P. Gandhidasan[1]
Senior Lecturer,
Mechanical Engineering Department,
The University of the West Indies,
St. Augustine, Trinidad, W.I.
Mem. ASME

Reconcentration of Aqueous Solutions in a Packed Bed: A Simple Approach

Introduction

In recent years attempts have been made to use packed beds in open-cycle liquid desiccant cooling systems for the dehumidification process and/or for regenerating weak aqueous solutions. The possibility of reconcentrating the aqueous solution in a packed bed by means of solar-heated air was investigated by Leboeuf and Löf [1] and Factor and Grossman [2]. The schematic of the reconcentration process is shown in Fig. 1. The weak absorbent solution, which leaves the absorber, is pumped to the top of the packed bed after passing through a solution-to-solution heat exchanger where it is preheated by the strong solution. Solar-heated air enters the packed bed at the bottom. Since the weak solution vapor pressure exceeds the vapor pressure of water in air, the moisture transfer takes place from the solution to the air. Cooled and humidified air exits at the top and warm, concentrated solution leaves the bottom of the packed bed. For each kilogram of water evaporated from the solution in the packed bed, one kilogram may be absorbed in the absorber and thus evaporated in the evaporator to provide cooling. Hence, the performance of the cooling system is directly related to the amount of water evaporated from the weak solution in the packed bed.

A step-wise heat and mass balance across the bed is used to determine the performance of the reconcentration process. However, due to the abundance of variables involved with the packed bed, the analysis becomes increasingly complex. To reduce the high computational cost, an air moisture removal effectiveness for the dehumidification process was defined (see reference [3]) based on the rigorous calculation for the heat and mass transfer occurring in the packed bed.

In this paper dimensionless vapor pressure and temperature difference ratios suitable for application in the reconcentration of aqueous solutions are defined. Further, a closed-form analytical solution is obtained to predict the mass of water evaporated from the weak absorbent solution, through a simplified vapor pressure correlation and the dimensionless vapor pressure and temperature difference ratios.

Dimensionless Vapor Pressure and Temperature Difference Ratios for a Reconcentration Process

In a packed bed, the reconcentration process involves simultaneous heat and mass transfer. During the reconcentration process, the moisture from the absorbent solution transfers to the air stream. Hence, a dimensionless moisture difference ratio, suitable for the reconcentration process in the packed bed, can be defined as the ratio of the actual change in moisture content of air to the maximum possible change in moisture content under given conditions as:

$$\alpha = \frac{HR_o - HR_i}{HR_{o,\max} - HR_i}. \tag{1}$$

The vapor pressure of hot and strong solution at the outlet of the bed is higher than that of warm and weak solution at the inlet. As long as the solution vapor pressure is higher than the air vapor pressure, reconcentration can take place. Therefore, the solution outlet conditions set a theoretical limit on the maximum vapor pressure, and therefore on the maximum humidity ratio that air can achieve.

In the limit, then

$$P_{a,o,\max} = P_{s,o} = HR_{o,\max}. \tag{2}$$

Equation (1) can be written in terms of vapor pressure as

$$\alpha = \frac{P_{a,o} - P_{a,i}}{P_{s,o} - P_{a,i}}. \tag{3}$$

For the reconcentration process the hot air is supplied from the solar collector, and therefore the air temperature is higher than the solution temperature. Hence, in addition to moisture transfer, heat will also transfer due to the difference in temperature. Therefore it is necessary to define a dimensionless temperature difference ratio similar to the dimensionless vapor pressure difference ratio. For the range of operating conditions assumed in the analysis, the vapor pressure of air and solution vary approximately linearly with temperature. Further, the primary objective is the transfer of the water vapor from the solution, and hence the temperature difference ratio must be defined in accordance with the dimensionless vapor pressure difference ratio to obtain a simple relationship. It can be defined as,

$$\beta = \frac{t_{a,i} - t_{a,o}}{t_{a,i} - t_{s,o}}. \tag{4}$$

In this paper the aforementioned dimensionless vapor pressure and temperature difference ratios are used to derive a simple

---

[1] Presently at the Department of Mechanical Engineering, Texas Tech University, Lubbock, TX 79409-1021.

Contributed by the Solar Energy Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS for publication in the JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received by the ASME Solar Energy Division, Aug. 17, 1989; final revision, June 13, 1990.

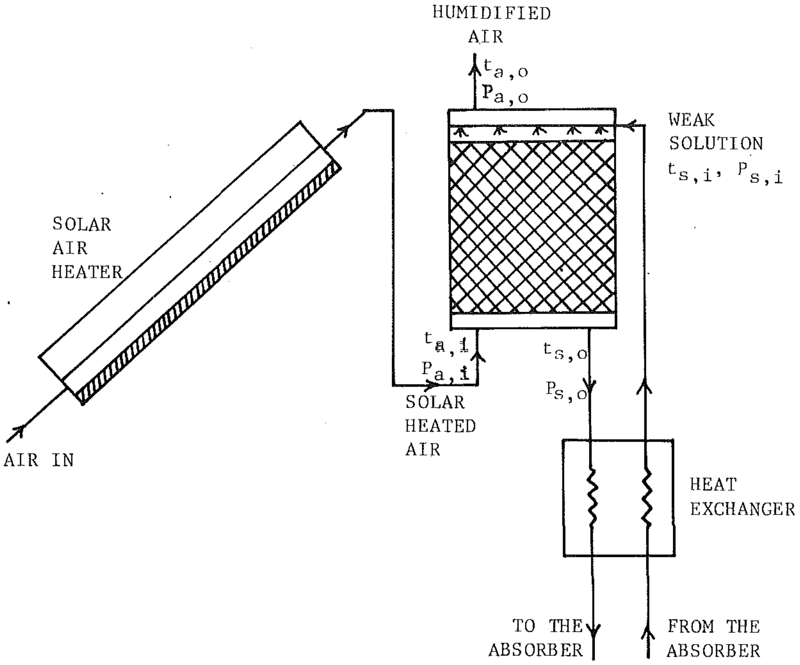

Fig. 1 Reconcentration of absorbent solution in a packed bed

expression to evaluate the performance of the reconcentration process.

System Analysis

Assuming constant specific heats for the fluids with respect to temperature, the overall heat balance of the packed bed can be written as

$$G_a(c_{p,a}t_{a,i}+y\,P_{a,i})+G_s c_{p,s} t_{s,i} = G_a(c_{p,a}t_{a,o}+y\,P_{a,o})+G_s c_{p,s} t_{s,o} \tag{5}$$

where $y=\dfrac{0.622\,h'_{fg}}{P_b}$ for small vapor pressures.

Equation (5) can be rewritten in terms of α and β as

$$c_{p,a}\beta(t_{s,o}-t_{a,i})+y\,\alpha(P_{s,o}-P_{a,i})=\frac{G_s c_{p,s}}{G_a}(t_{s,i}-t_{s,o}). \tag{6}$$

$P_{s,o}$ and $t_{s,o}$ as a function of initial parameters can be obtained as follows: The relationship between the vapor pressure of the solution at the outlet and its temperature and concentration is given by reference [4],

$$P_{s,o}=a+b\,t_{s,o}+\frac{c}{\xi_{s,o}}, \tag{7}$$

where a, b, and c are empirical constants for the range of conditions of interest.

The effect of flow rate of solution on the rate of desorption is given in terms of inlet and outlet concentration of the solution as

$$\frac{1}{\xi_{s,o}}=\frac{1}{\xi_{s,i}}\left(1-\frac{m}{G_s}\right). \tag{8}$$

The mass of water evaporated from the solution and absorbed by the air stream is given by

$$m=\frac{G_a y}{h'_{fg}}(P_{a,o}-P_{a,i}). \tag{9}$$

By combining equations (3) and (9), the vapor pressure of the solution at the outlet of the packed bed can be obtained and is given by

$$P_{s,o}=\frac{m\,h'_{fg}}{\alpha\,G_a y}+P_{a,i}. \tag{10}$$

The solution temperature at the outlet of the bed can be obtained by combining equations (7), (8), and (10) and is given by

$$t_{s,o}=\frac{1}{b}\left[\frac{m\,h'_{fg}}{\alpha\,G_a y}+P_{a,i}-\frac{c\left(1-\dfrac{m}{G_s}\right)}{\xi_{s,i}}-a\right]. \tag{11}$$

By substituting the values for $P_{s,o}$ and $t_{s,o}$ from equations (10) and (11), respectively, in equation (6), the mass of water evaporated from the absorbent solution can be determined. It is given by

Nomenclature

C = heat capacity rate
c_p = specific heat
G = mass flow rate
h'_{fg} = heat of vaporization of water from the absorbent solution
HR = humidity ratio of air
m = amount of water evaporated from the weak solution
P = water vapor pressure
t = temperature
α = dimensionless vapor pressure (moisture) difference ratio
β = dimensionless temperature difference ratio
ξ = concentration of the absorbent solution

Subscripts

a = air
b = barometric
i = inlet
max = maximum
o = outlet
s = absorbent solution

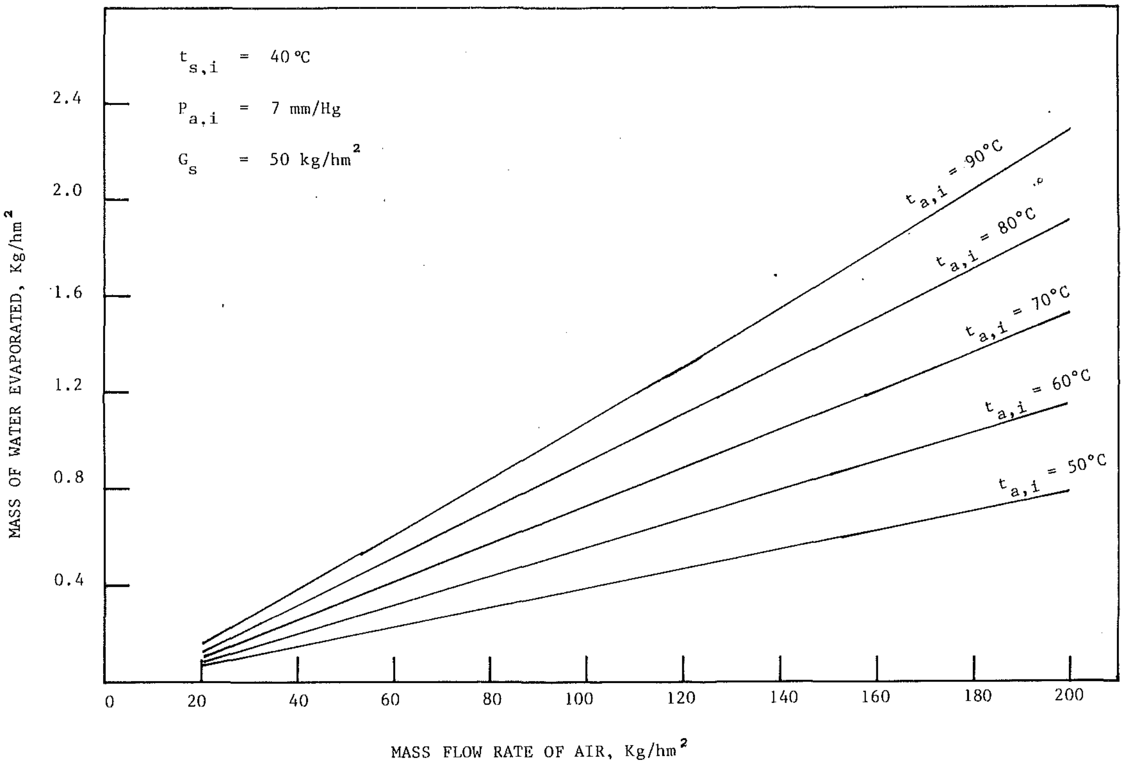

Fig. 2 Effect of air inlet temperature on rate of desorption

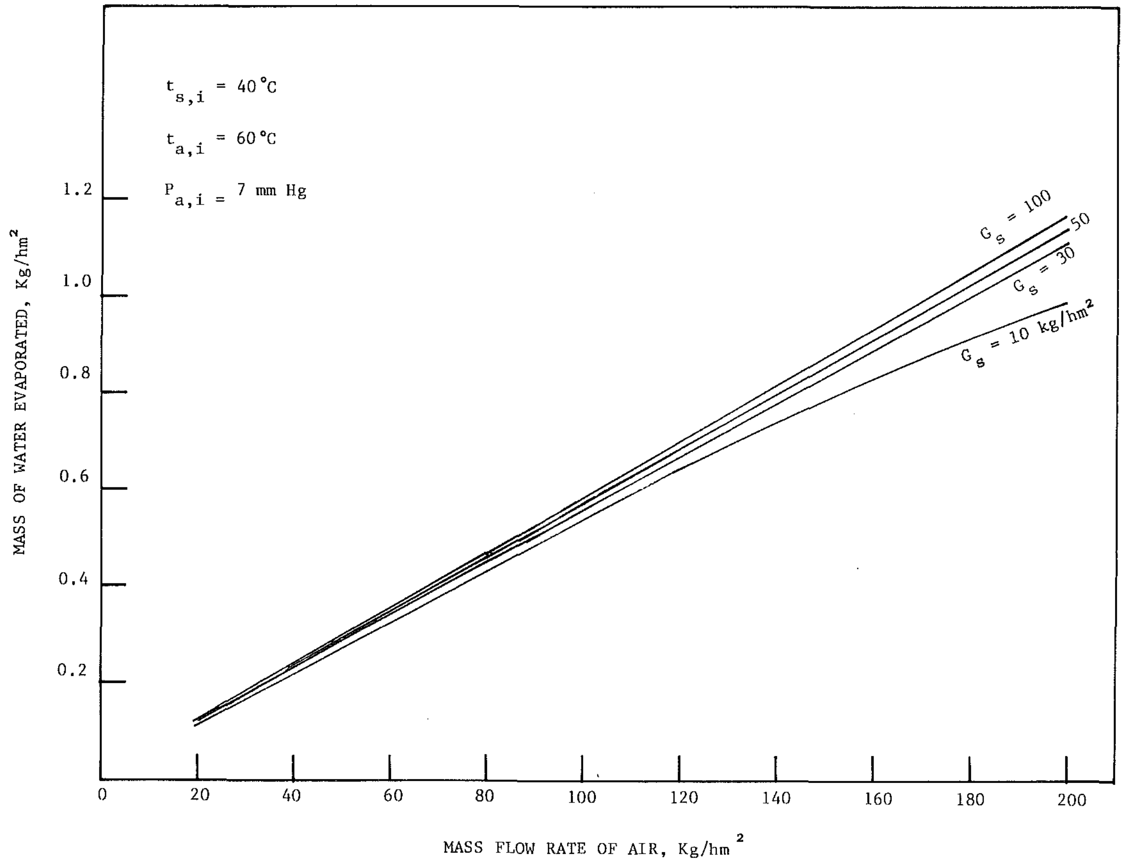

Fig. 3 Effect of solution flow rate

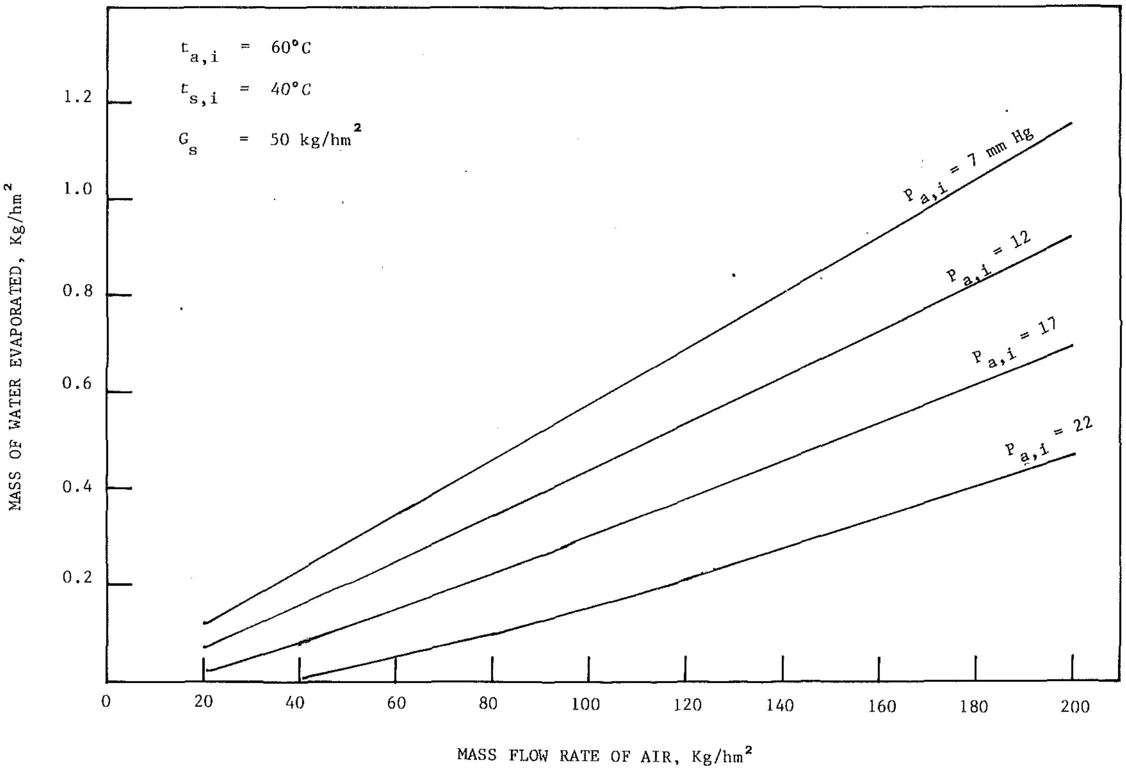

Fig. 4 Effect of initial water vapor pressure in air

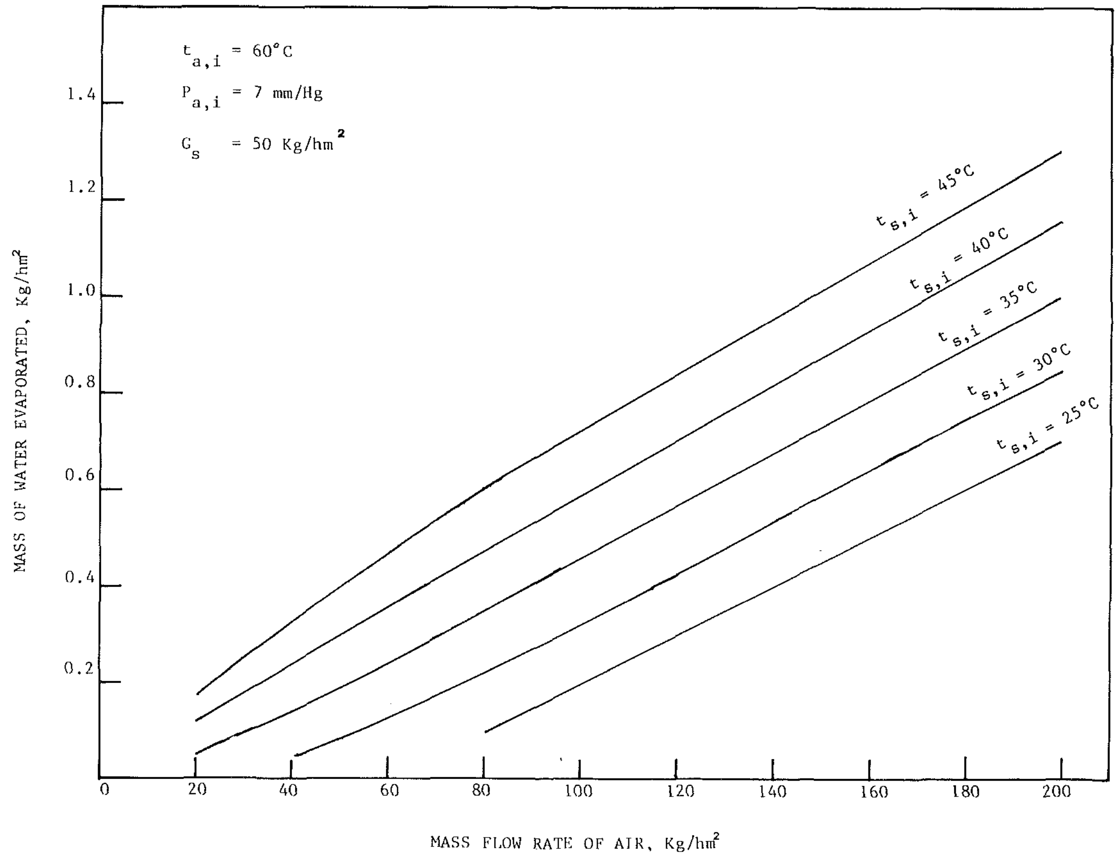

Fig. 5 Effect of preheating the solution

$$m = \frac{C_a t_{a,i} \beta + C_s t_{s,i} - \frac{1}{b}\left(P_{a,i} - a - \frac{c}{\xi_{s,i}}\right)(C_a \beta + C_s)}{\frac{1}{b}(C_a \beta + C_s)\left[\frac{h'_{fg} c_{p,a}}{C_a y \alpha} + \frac{c\, c_{p,s}}{C_s \xi_{s,i}}\right] + h'_{fg}} \qquad (12)$$

where C_a and C_s are the heat capacity rate of air and solution, respectively, and is given by $C_a = G_a c_{p,a}$ and $C_s = G_s c_{p,s}$. If the value h'_{fg} is assumed constant with respect to temperature and concentration of the solution, then the rate of desorption becomes a function of initial parameters and the heat capacity rate of the fluids and dimensionless vapor pressure and temperature difference ratios.

Results and Discussion

For the present study calcium chloride solution is used as the absorbent. For the range of operating conditions assumed in the present analysis, the constants a, b, and c in equation (7) for brine concentrations of 45–47 percent are found to be (i) for solution temperatures of 45–60°C, $a = -290.8$, $b = 3.2$, and $c = 6708.9$ and (ii) for solution temperatures of 35–45°C, $a = -114.8$, $b = 1.51$, and $c = 3169.1$. It is further assumed that for the weak solution, the heat of vaporization of water from the solution for these conditions is a constant of 2551.6 kJ/kg. It may be noted that α and β also depend upon the type of packing material used. A simple calculation based on the results of [5] indicates that for a packed bed with 1-in. Raschig rings, α and β varies from 0.5 to 0.8. However, in the present analysis, for numerical calculations it is assumed that $\alpha = \beta = 0.8$.

The effect of the regeneration temperature of air on rate of desorption of water is shown in Fig. 2. For a particular regeneration temperature as the flow rate of air increases, the mass of water evaporated from the solution also increases. The higher regeneration temperature yields the greater rate of desorption. Figure 3 shows the water loss rate for different flow rates of air and solution. It is interesting to note that the change in solution flow rate has no significant effect on the system performance.

The packed bed performance due to changes in initial water vapor pressure in air is shown in Fig. 4. If the initial water vapor pressure in air is less (that is, dry air), it tends to absorb more moisture from the solution, and hence the water loss rate is more. When the entering air is humid, the absorption rate is less due to low potential for mass transfer, and hence the desorption rate is less.

The effect of preheating the solution (that is, inclusion of a heat exchanger in the cycle) on the rate of desorption is shown in Fig. 5. As the solution inlet temperature increases, the mass of water evaporated from the solution also increases owing to the increase in mass transfer potential.

Conclusion

A simple analytical investigation of reconcentration of aqueous solutions occurring in a packed bed using solar heated air is carried out through a simplified vapor pressure correlation and dimensionless vapor pressure and temperature difference ratios. It is found that the air inlet temperature and its vapor pressure and the solution inlet temperature have significant effect on the regeneration performance. For preliminary design purposes, the simple expression derived in this paper can be used to predict the mass of water evaporated from the weak absorbent solution in the packed bed.

Acknowledgments

The author wishes to express his thanks to Prof. S. Satcunanathan of the Mechanical Engineering Department for helpful discussions.

References

1 Leboeuf, C., and Löf, G. O. G., "Open Cycle Absorption Cooling Using Packed Bed Absorbent Reconcentration," *Proceedings of the 1980 Annual Meeting of the American Section of the International Solar Energy Society*, p. 205.

2 Factor, H. M., and Grossman, G., "A Packed Bed Dehumidifier/Regenerator for Solar Air Conditioning with Liquid Desiccants," *Solar Energy*, Vol. 24, 1980, p. 541.

3 Ullah, M. R., Kettleborough, C. F., and Gandhidasan, P., "Effectiveness of Moisture Removal for an Adiabatic Counterflow Packed Tower Absorber Operating with $CaCl_2$-Air Contact System," ASME JOURNAL OF SOLAR ENERGY ENGINEERING, Vol. 110, No. 2, 1988, p. 98.

4 Kakabaev, A., and Khandurdyev, A., "Absorption Solar Refrigeration Unit with Open Regeneration of Solution," *Applied Solar Energy*, Vol. 5, No. 4, 1969, p. 69.

5 Leboeuf, C. M., and Löf, G. O. G., "Analysis of a Licl Open-Cycle Absorption Air Conditioner which Utilizes a Packed Bed for Regeneration of the Absorbent Solution Driven by Solar Heated Air," Final Report, for U.S. Department of Energy, Colorado State University, Colo., Contract No. EG-77-S-02-4546, Oct. 1978.