearly linear between them. If the bed is homogeneous, a single desiccant must operate between states 1 and 2 in Figure 1. If the bed is divided into two sections, the first section must operate between states 1 and A, while the second section must operate between states A and 2. By sectioning or staging the desiccant bed, the range of thermodynamic states that the desiccant must operate between is reduced. This allows the use of more specialized desiccants in each section. Figure 2 shows the adsorption characteristics of two hypothetical, specialized desiccants along with silica gel. The specialized desiccants have the same maximum moisture capacity as silica gel, but they adsorb and desorb over a much narrower range of relative humidities.

If the relative humidity range within each bed section can be controlled well, the moisture cycled by the entire bed should increase. To do this the regeneration of the bed must be carefully controlled. The idea that more moisture can be cycled is predicated on the idea that during regeneration, the outlet air from one stage will effectively regenerate the next stage. Referring to Figure 1, the temperature of the regeneration air (point 3) must be raised to give a relative humidity that is lower than that of point 2, so that the last bed section can be fully regenerated. As the number of stages is increased this difference in relative humidities can be decreased, and so the regeneration temperature can be decreased.

This type of simplified analysis indicates that a significant gain could be realized with staging. However, the heat and mass transfer within a cycling desiccant bed is a complex problem, and many variables effect the performance of cooling machines. Therefore, computer simulations have been used to determine just how system performance is effected by the staging strategies indicated by the previous analysis.

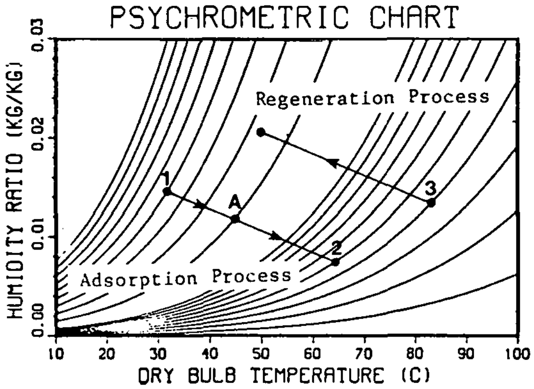

Fig. 1. Typical Process Lines for Adsorption and Regeneration. (Relative humidity lines are in log scale from 1% to 100%.)

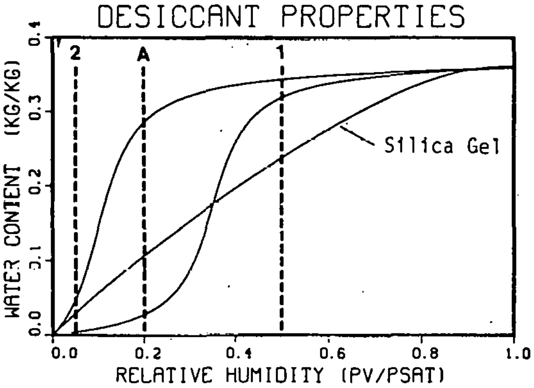

Fig. 2. Equilibrium Water Content vs. Relative Humidity for Silica Gel and Two Desiccants for Staging

2. COMPUTER ANALYSIS

The performance of staged desiccant beds was analyzed in detail by expanding the desiccant heat and mass transfer computer model developed at SERI to simulate a complete desiccant cooling system. Rather than solving a set of differential equations by conventional finite difference techniques, the model treats the heat and mass transfer processes in an uncoupled manner and employs effectiveness equations from the theory of heat exchangers. This approach eliminates the need for a transformation of variables. As a result, the mathematics of the problem is greatly simplified, facilitating a better understanding of the physical basis for the behavior of the desiccant bed. This model has been validated for the single blow case by comparison with the experimental data of Koh (6) for the regeneration of packed beds of silica gel.

To simulate the steady state operation of a complete cooling system, the desiccant model is cycled back and forth through adsorption and regeneration until steady state is reached. The other components of the system, two evaporative coolers and a sensible heat exchanger, are included simply by specifying the component effectiveness and performing the appropriate energy balance.

System parameters used in this study are summarized in Table 1. The thickness and face area of the desiccant bed, as well as the air flow rates, are similar to those used in the AiResearch prototype machine (3). For this paper, the system is assumed to operate in the ventilation mode with balanced flow rates and equal time periods for adsorption and regeneration. Indoor and outdoor conditions are the ARI standard for rating the performance of air conditioning systems. A regeneration temperature of 83°C could be obtained with flat plate collectors and might be a typical operating temperature in field applications. Higher and lower regeneration temperatures were looked at, and the benefit from staging was similar to that obtained at 83°C.

The performance of a silica gel bed was used as a standard by which to judge the performance of staged desiccants. The equilibrium properties of silica gel can be well represented by a single correlation between relative humidity and water content (Figure 3a). Similarly, the equilibrium properties of hypothetical desiccants for staging were represented by equations of the form

$$X = C_1 + \arctan((RH - C_3)/C_4)/\pi + C_5 RH \quad (1)$$

where X is the fractional water content of the desiccant and RH is the relative humidity of the surrounding air. This equation produces the S-shaped curves shown in Figures 2 and 3b. Hypothetical desiccants were chosen from a file of 97 such property curves that varied in steepness and in the value of relative humidity corresponding to the inflection point of the curve. The performance of single desiccants as well as staged beds combining two, three, and four desiccants were compared in a total of over 240 individual system simulations.

3. RESULTS AND DISCUSSION

A primary motivation for investigating staging was to find a way to reduce the parasitic power requirements of desiccant cooling systems. Parasitic losses due to pressure drop across the desiccant wheel can be reduced either by increasing the cooling capacity per unit mass of air, allowing a reduction in design flow rate, or by obtaining the same capacity with a thinner desiccant bed. Both of these strategies were investigated. The adsorption properties of silica gel and the staged bed that worked the best are shown in Figures 3a and 3b, and the simulated system performance characteristics are summarized in Tables 2 and 3. Table 2 shows the effect of rotation period on cooling capacity and thermal COP. Silica gel displays an optimum in both values near a rotation period of 16 minutes (8 for adsorption and 8 for regeneration), whereas, the staged bed performs optimally near a 34 minute period. Under these operating conditions the staged bed gives increases of 10% in capacity and 6.8% in COP. Table 3 shows the effect of changing the bed thickness while maintaining a 16 minute period. The staged bed can be thinned to about .0217m (by linear interpolation) and still give the same capacity as the .0318m silica gel bed. When period is optimized, the staged bed can be thinned even further, as shown by the last entry in Table 3. The result is a 37% decrease in bed thickness.

Parasitic power has a cubic dependence on the flow rate of process air, but only decreases linearly with bed thickness. Therefore, these two strategies for staging would have similar effects on losses due to pressure drop across the desiccant bed. However, the COP is considerably lower with the thin bed. Additionally, a reduction in design flow rates decreases parasitic losses in all components. These considerations favor the strategy of increasing specific capacity while keeping bed thickness the same.

A 10% increase in capacity is significant. However, it is less than was hoped for on the basis of the simple psychrometric analysis. That analysis suggested that a properly staged bed would cycle a much larger fraction of its own weight in moisture than does silica gel. Figures 4a and 4b show the loading profiles within the silica gel and staged beds, respectively. The staged bed cycles more than twice as much water, 8.5% by weight compared to 4% for silica gel. However, the rotation period is twice as long, so there is not a large increase in the rate of moisture transfer. The equilibrium psychrometric analysis also indicated that one could expect the staged bed to produce much drier air in the adsorption process, because regeneration should be much more complete. Computer simulations showed that the average outlet humidity of the adsorption process air is only slightly lower when staging is used.

The physical phenomena that produce these results are displayed most effectively by Figures 5a and 5b. These are psychrometric

Table 1. SYSTEM PARAMETERS

Desiccant Bed:
Total face area = 1.97 m^2
Bed thickness = .0318 m
Particle diameter = .00193m

Flow Rates (dry air basis):
Adsorption - .333 kg/s
Regeneration - .333 kg/s

Operating Conditions:
Indoor - 26.7°C db, 19.4°C wb
Outdoor - 35°C db, 23.9°C wb
Regeneration - 83°C db

Component Effectivities:
Evaporative coolers - .90
Sensible heat exchanger - .90

Table 2. EFFECT OF PERIOD ON PERFORMANCE

Period (min)	Silica Gel		Staged Bed	
	Capacity (kW)	COP	Capacity (kW)	COP
10	2.794	.398	2.837	.398
12	2.855	.401	2.935	.407
14	2.981	.401	3.004	.414
16	2.909	.398	3.054	.418
18	2.915	.394	3.091	.421
22	2.900	.382	3.142	.425
26	2.857	.366	3.173	.426
30	2.792	.347	3.191	.426
34	2.709	.326	3.200	.425
38	2.616	.305	3.201	.422

Bed thickness = .0318 m

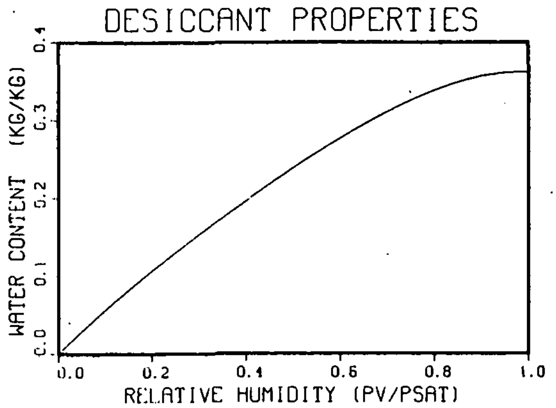

Fig. 3-a. Equilibrium Water Content vs. Relative Humidity for Silica Gel

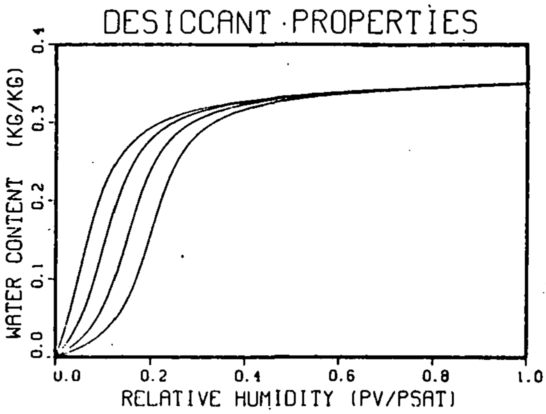

Fig. 3-b. Equilibrium Water Content of Hypothetical Desiccants for Staging

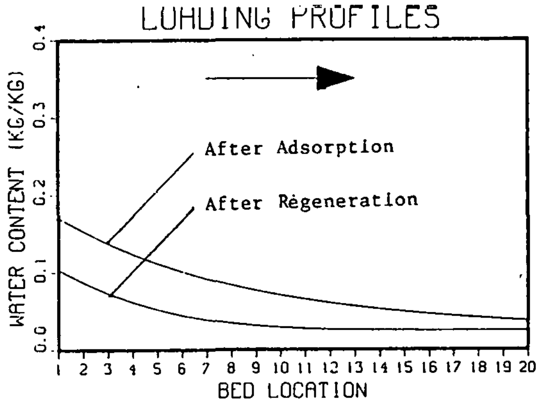

Fig. 4-a. Loading Profiles in the Silica Gel Bed (16 minute period, arrow indicates flow direction of adsorption air)

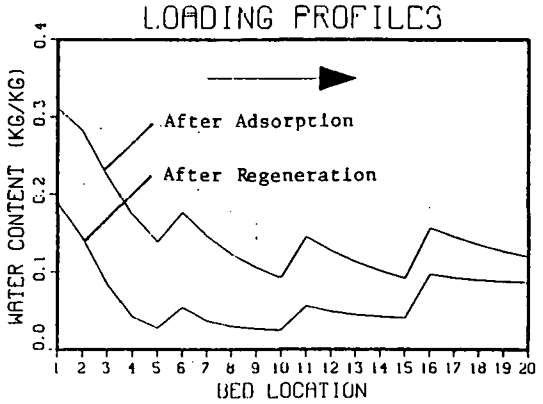

Fig. 4-b. Loading Profiles in the Staged Bed (34 minute period)

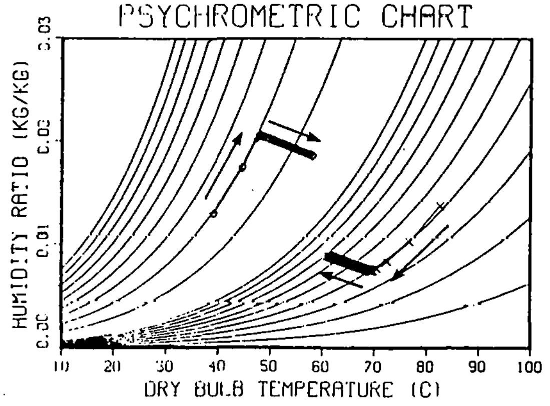

Fig. 5-a. Conditions of Process Air Leaving the Silica Gel Bed (adsorption -(x), regeneration -(0), symbols at 12 second intervals)

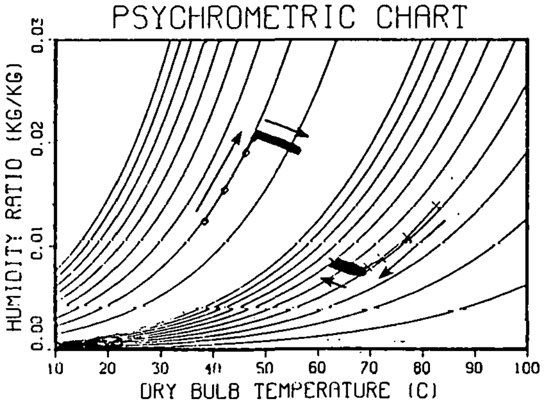

Fig. 5-b. Conditions of Process Air Leaving the Staged Bed (symbols spaced at 12 second intervals)

Table 3. EFFECT OF BED THICKNESS ON PERFORMANCE OF THE STAGED BED

Thickness (m)	Capacity (kW)	COP
.03	3.040	.411
.0275	3.014	.401
.025	2.978	.388
.0225	2.931	.372
.02	2.866	.354
.02*	2.916	.355

*Period = 24 minutes. Period = 16 minutes for all other entries.

charts showing the conditions of the process air leaving the two desiccant beds during cyclic operation. The process lines for the two beds trace almost exactly the same paths. During both adsorption and regeneration the outlet air goes through a very rapid transient that lasts only about 40 seconds and runs along lines of nearly constant relative humidity. The trajectory of the process curve then changes, and outlet air conditions move slowly toward the conditions of the inlet air. The major difference between the staged bed and silica gel is that the progress of the outlet air toward the inlet condition is much slower. During adsorption the process line terminates at 7% relative humidity with silica gel, but reaches only 6% with the staged bed, even though the rotation period is twice as long. The same effect is seen during regeneration. The reason for this slowing of the breakthrough curve can only be that staging decreases the length of the effective MTZ (mass transfer zone). This is done, as the simplified analysis suggested, by matching the properties of each desiccant stage to the range of relative humidities occuring in that section of the bed during cyclic operation. The result is that each desiccant is operating on the steep portion of its capacity curve, and this improves mass transfer.

4. CONCLUSIONS

Both a simplified psychrometric analysis and detailed computer simulations have been employed to evaluate the potential gains in cooling performance that could be obtained by using nonhomogeneous or staged desiccant beds. A staged bed of four hypothetical desiccants allowed a 10% increase in system cooling capacity and a 6.8% increase in thermal COP over a silica gel bed. The same staged bed could be reduced by 37% in thickness while producing the same cooling capacity as the silica gel bed. Both effects can reduce the parasitic power requirements of desiccant cooling systems. Whether or not these potential improvements will warrant an effort to develop new desiccants with the indicated properties is not yet known.

The computer program developed in this study has proven to be a useful tool in understanding the physical behavior of the desiccant materials. It will continue to be used to further investigate the staging concept and to examine other strategies for improving the performance of desiccant cooling systems.

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