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MASTER

OPEN-CYCLE ABSORPTION COOLING USING PACKED-BED ABSORBENT RECONCENTRATION

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NOTICE

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ABSTRACT

The technical feasibility of a lithium chloride open-cycle absorption air conditioner using solar-heated air for reconcentration of the absorbent solution is examined. In contrast to a successfully operating Soviet design (in which absorbent reconcentration is accomplished by trickling the solution across a sloping black roof exposed to the sun), this study involves a packed-bed concentrator. Solar-heated air reconcentrates the solution by vaporizing water (the refrigerant) from the solution in the packed bed, enabling the system to be incorporated into a conventional solar air-heating system and avoiding numerous problems associated with the roof concentrator.

A thermodynamic analysis provides the criteria for the design of the packed bed. Heat and mass transfer processes occurring simultaneously in the bed are modeled using an iterative technique with the aid of a digital computer. The size of the packed-bed required to reconcentrate the absorbent solution at a rate corresponding to 10,550 W of cooling is determined, using flow rates, temperatures, and humidities typical of residential solar air-heating systems. Based on these results, the system air conditioning capability with solar energy input is predicted over the course of a clear summer day for Fort Collins, Colorado, and St. Louis, Missouri. Sufficient cooling capacity to meet a 10,550 W peak load using a 70 m^2 flat-plate collector array is predicted by the model for both locations.

1. INTRODUCTION

The concept of an open-cycle lithium chloride absorption air conditioner has been examined as a possible cooling scheme for an air solar heating system. Soviet researchers have built and analyzed a 35,170 W cooling system which operates on this principle in an apartment building near Ashkabad in the USSR (1). In contrast to conventional absorption refrigeration systems employing lithium salt solutions in which both the absorbent and refrigerant circulate in a closed cycle, this open cycle recirculates only the absorbent. Water, the refrigerant, is continually evaporated to the atmosphere, and must therefore be continuously added to the cycle. The condenser and generator of a conventional closed-cycle system are not necessary, so there is a substantial reduction in equipment requirements.

Reconcentration of the lithium chloride solution in the Russian air conditioner is accomplished by trickling it across a gently sloping black roof that is directly exposed to the sun. The absorbed energy, and a hot, low-humidity atmosphere, result in the reconcentration of the solution for return to the absorber. In the absorber, water vapor from the evaporator is again absorbed, and the cycle continues. The system has been successfully operating for about five years. However, the design has limitations that prohibit its use in more humid locations. For instance, rainfall and high relative humidities cannot be tolerated, because dilution of the solution and inadequate reconcentration would prevent satisfactory operation.

To broaden the applicability of the open-cycle system to less arid locations, an analysis was made of reconcentrating the absorbent solution in a packed bed (stripping column) using solar-heated air to drive off the refrigerant vapor.

The procedure was as follows. The flow rate and concentration requirements of the reconcentrating unit (packed bed) were determined using a thermodynamic analysis of the open-cycle cooling system. A steady-state performance model of the bed was developed. It was used to find the required dimensions of a packed bed capable of sufficient absorbent solution reconcentration for 10,550 W of cooling, subject to a variety of operating conditions. Based on this analysis, performance of the open-cycle cooling system with a packed-bed reconcentrator was modeled for weather data typical of summer in Fort Collins, and for a more humid climate, that of St. Louis.

2. DESCRIPTION OF THE OPEN-CYCLE ABSORPTION COOLING SYSTEM

A schematic of the open-cycle absorption cooling system examined in this work appears in Fig. 1. Figure 2 is a diagram of the components, with state points identified and typical temperatures, pressures, and concentrations labeled. The evapo-

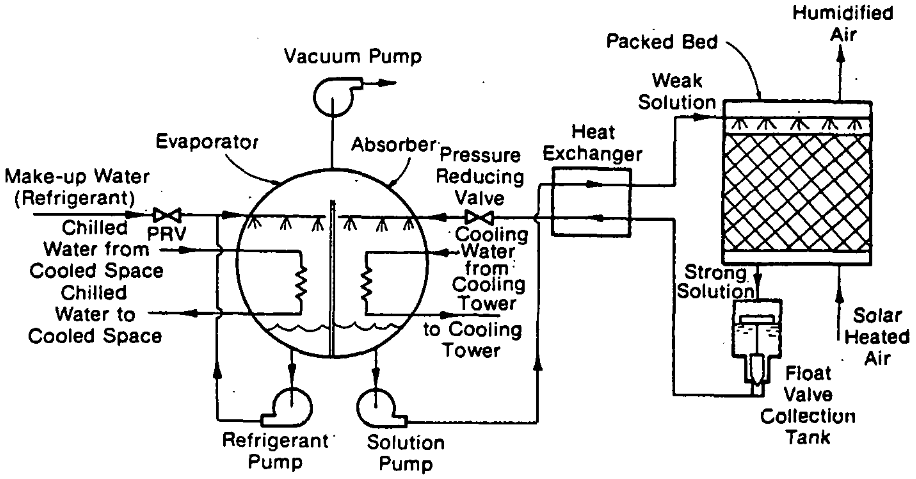

Fig. 1. Schematic of the Open-Cycle Absorption Cooling System

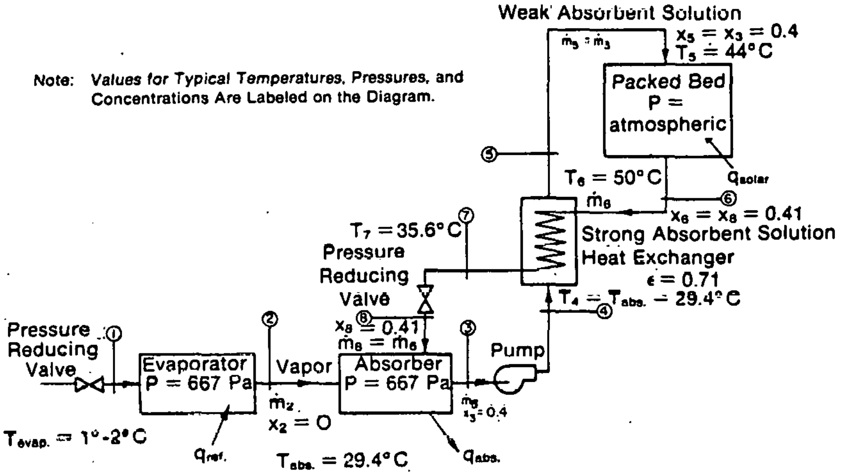

Fig. 2. Block Diagram of System Components

rator-absorber unit is kept at a pressure of 667 Pa by a small vacuum pump that removes noncondensibles dissolved in the make-up water. Water in the evaporator vaporizes at 1°-2° C, and the vapor is absorbed by an aqueous LiCl solution in the absorber. Energy for vaporizing this refrigerant is received from the coolant being returned from the living space at temperatures of 10°-15° C, thereby providing chilled water at 4°-8° C for cooling the building. The absorber temperature is maintained by heat exchange with water from a cooling tower. Diluted absorbent solution leaves the absorber and is pumped to the reconcentrating unit, first passing through a heat exchanger where it is preheated by the concentrated solution. The reconcentrating unit is a packed bed, or column, selected because it facilitates heat and mass exchange by providing a large surface area in a relatively small volume. Solar-heated air enters the packed bed at the bottom and evaporates water from the absorbent solution, which is distributed over the top of the packing. Cooled and humidified air exits at the top and is exhausted to the atmosphere. Warm, concentrated solution leaves the bottom of the packed bed and passes through a heat exchanger, where it is cooled by heat transfer to the weak solution leaving the absorber. Before entering the absorber, the strong solution passes through a valve or constriction, where its pressure is reduced to about 667 Pa.

Net cooling effect arises from the heat required to evaporate the water in the evaporator (latent heat of vaporization). For each kilogram of water evaporated in the packed bed, one kilogram may theoretically be absorbed in the absorber and thus evaporated in the evaporator to provide cooling of the conditioned space.

3. THERMODYNAMIC ANALYSIS

The thermodynamic analysis of this system is very similar to that of a closed cycle. Referring to Fig. 2, an energy balance on the evaporator yields the required rate of refrigerant flow, $\dot{m}_2$:

$$q_{ref} = \dot{m}_2\left(H_2 - H_1\right) = \dot{m}_2 H_{fg} \quad , \qquad [1]$$

where q_{ref} is the heat absorbed in the evaporator, and H_{fg} is the latent heat of vaporization. The heat removal required to bring the incoming make-up water down to the evaporator temperature is small compared with H_{fg} and is neglected in this analysis.

For the absorber, conservation of mass may be expressed by:

$$\dot{m}_3 = \dot{m}_8 + \dot{m}_2 \quad . \qquad [2]$$

The absorbent material must also be conserved in this system, thus:

$$\dot{m}_3X_3 = \dot{m}_8X_8 + \dot{m}_2X_2 \quad , \qquad [3]$$

where X is the concentration of the LiCl in the solution.

When a given air conditioning capacity, evaporator temperature (and hence absorber pressure), cooling tower capacity, and a desired strong absorbent solution concentration are specified, corresponding values for the weak absorbent concentration and the required flow rates may be calculated from Eqs. [1], [2], and [3] and from equilibrium data for the absorbent. Based on this information, the criteria for the design of the packed bed may be established.

4. PACKED-BED ANALYSIS

In the packed bed, the humidification process involves simultaneous heat and mass transfer. This analysis assumes the process to be gas-phase controlling (i.e., all resistance to mass transfer is in the gas phase). Heat and mass transfer coefficients are assumed constant throughout the packed bed. A step-wise heat and mass balance across the tower was used to determine tower performance, following the steady-state analysis presented by Treybal (2).

Figure 3 is a schematic of a differential section of the packed tower. Shown are: superficial mass velocity of the liquid (L'); superficial mass velocity of the gas (G'); absolute humidity of the air (Y); mass fraction of LiCl in the liquid (X); gas temperature (T_G); liquid temperature (T_L); height of the tower section (dZ); temperature of the interface between the air and the liquid (T_{int}); and absolute humidity of air that would be saturated at the interface temperature (Y_{int}).

To predict the performance of the cooling system, a steady-state model of the packed-bed operation was developed, based on material balances, energy balances, and transfer rate equations. A mass balance for the vapor for any differential section may be written as:

$$dL' = G'\,dY \quad . \qquad [4]$$

The rate of the mass transfer of the vapor is

$$G'\,dY = -k_Ga_M(Y_n - Y_{int})\,dZ \quad , \qquad [5]$$

where k_Ga_M is the gas-phase mass transfer coefficient. An energy balance on the gas phase for this differential section may be expressed as:

$$G'C_{Gn}\,dT_G = -h_Ga_H(T_{Gn} - T_{int})\,dZ \quad , \qquad [6]$$

where h_Ga_H is the gas-phase heat transfer coefficient, and C_{Gn} is the specific heat of the gas at n.

The liquid-phase energy balance for this section may be written

$$L'_nC_{Ln}\,dT_L = G'C_{Ln}\left(T_{int} - T_{Ln}\right)dY - h_La_H\left(T_{int} - T_{Ln}\right)dZ \quad , \qquad [7]$$

where h_La_H is the liquid-phase heat transfer coefficient.

Finally, an energy balance on the entire section results in

$$L'_nC_{Ln}\,dT_L = G'C_{Gn}\,dT_G + G'\left(Q_{dhs} + H_{fg}\right)dY \quad , \qquad [8]$$

where Q_{dhs} is the differential heat of solution of aqueous LiCl, and H_{fg} is the latent heat of vaporization.

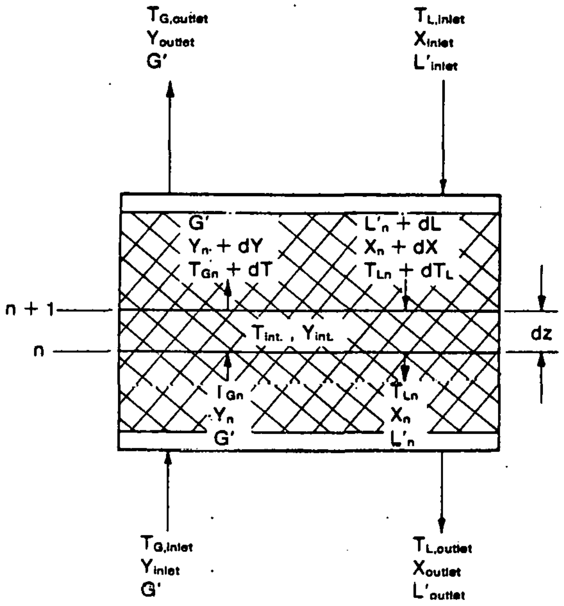

Fig. 3. Differential Section of Packed Bed

Working from the bottom upward, successive differential sections of the bed may be examined by applying Eqs. [4] through [8]. This analysis may be used to size a bed for specific operating conditions or to simulate performance for a bed of fixed dimensions. A value for T_{int} must be assumed and iteratively verified for each section. Similarly, a value for the liquid-phase exit temperature, $T_{L,outlet}$ must be assumed and checked at the top of the bed.

Based on the preceding analysis, a computer program was written to simulate the performance of the packed bed and used to generate the results of the following sections.

5. SIZING THE PACKED BED FOR A 3-TON LOAD

A 10,550 W air conditioning capacity was chosen for this study, as it is a typical cooling load for a residence. At the evaporator pressure of 667 Pa, the latent heat of vaporization of water, H_{fg}, is 2500 kJ/kg. To supply the 10,550 W load, 15.2 kg of water must be evaporated in the evaporator per hour, and thus 15.2 kg/h must be driven off the LiCl solution in the packed bed.

It was necessary to determine the size of a packed bed that could provide 10,550 W of refrigeration subject to a given set of inlet conditions. Air flow rates corresponding to a 70 m^2 collector array with a design flow rate of 10 or 15 ℓ/s-m^2 (conditions comparable to those in CSU Solar House II) (3) were chosen for this analysis. The specific mass velocity of the gas (G' in Fig. 3) was computed by dividing the total mass flow rate by the cross-sectional area. Selection of the proper bed area for each collector flow rate was based on hydrodynamic considerations beyond the scope of this paper. Details may be found in Ref. (4).

Figure 4 shows the required bed height to provide 10,550 W of cooling for air inlet temperatures of 50°-80° C, and for three values of inlet specific humidity corresponding to 13%, 30%, and 63% relative humidity at 26.7° C and sea level. The packing type is 1.5-in Berl saddles, with a mass transfer coefficient ($K_G a_M$) of 12,800 kg/h-m^3-[kg water/kg air]. Heat exchanger effectiveness was fixed at 0.85. The bed cross-sectional area was .63 m^2 for the 10 ℓ/s-m^2 collector flow rate, and .94 m^2 for the 15 ℓ/s-m^2 flow rate. Superficial mass velocity for the gas was 4893 kg/h-m^2 for both beds, and the superficial liquid velocity entering the packings was 978 kg/h-m^2.

The most significant result of Fig. 4 is that the computed bed volumes are all less than .566 m^3. This is a direct result of the fairly high mass transfer coefficient for Berl saddles and the high air flow rates employed. For example, a total volume of .21 m^3 (.63 m^2 x .34 m), an average driving force of 0.00564 kg water/kg air, and a mass transfer coefficient of 12,800 kg/h-m^3-[kg water/kg air] will evaporate the desired 15.2 kg water/h when L' is 978 kg/h-m^2 and G' is 4893 kg/h-m^2.

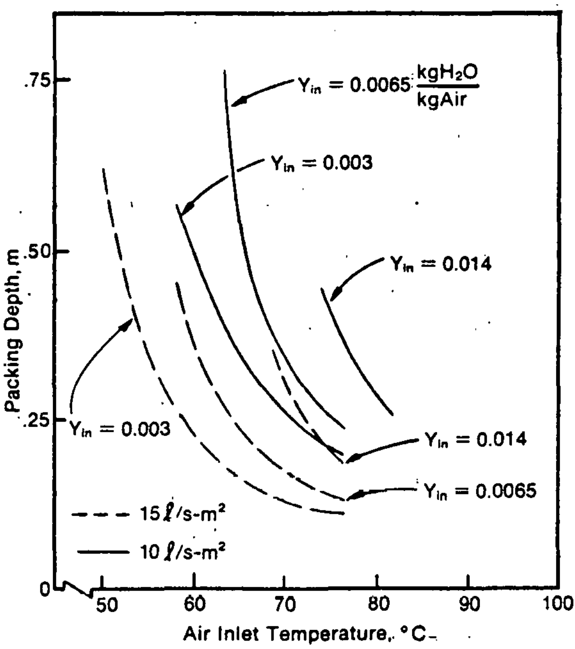

Fig. 4. Required Bed Height for 3 Tons of Cooling as a Function of Air Inlet Temperature

6. SYSTEM PERFORMANCE WITH SOLAR INPUT

The final objective of this study was to establish a direct relationship between solar energy input and system performance. A detailed performance simulation over an entire summer is not warranted at this time due to the uncertainty involved in transfer coefficients and in operating a real, physical system. However, information obtained by modeling performance of a residential system for a clear, hot summer day could be very useful for the design of a prototype unit. Both a dry and a humid climate were modeled, since ambient humidity affects the operation of this sytem.

Insolation and temperatures typical of July in Fort Collins and St. Louis are shown in Fig. 5. Figure 6 shows the performance in Fort Collins of a system with a .34 m packed bed and a 70 m^2 array of Solaron Series 3000 panels, tilted at 30°, for flow rates of 10 and 15 ℓ/s-m^2. At 10 ℓ/s-m^2, 10,550 W of cooling are provided for nearly two hours, 11:30 a.m. to 1:30 p.m., and about 3500 W are available at 9:00 a.m. and 4:00 p.m. Improved collector efficiency, which results when operating at a flow rate of 15 ℓ/s-m^2 of collector rather than 10 ℓ/s-m^2, did not improve the system performance for these conditions. The benefits of high outlet temperatures at the lower flow rate appear to outweigh those of increased collector efficiency at higher air flow rate and the same ambient conditions.

Performance of the system modeled on a clear day in a humid climate typical of July in St. Louis is illustrated in Fig. 7. A .61 m packed bed was used, with the same 70 m^2 collector array, at a flow rate of 10 ℓ/s-m^2. The system can provide 10,500 W of refrigeration for 1.5 hours, from 11:30 a.m. to 1:00 p.m.

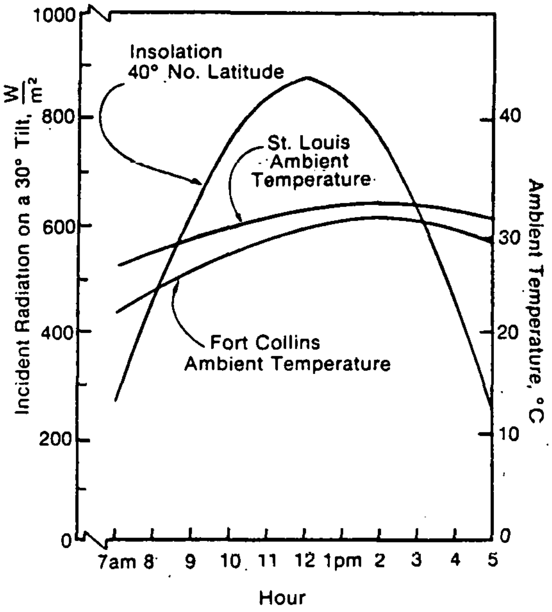

Fig. 5. Incident Solar Radiation and Ambient Temperatures, Clear July Day in Fort Collins and St. Louis

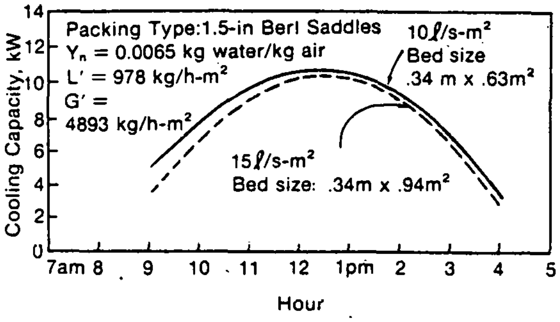

Fig. 6. Cooling Capacity for a Clear July Day in Ft. Collins

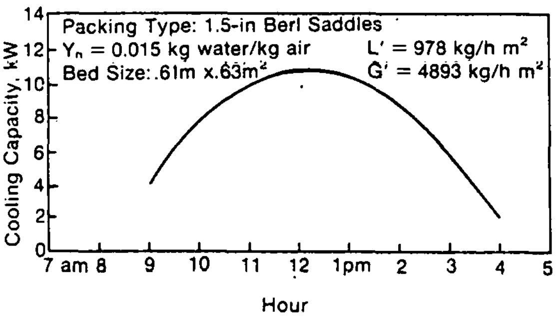

Fig. 7. Cooling Capacity for a Clear July Day in St. Louis.

7. CONCLUSIONS

The technical feasibility of an LiCl open-cycle absorption cooling system with a packed column for regeneration of the absorbent solution driven by solar-heated air has been predicted. Criteria for the design of a packed bed have been established, using a thermodynamic analysis to determine flow rate and concentration requirements. A steady-state performance model of the packed bed was developed that incorporates the simultaneous heat and mass transfer processes occurring throughout the bed. Using this model, requirements for the physical dimensions of a bed that can evaporate 15.2 kg of water per hour (and 10,550 W of cooling) subject to a range of air inlet temperatures and specific humidities were determined. Using air flow rates available from a 70 m^2 flat-plate collector array, it was found that the desired 10,500 W cooling capacity could be provided by a packed bed of .6 m or less. The range of inlet air temperatures for the desired cooling capacity was considered within the realm attainable by flat-plate collectors operating at flow rates of 10 and 15 ℓ/s-m^2.

Because the cooling ability of the system is a strong function of ambient humidity, it was of interest to model the performance in a location where summer humidity levels are fairly high (as they are in St. Louis), as well as in the relatively dry summer climate of Fort Collins. A 30% relative humidity (at 26.7°C) is typical of Fort Collins, while values of nearly 70% are common during a St. Louis summer.

The system was shown to be feasible in both summer climates. Acceptable performance was obtained for weather conditions typical of July in Fort Collins and in St. Louis. However, clear days were modeled for both locations, and less than adequate cooling would probably be available on a hot, cloudy day.

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