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STUDY OF PARAMETERS AFFECTING THE PERFORMANCE OF SOLAR DESICCANT COOLING SYSTEMS

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ABSTRACT

The performance of a solar desiccant cooling system depends on the performance of its components, particularly the desiccant dehumidifier and solar collectors. The desiccant dehumidifier performance is affected by the properties of the desiccant, particularly the shape of the isotherm and the regeneration temperature. The performance of a solar collector, as one would expect, depends on its operating temperature, which is very close to the desiccant regeneration temperature. The purpose of this study was to identify the desiccant isotherm shape (characterized by separation factor) that would result in the optimum performance — based on thermal coefficient of performance and cooling capacity — of a desiccant cooling cycle operating in ventilation mode. Different regeneration temperatures ranging from 65°C to 160°C were investigated to identify the corresponding optimum isotherm shape at each. Thermal COP dictates the required area of the solar collectors, and the cooling capacity is an indication of the size and cost of the cooling equipment. Staged and no-staged regeneration methods were studied.

1. INTRODUCTION

Solar energy can help offset the net cooling load of a building. Many system arrangements or cycles are possible; solar collectors (flat plate, parabolic trough, evacuated tube, etc.) can be used to provide energy to absorption cooling, desiccant cooling, and even refrigeration cycles. Active combinations of solar hybrids coupled with heat-activated heat pumps or electrically driven air conditioners are possible. The concept of solar cooling makes sense because the cooling load is roughly in phase with the availability of solar energy. Furthermore, combined heating, hot water, and cooling season usage helps to decrease the amortization of the system. Although there is a large potential market for solar cooling, the existing solar cooling systems are not competitive with electrically driven or gas-fired air conditioning systems. The cost of solar cooling systems can be reduced by lowering the cost of components and improving their performance. The combined reduction in required collector area and in cost per unit area of the collector will significantly reduce the cost of the solar components.

Desiccant cooling was initially considered to be a good choice for using the low-temperature heat available from flat-plate collectors. However, lower temperatures resulted in decreased cooling performance, thereby increasing the size and cost of the solar cooling system. In recent years, the Gas Research Institute has supported development of high-temperature regeneration desiccant materials and cycles because of the improved thermodynamic performance at higher regeneration temperatures. Development of efficient high-temperature regeneration desiccant cooling systems will provide an opportunity for using high-temperature solar collectors. The efficiencies of solar collectors usually decrease with an increase in operating temperature. As a result, an increase in temperature can have two opposing effects on the performance of a solar desiccant cooling system. As part of this study, we were interested in determining how the performance of a solar desiccant cooling system improved when the regeneration temperature was increased.

The desiccant cooling ventilation cycle was used for this study because the first system introduced to the market was based on this cycle. The desiccant cooling ventilation cycle uses a rotary desiccant dehumidifier, a heat exchanger, two evaporative coolers, a desiccant regeneration heater, and ancillary equipment such as fans and pumps. In this cycle, shown in Figure 1, outside air is dried in the dehumidifier and then cooled by regenerative evaporative coolers and supplied to the conditioned space. The regeneration heater (powered by solar energy) heats the air, which reactivates the desiccant by driving the moisture from it. Unlike vapor compression systems, desiccant cooling systems do not use chlorofluorocarbons (CFC) that contribute to the depletion of Earth's ozone layer.

The performance of a desiccant cooling cycle depends strongly on the properties of the desiccant — such as isotherm shape, heat of adsorption, heat capacity, and

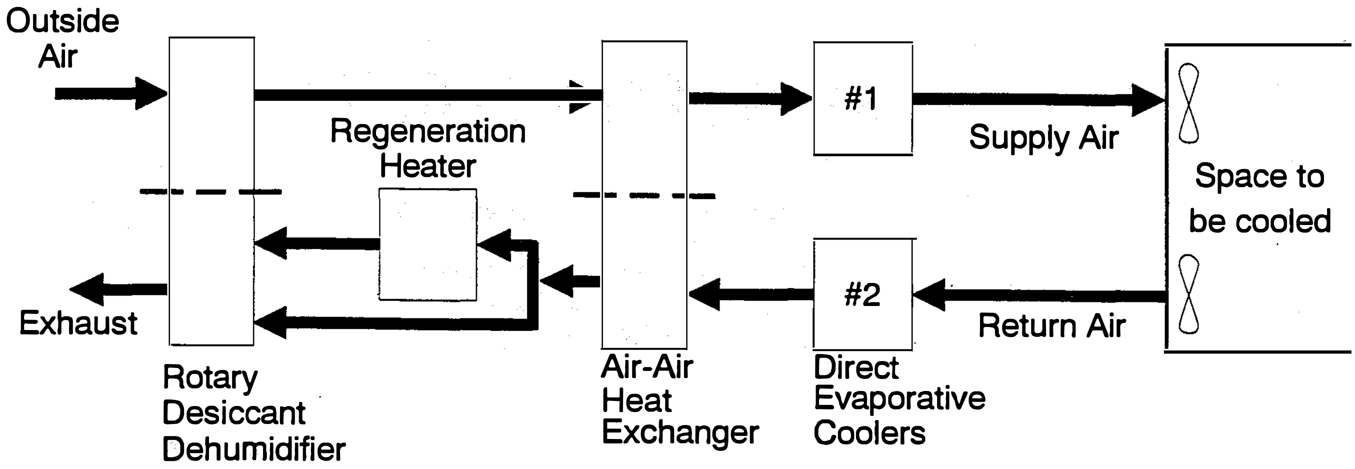

Fig. 1. Schematic Diagram of a Desiccant Cooling System

moisture capacity — and on operating conditions such as regeneration temperature and ambient and indoor conditions.

The purpose of this study was to identify the characteristic shape of the desiccant isotherm as a function of regeneration temperature that would result in the optimum performance for a solar desiccant cooling cycle operating in ventilation mode. Judgments of performance were based on thermal coefficient of performance and cooling capacity of the system.

2. ANALYSIS

2.1 Desiccant Isotherm

The characteristic isotherm of a desiccant describes the relationship between the moisture capacity of a desiccant as a function of relative air humidity for a given temperature. For this study, the desiccant isotherms examined were Brunauer Types I and III because previous studies have shown their potential over other desiccant types (1)(2). The relationship between moisture uptake and relative humidity for Type I and III desiccants is represented mathematically as:

$$W^* = \frac{RH^*}{R + RH^* - R \cdot RH^*} \quad (1)$$

The isotherm shapes of various Type I and III desiccants are shown in Figure 2. This figure shows that Type I isotherms correspond to desiccants with a separation factor of R < 1, and Type III isotherms correspond to desiccants with a separation factor of R > 1. A maximum moisture uptake of 0.4 kg water/kg desiccant was selected for our study. This is a typical value for a desiccant such as silica gel. Separation factors were varied between R = 0.05 (Type I moderate) and R = 1.5 (Type III moderate).

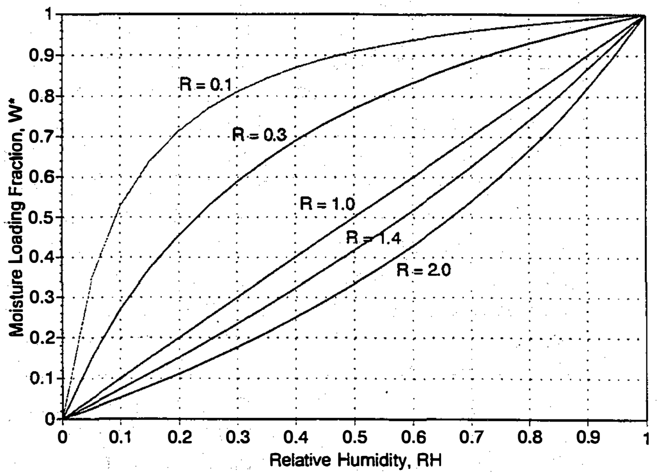

Fig. 2. Normalized Moisture Capacity for Various Type I and III Isotherms

2.2 Modeling Approach

A numerical analysis based on a system simulation of a desiccant cooling system was employed to identify the optimum isotherm shape for both high-temperature and low-temperature solar cooling applications. We used a modified version of the DCSSMX code to simulate the desiccant cooling cycle operating in ventilation mode. The DCSSMX code is the same desiccant cooling system simulation model that has been employed by the Gas Research Institute to identify desired desiccant properties in high-temperature applications (2). A summary of the various physical and modeling parameters used in this investigation is given in Table 1. The dehumidifier performance values are based on a dehumidifier tested by Bharathan et al. (3). The indoor and outdoor conditions are based on standard Air Conditioning and Refrigeration Institute design conditions.

TABLE 1. SYSTEM PARAMETERS AND CONDITIONS

Dehumidifier	
Matrix Density	157 kg desiccant/m^3
Matrix Heat Capacity	1960 kJ/kg-K
Desiccant Mass Fraction, f	1
Total Frontal Area	0.245 m^2
Matrix Depth	0.2 m
Passage Hydraulic Diameter	2.3 mm
Total Transfer Area	47.5 m^2
Adsorption or Regeneration Air Flow Rate	0.2 kg/s
Adsorption/Regeneration Flow	balanced flow/balanced area
Number of Heat Transfer Units	22.5 - 29.5
Process Lewis Number	1
Desiccant	
Isotherm Type	Brunauer Type I and III, $0.05 < R < 1.5$
W_{max}	0.4 kg water/kg desiccant
Regeneration	65°C - 160°C air temperature
Staged Regeneration	30% staged, PERC = 0.3
No-staged Regeneration	no staging, PERC = 1.0
Outdoor Conditions	1 atm., 35°C, 0.014 kg moisture/kg dry air
Indoor Conditions	1 atm., 26.7°C, 0.011 kg moisture/kg dry air
Sensible Heat Exchanger	
Heat Exchanger Effectiveness	0.93
Evaporative Coolers	
Cooler Effectiveness	0.95

2.3 Regeneration Methods

A schematic of the staged and no-staged regeneration schemes is shown in Figure 3. The main difference between these two methods lies in their complexity and performance. In staged regeneration, only a fraction of the regeneration airstream is heated to the design regeneration temperature. The remainder of the regeneration airstream is made up of warm air returning from the conditioned space that has recovered a portion of the heat of adsorption via heat exchange between the downstream dehumidifier flow and the upstream regeneration flow. In this scheme, only a small portion of the regenerated area, at the end of the regeneration cycle, is exposed to the highest temperature airstream. The fraction of the desiccant exposed to the design regeneration temperature in this investigation was chosen to be PERC = 0.3. This value was selected based on the work done by Collier et al. (2), which suggested that the maximum thermal COP is achieved for a PERC of 0.3 with a separation factor of R = 0.1 and a regeneration temperature of 95°C.

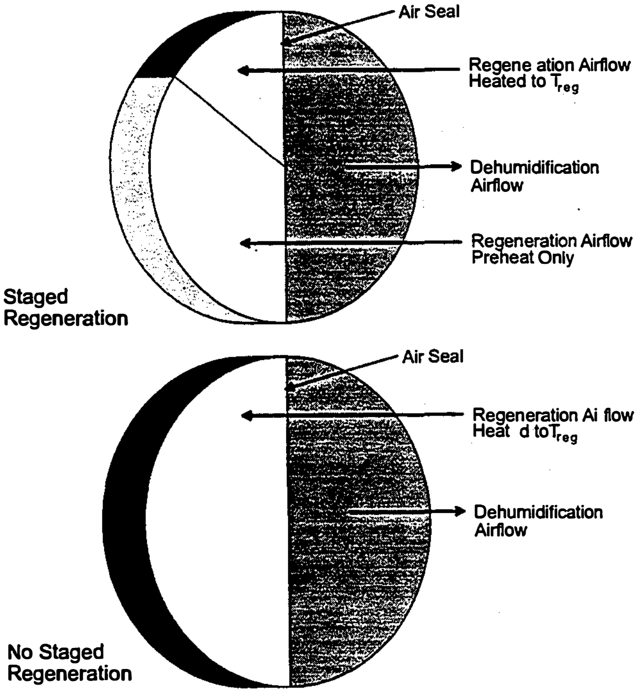

Fig. 3. Schematic Diagram of Staged Regeneration and No-staged Regeneration Schemes

The entire regeneration airstream is heated to the design regeneration temperature in the no-staged regeneration scheme (i.e. PERC = 1.0). Although the elimination of two airstreams at two different temperatures makes this design simpler than a staged scheme, it tends to over-regenerate the desiccant. One would expect that a process in which the temperature is gradually and continuously increased over the length of the regeneration cycle would be significantly closer to a reversible process than one in which the entire cycle is suddenly and abruptly exposed to a step increase in airstream temperature. Staged regeneration attempts to do this while minimizing the tradeoffs in complexity.

The difference between these two schemes has a marked influence on their performance and on the resulting optimum system parameters, as we will discuss in the following sections.

3. RESULTS AND DISCUSSION

3.1 No-staged Regeneration

The performance of a desiccant cooling system employing no-staged regeneration is shown in Figure 4. Each point on this graph represents a relative maximum performance value and is obtained after numerous parametric runs. The final plotted data represent the maximum cooling capacity and corresponding COP occurring over a range of cycle times. The thermal COP increases almost linearly as the regeneration temperature is decreased. A maximum thermal COP of about 0.84 is indicated at the lowest regeneration temperature examined.

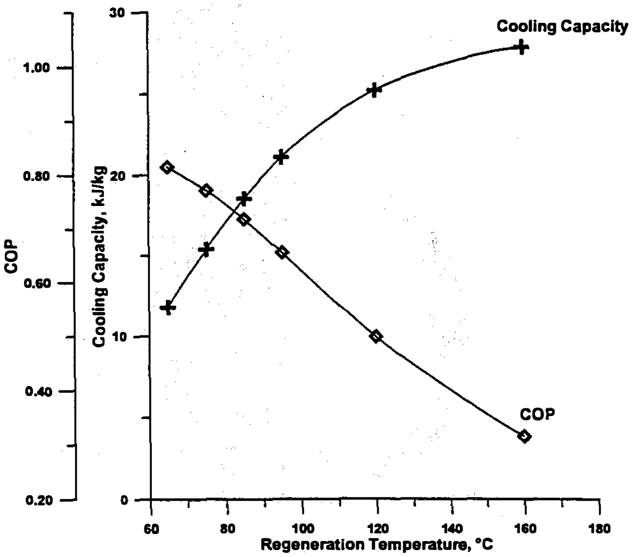

Fig. 4. Maximum Cooling Capacity Performance with Corresponding COP, No-staged Regeneration

When no-staged regeneration is employed, the entire regeneration area is exposed to the design regeneration temperature. This regeneration method exposes the desiccant matrix to the drying airstream for a much longer period than is necessary, resulting in the over-regeneration of the desiccant. Over-regeneration results in a drier and hotter desiccant matrix at the start of the dehumidification cycle. While this can yield an increase in cooling capacity, it generally degrades the thermal COP because of the inefficient use of the thermal energy used for regeneration. At high regeneration temperatures the over-regeneration of the desiccant matrix becomes more pronounced and the COP suffers accordingly. At low regeneration temperatures the over-regeneration of the desiccant is less pronounced and we would expect the thermal COP to improve. In Figure 4, we see that thermal COP performance improves as we reduce the regeneration temperature, and the maximum COP value is encountered at the lowest temperature investigated.

Cooling capacity exhibits the opposite behavior, increasing with increasing regeneration temperature and leveling off at higher temperatures. As we would expect, higher regeneration temperatures generally result in increased cooling capacity. The maximum value for cooling capacity, 27.9 kJ/kg, occurs at T_{reg} = 160°C.

If cooling capacity and size of equipment is the driving concern and the cost of thermal energy is not a concern, then no-staged regeneration provides a good fit. The cost of thermal energy in a solar desiccant cooling system, however, is a major concern and has a significant impact on the overall size of the system. Under these circumstances a tradeoff between cooling capacity per unit size versus equipment size and cost of the solar collectors must be closely examined.

Maximum system performance for regeneration temperatures ranging from 65°C to 160°C occurs over a wide range of separation factors. The associated separation factors vary between Type I moderates (R = 0.1) and nearly linear isotherms (R = 1); the separation factors corresponding to maximum system performance are displayed in Figure 5. For no-staged regeneration, our two performance criteria of thermal COP and system cooling capacity do not correspond to the same value of R. Maximizing cooling capacity favors a Type I moderate isotherm, while emphasizing COP performance favors a more linear isotherm.

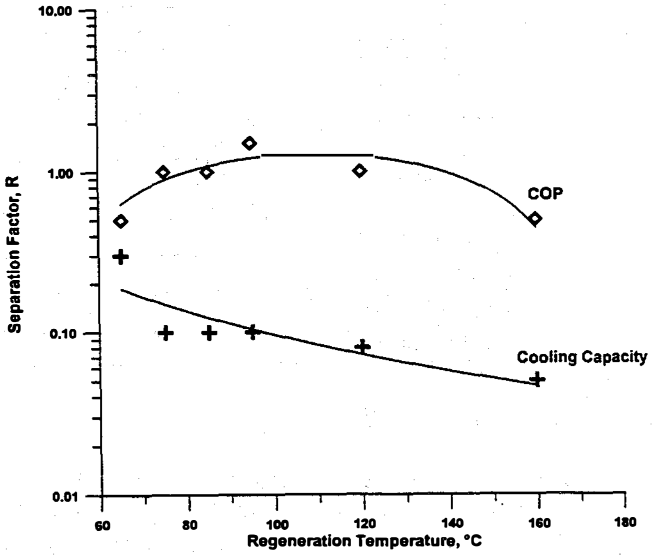

Fig. 5. Optimum Separation Factors Resulting in Maximum Thermal COP and Maximum Cooling Capacity Performance, No-staged Regeneration

3.2 Staged Regeneration

The performance of a staged regeneration desiccant cooling system, for regeneration temperatures between 65°C and 160°C, is displayed in Figure 6. The maximum thermal COP for this staged system (PERC = 0.3) is approximately 1.02 and occurs at a regeneration temperature of 110°C. This is 20% higher than the maximum COP obtained when using no-staged regeneration. For regeneration temperatures above this value, the COP drops off. This is because as the regeneration temperature increases the airstream fraction (PERC) required to just regenerate the desiccant decreases; if the PERC is not decreased as T_{reg} increases, the desiccant will be over-regenerated. As we have seen in the no-staged regeneration case, this results in decreased cycle efficiencies. Likewise for regeneration temperatures below 110°C, we would expect that an increase in the PERC value would result in increased system efficiencies, up to a point. Collier et al. (2) have shown that the drop in COP at 160°C can be offset by reducing the regenerated fraction to PERC = 0.2. This would also result in a slightly reduced cooling capacity.

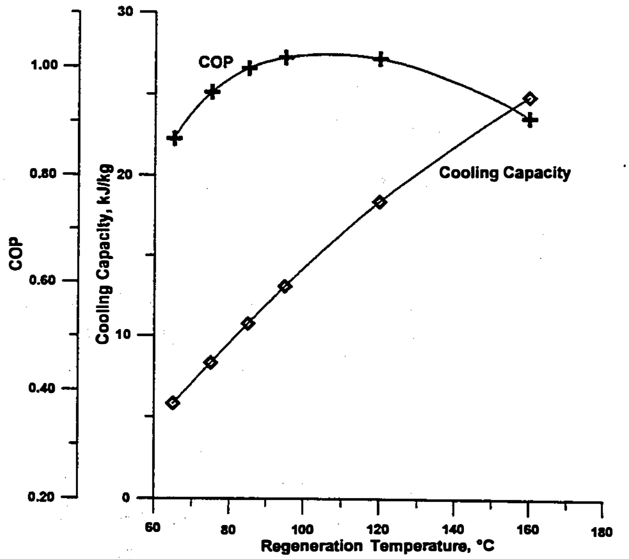

Fig. 6. Maximum Thermal COP and Cooling Capacity Performance, Staged Regeneration, PERC = 0.3

Maximum cooling capacity occurs at T_{reg} = 160°C and is 24.9 kJ/kg. This is approximately 10% less than the maximum achievable cooling capacity at T_{reg} = 160°C when no-staged regeneration is used. This is a relatively small tradeoff in cooling capacity and results in a vast improvement in the system's COP and the resultant amount of thermal energy required for regeneration.

When staged regeneration is employed, optimum performance of the system in terms of thermal COP seems to favor two different values of R, one for what might be termed low-temperature applications and a second for high-temperature applications (see Figure 7). A separation factor of 0.25 appears to be favored for low-temperature solar applications, where T_{reg} < 80°C. As the regeneration temperature increases, the preferred separation factor decreases, reaching a value just under 0.1 for high-temperature solar applications, T_{reg} > 120°C. This agrees with Collier et al. (2), who found that at a regeneration temperature of 160°C optimum COP performance occurs at R = 0.1.

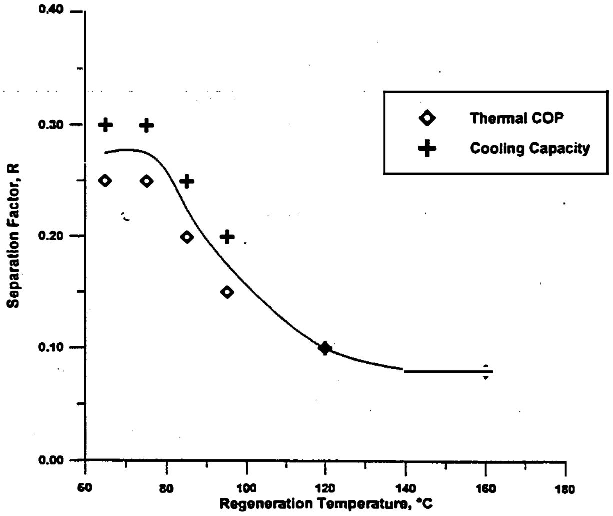

Fig. 7. Optimum Separation Factors Resulting in Maximum Thermal COP and Maximum Cooling Capacity Performance, Staged Regeneration, PERC = 0.3

Optimum system performance, based on cooling capacity, follows a trend similar to that of thermal COP. The preferred value of separation factor at low regeneration temperatures is 0.3. This value is slightly higher than the separation factor that maximizes thermal COP. For high-temperature applications, the preferred value for R converges to the same value as found for COP, approximately R = 0.1.

The variation in the separation factors yielding maximum thermal COP and cooling capacity performance is plotted in Figure 7. A curve representing the compromise in performance between COP and cooling capacity is also displayed. This curve is designated as the optimum values for separation factor, and it represents the best combination of COP and cooling capacity performance. The optimum separation factor for low-temperature applications is approximately R = 0.28, while the optimum for high-temperature applications is, as discussed previously, approximately R = 0.1.

4. CONCLUSION

No-staged regeneration, while inherently simpler than a staged regeneration method, requires significant compromises in the performance of the overall system. Maximum thermal COP and maximum cooling capacity performance are achieved at completely different separation factors, especially at regeneration temperatures above 80°C.

In addition, the regeneration temperature has opposing effects on thermal COP and cooling capacity, increasing one while decreasing the other. As a result, significant tradeoffs must generally be accepted when optimizing for either thermal COP or cooling capacity.

Staged regeneration adds additional complexity to the desiccant cooling system, but provides an excellent combination of cooling capacity and thermal COP performance. At high regeneration temperatures ($T_{reg} > 120°C$), a separation factor of $R = 0.1$ maximizes both COP and cooling capacity. At low regeneration temperatures ($T_{reg} < 80°C$), the value of R resulting in maximum COP performance differs slightly from the value corresponding to maximum cooling capacity. A compromise of $R = 0.28$ at these temperatures results in only a slight degradation in overall performance.

From the previous results, we can observe that staged regeneration, when used in high-temperature applications ($T_{reg} > 120°C$), generally reduces the size and cost of a solar desiccant cooling system. For most low-temperature applications ($T_{reg} < 80°C$), it would appear that no-staged regeneration is preferred.

5. NOMENCLATURE

CC = cooling capacity, kJ/kg or kW/(kg/s)
COP = thermal coefficient of performance
PERC = fraction of the regeneration airstream that is heated to T_{reg}
R = separation factor
RH = relative humidity
RH^* = temperature adjusted relative humidity, RH/TE
T_{ref} = reference temperature of isotherm
T_{reg} = regeneration temperature ($65°C < T_{reg} < 160°C$)
TE = temperature effect compensation factor to adjust RH at temperatures other than T_{ref}
W = moisture loading at RH^*, kg water/kg desiccant
W_{max} = maximum moisture uptake at T_{ref}, kg water/kg desiccant
W^* = moisture loading fraction, W/W_{max}

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