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Solar Assisted Open Cycle Absorption Cooling

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ABSTRACT

This paper presents a review of the research activities performed in the area of solar assisted open-cycle absorption cooling (SAOCAC). This method of cooling causes no environmental problems and has shown good potential for use in space cooling applications. The important variables affecting the performance of SAOCAC have been identified. The heat and mass transfer correlations for glazed and unglazed collectors/regenerators (C/Rs) have also been described. The performance of glazed and unglazed C/Rs operating under different meteorological conditions has been investigated. An unglazed C/R was found to perform better than a glazed C/R under arid weather conditions.

INTRODUCTION

Two issues, ozone depletion and the greenhouse effect, have created considerable public concern in recent years. The fully halogenated chlorofluorocarbons (CFCs), which have provided much needed refrigeration and air conditioning for about sixty years, are found to be among the gases responsible for the depletion of the ozone layer, and for creating global warming. According to the Montreal Protocol, these CFCs must be phased out by the year 2000. The search for new refrigerants and the adaptation of the existing machinery to the alternative refrigerants have created considerable research activities. Efforts have also been devoted to the development of alternative methods of refrigeration and air conditioning.

Solar energy is free and it produces no environmental pollution. The availability of this energy makes it, theoretically at least, highly attractive for use in space cooling applications. In an attempt to find a suitable solar system to produce cooling economically, a number of different approaches have been pursued by solar energy researchers. A great majority of these have dealt with the adaptation of absorption cooling systems, heat engines and dehumidification processes. Although technically these approaches were found feasible, economically they were not viable due, mainly, to initial costs and consumption of large quantities of electricity.

The open cycle absorption cooling system, where a liquid absorbent is exposed to the atmosphere through a glazed/unglazed solar collector for regeneration, is another approach which has stimulated considerable interest. This system uses solar energy to increase the concentration of a solution, acting as the absorbent, by evaporating a portion of the refrigerant, which is water. The increased concentration leads to a higher chemical potential, which enables it to drive a cooling process. The two significant barriers to the application of solar energy for cooling, i.e. high collector costs and large power requirements, have been addressed by the open cycle absorption cooling in a significant way.

This paper presents a brief review of research activities in the area of open-cycle absorption cooling using solar energy. The important variables, which affect the performance of the system, have been identified. Results of a parametric study of the important variables on a large prototype system operating under the arid meteorological conditions of Arizona, USA have also been included.

DEVELOPMENT OF OPEN-CYCLE A/C SYSTEM

Before a discussion of the open-cycle absorption cooling system, a brief description of the vapour compression cycle and closed cycle absorption system is included to provide a basis of comparison. Figure 1 shows the schematic diagram of a vapour compression cycle. The refrigerant vapour is compressed by the compressor and delivered to the condenser for condensation. This liquid passes from the high pressure side to the low pressure side through an expansion device. The evaporation of refrigerant takes place in the evaporator producing a cooling effect. Figure 2 shows the schematic diagram of a closed cycle absorption cooling system. The compressor of the vapour compression cycle has been replaced by four components, as shown in Fig. 2. The refrigerant vapour is absorbed in the absorber into a concentrated absorbent solution, commonly known as strong solution. This heat of absorption is removed from the absorber by external means. The diluted absorbent solution, known as weak solution, is pumped into the generator, where it is heated by means of a high temperature heat source. This heat in the generator evaporates the refrigerant in the weak solution producing a strong solution of absorbent. The refrigerant vapour is condensed in the condenser, passes through an expansion valve and evaporates in the evaporator, similar to the vapour compression cycle, creating the cooling effect. A pump requires less energy input than a compressor, which is an advantage.

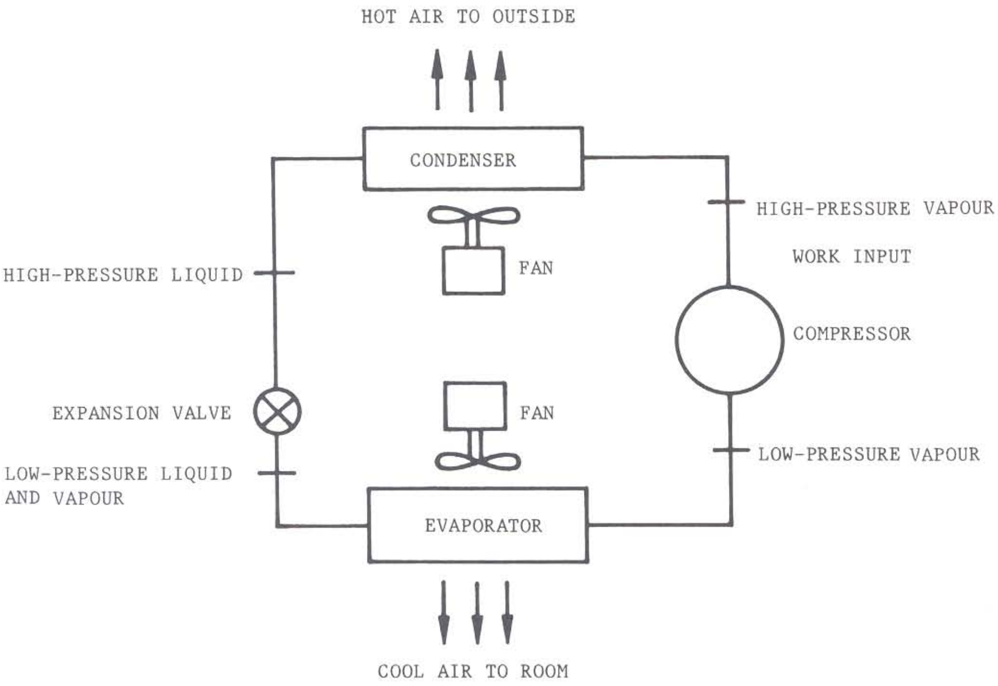

Fig. 1. Schematic diagram of a vapour compression air conditioning system.

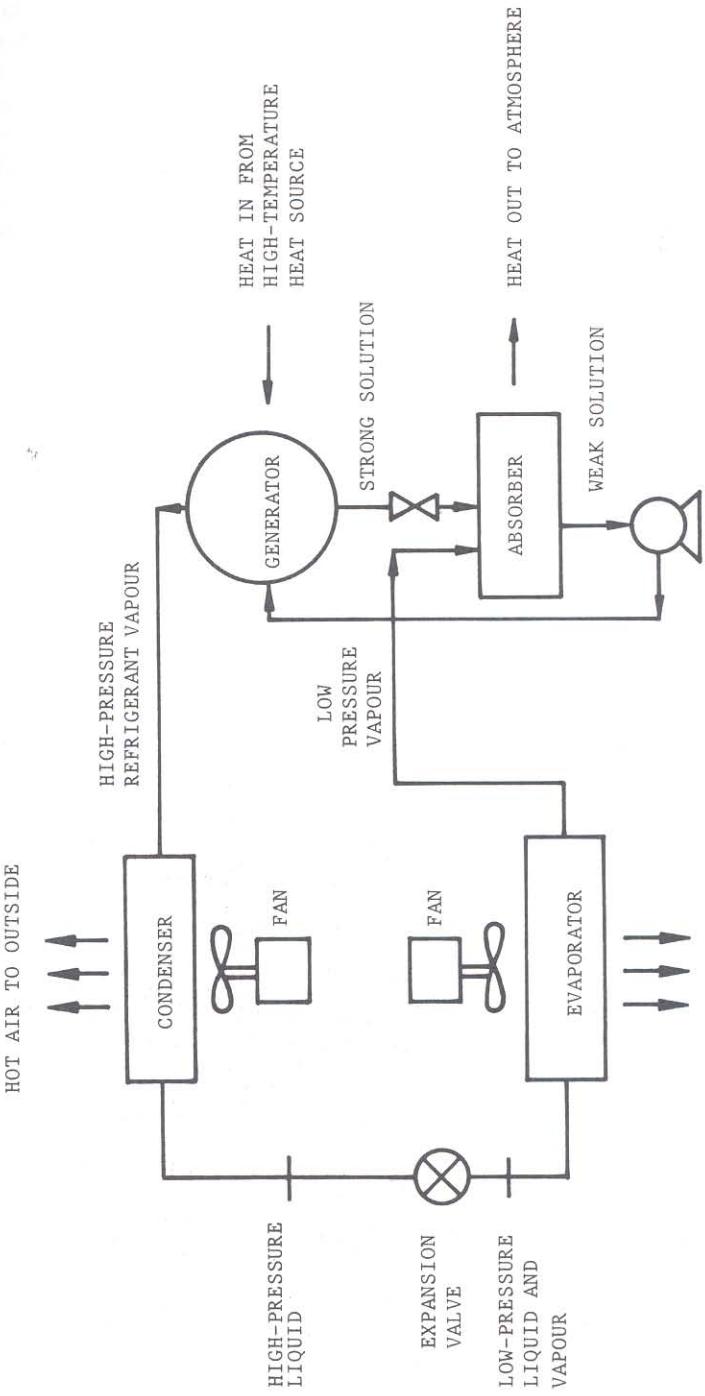

Fig. 2. A closed-cycle absorption cooling system.

Figure 3 shows the schematic diagram of an open-cycle absorption cooling system. The open-cycle absorption cooling system differs from the closed cycle system in that the weak absorbent solution is regenerated by evaporating refrigerant into the earth's atmosphere instead of to a condenser. Hence, the condenser is eliminated from the cycle. The collector becomes the regenerator and the generator of the closed cycle is eliminated. Similar to the closed cycle, the open-cycle requires a working fluid, which is a binary mixture of an absorbent and refrigerant. The refrigerant required for the open cycle is always water, which is continually replaced from an external source. The composition of the working fluid may vary from system to system. Lithium chloride-water, calcium chloride-water, lithium bromide-water, zinc chloride-water and mixtures of these are the likely candidates for the working fluid. Triethylene glycol-water and organic liquids may also be used as a working fluid.

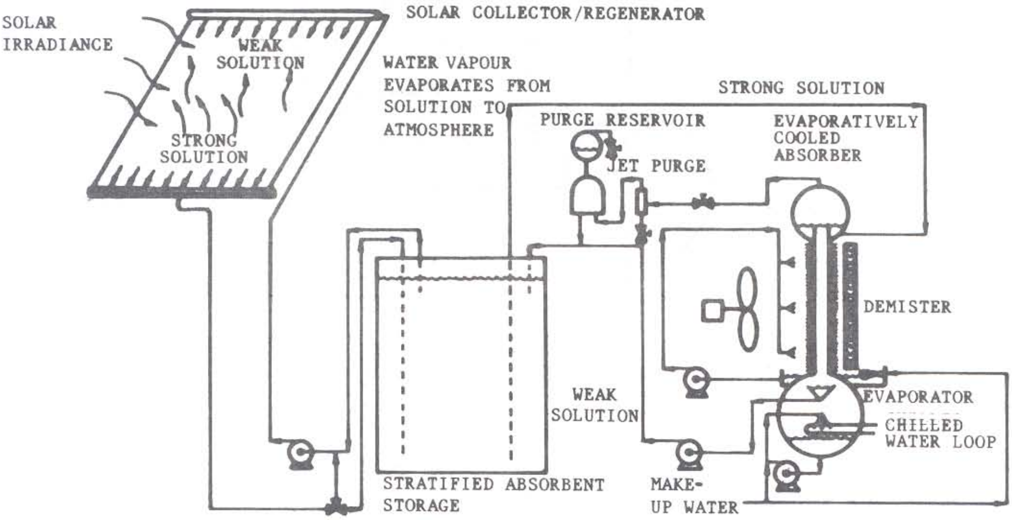

Fig. 3. A solar assisted open-cycle absorption cooling system.

A flat, tilted surface, which is black or painted black, and open to the atmosphere may act as a collector/regenerator (C/R). The working fluid flows as a thin film over the surface. The C/R may be glazed or unglazed and the air movement over the surface may be either in forced or free convection. The flow of the working fluid over the tilted C/R is caused by the gravitational forces and the water is evaporated mainly due to the addition of solar energy into the film of liquid. The C/R may be much simpler and cheaper than the conventional collector.

The regeneration of the solution takes place as a result of the evaporation and a strong solution leaves the bottom of the collector/regenerator. This strong solution is delivered to the absorber to absorb water vapour arriving from the evaporator. The evaporation of the refrigerant on the coils of a chilled water loop passing through the evaporator provides the cooling effect.

The chemical dehumidification cycle works in a manner similar to that' of absorption air conditioning, absorbing water vapour at a low temperature and releasing the water vapour at a higher temperature. The working substance used for the drying of a gas is usually called desiccant or sorbent and it can be either solid or liquid.

Selection of Working Fluid

Many organic and inorganic compounds with boiling points ranging between -50 and 100°C are considered to be eligible for refrigerant in a solar assisted absorption cooling system [25]. However, in the selection of a refrigerant, the criteria to be considered are toxicity, corrosivity and chemical stability [22]. The availability and cost should also be taken into account. For toxicity, a threshold limit value (TLV), which indicates the maximum amount of substance to which a healthy person can be exposed for 8 hours a day, five days per week without any danger to health, can be used as a good criterion.

For a measure of the corrosivity and chemical stability, the potential reactivity of these substances under typical operating conditions in the cycle should be known. The refrigerant considered unfavourable can be eliminated by following the criteria described here. For safety and economy, the pressure level in the system should be maintained slightly above ambient. To reduce pumping power, a refrigerant with high latent heat of vaporization per unit mass is normally chosen. Among the compounds, which qualify as refrigerants for closed cycle absorption cooling system, water and ammonia have high heats of evaporation and these two are most commonly used. For open cycle absorption cooling, water is commonly used as a refrigerant.

In order to select absorbents for open-cycle solar absorption cooling, toxicity, corrosivity, stability, boiling and melting points, and mutual solubility with the refrigerant should be considered as criteria [22]. The maximum allowable melting point of the absorbent depends on the possibility of the crystallization.

In the selection of a refrigerant-absorbent combination, the following characteristics should be considered [22]:

a) At the required temperature and pressure in the absorber, the equilibrium solubility should be high.
b) The absorption of refrigerant in the absorbent should be rapid.
c) The production of pure refrigerant vapour from the rich mixture of refrigerant-absorbent should be as simple as possible.
d) The absorbent is required to be either non-volatile or very much less volatile than the refrigerant.
e) Low viscosity of the solution.
f) Low freezing point of the liquid – lower than the lowest temperature in the system.

Ammonia-water and water-lithium bromide were preferred over other combinations for closed-cycle absorption cooling, the latter showing better coefficient of performance than the former [22, 23]. However, for open-cycle solar absorption cooling, water-lithium bromide has been in common use. The refrigerant-absorbent pairs, such as water-lithium chloride and water-calcium chloride have also been used by many researchers [4, 17, 24].

Comparative Description

The advantages and disadvantages of open-cycle absorption refrigeration systems are as follows [17]:

Advantages

1. The use of roof surface as the collector/regenerator considerably reduces the costs of the system.

2. The ambient water vapour pressures are much lower than those experienced in the generator and condenser of a closed-cycle absorption machine and, consequently, an efficient regeneration of the absorbent by evaporating water into the atmosphere can be achieved.
3. Lower temperature requirements in the generator make it an ideal application of solar energy.
4. It has low parasitic power requirements.
5. The storage in the form of chemical energy at ambient temperature and pressure avoids degradation in potential over long periods of time.
6. The open-cycle absorption refrigeration system shows the potential for application as a heat pump for summer cooling as well as winter heating, providing a better utilization of the system.

Disadvantages

1. The solution is susceptible to contamination by dust and airborne particles. It may also be diluted by rain.
2. A vacuum pump is required for the absorber to remove non-condensable gases, which are considered detrimental to the performance of the system.
3. The solution is considered corrosive in nature.
4. The losses of water at the C/R make the concept impracticable in areas where water is an expensive resource.

REVIEW OF RESEARCH PERFORMED

A description of the research work performed by various investigators on the solar assisted open-cycle absorption cooling system is included here. The solar assisted open-cycle absorption cooling system has two important components: the collector/regenerator and the absorber/evaporator. Some of the investigators dealt with the system, while the others studied only the collector/regenerator for the regeneration of absorbent solution.

Bjurstrom and Raldow [1] described the early history of the absorption process for heating, cooling and energy storage. Auh [2] conducted a survey on absorption cooling technology in solar applications and evaluated absorption refrigeration machines designed for use with solar energy. Although ammonia-water absorption chillers have found wider applications, the use of lithium bromide-water is gaining momentum due to the toxicity of ammonia. Lof [3] made an early proposal to use solar energy to regenerate an absorbent solution for use as a desiccant. A dehumidifier was proposed by Dunkle [29], and Close and Dunkle [30] to dry an air stream which was subsequently cooled to attain comfort condition with the use of evaporative cooling. Among the early investigators, Hollands [4] used a solar still for the regeneration of the lithium chloride solution.

The use of an open-cycle absorption cooling system with the regeneration of an absorbent solution on an inclined unglazed solar collector/regenerator was first proposed by Kakabaev and Khandurdyev [5]. They built a laboratory-scale model to provide for the cooling needs of two rooms in a laboratory and subsequently a large scale pilot plant was built to provide for the cooling needs of a three storey, nine unit apartment building [6, 7]. The absorbent solution used with this plant was lithium chloride. They monitored the plant for about four years and reported that it performed well. In an attempt to find a less expensive absorbent material, they used a mixture of calcium chloride and lithium chloride, which caused foaming. They studied the regeneration of an absorbent solution on the roof and the resultant reduction of heat flux through the roof [8]. Kakabaev et al. [9] investigated the use of a glazed collector/regenerator with forced convection between the glazing and collector/regenerator surface. The performance of a glazed regenerator was found better than an unglazed one under conditions of high humidity.

Collier [10] performed an investigation, which was similar to that of Kakabaev and Khandurdyev [5], to determine the mass transfer from an absorbent solution in an open flow unglazed collector/regenerator. The cooling capacity of the system was determined by the amount of water evaporated from the absorbent solution. This analysis used meteorological data from five cities with the available correlations for heat transfer coefficients for a horizontal flat plate. These results showed good potential and subsequently further studies were initiated at the Arizona State University in Tempe, Arizona [11], and Research and Engineering Center of Lockheed Missiles and Space Company, Huntsville, Alabama [12]. Schlepp and Collier [13] studied the use of collector/regenerator for heating as well as cooling purposes.

The contamination of the absorbent solution by rain water and pollen was experienced by the Lockheed group and they glazed their collector/regenerator in a follow up study [14]. The top and bottom of the collector/regenerator were open to facilitate the flow of ambient air and an air gap of 15 centimeters was provided between the liquid absorbent surface and the glazing.

Chen [15], and Chen and Wood [16] continued their work at the Arizona State University and simulated the collector/regenerator process in greater detail taking into account the local meteorological conditions. Novak [17] carried out experiments on an unglazed collector/regenerator and derived empirical correlations for heat and mass transfer coefficients. Nelson [18] made a comparative study of the performance of an unglazed and glazed collector/regenerator. The glazed collector showed an improved performance compared to an unglazed collector/regenerator when the ambient humidity was higher. The experimental results on a glazed and an unglazed collector/regenerator, as reported by Hawlader et al. [19], failed to achieve this improved performance, which perhaps could be attributed to the design of the collector/regenerator.

Lenz et al. [20] studied an open-cycle absorber/evaporator and noticed a reduction of mass transfer in the absorber due to the presence of non-condensable gases. Yang [21] also discovered similar effects when performing experiments with an open-cycle absorber/evaporator.

One of the most important components of an open-cycle absorption cooling system is the collector/regenerator(C/R). The performance of the system depends to a great extent on the performance of the C/R. The regeneration of the absorbent solution by evaporating a portion of the refrigerant, which is water mainly in this case, is an important aspect of the cycle. The amount of water removed at the C/R from the refrigerant-absorbent solution determines the cooling capacity of the system. The influence of different variables affecting the performance of the C/R is described in the next section.

COLLECTOR/REGENERATOR PERFORMANCE

The performance of the C/R has been studied by many researchers [17-19, 26, 31]. In the simulation of performance, Collier [26] used existing heat and mass transfer correlations, which were found to describe actual conditions of the C/R inadequately. Mullick and Gupta [32] reported the results of an early investigation on the efficiency of solar regeneration. These results, as shown in Fig. 4, were also compared with those reported by Hollands [4] and considerable improvements were achieved by Mullick and Gupta [32]. An extensive experimental programme [17, 27] was undertaken at the Center for Energy Systems Research, Arizona State University. Table 1 shows the typical meteorological conditions under which experiments were conducted. These studies led to the formulation of the following correlations for heat and mass transfer, and the efficiency of the C/R for

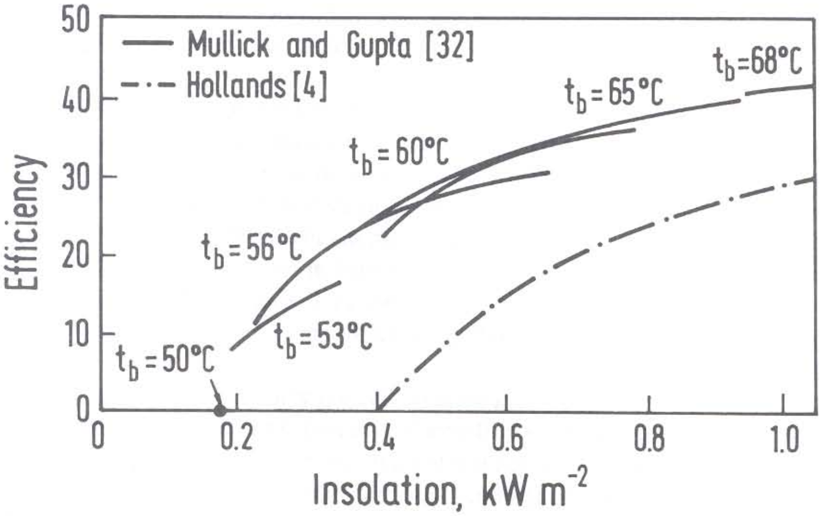

Fig. 4. Efficiency of solar desorber.

Table 1. Meteorological data of Arizona, USA for the year 1990 [28].

Latitude: 33°19.5' N, Longitude: 111° 38' W, Elevation: 425 m

Month	Daily Av. Temp. °C	Relative Humidity Average %		Wind Speed m/s	Radiation MJ/m² day
		Maximum	Minimum		
January	10.6	85	29	1.34	12.44
February	11.7	89	32	1.34	15.08
March	17.2	64	21	1.79	18.73
April	22.2	53	18	2.23	24.76
May	25.6	33	11	2.23	29.29
June	32.8	30	10	2.23	30.25
July	32.2	62	27	2.68	26.10
August	30.6	65	27	2.23	24.59
September	29.4	74	30	1.79	20.74
October	23.9	42	17	1.34	18.10
November	16.7	72	24	1.34	13.11
December	10.0	83	34	1.34	10.13

both glazed and unglazed conditions [27]. These correlations are useful for the prediction of heat and mass transfer from the regenerator.

For an unglazed C/R:

$$\begin{aligned} Nu_L &= 10^{-27.32}\ Re_L^{0.302}\ Gr_L^{*1.611}\ N^{*-1.312} \\ Sh_L &= 10^{22.54}\ Re_L^{0.057}\ Gr_L^{-1.616}\ N^{-0.799} \\ \eta &= 10^{-2.347}\ Re_L^{-0.057}\ Gr_L^{*0.255}\ N^{*1.027} \end{aligned}$$

For a glazed C/R:

$$\begin{aligned} Nu_b &= 10^{-8.502}\ Re_L^{0.032}\ Z^{*-31.52}\ Ra_b^{*0.224} \\ Sh_b &= 10^{0.157}\ Re_L^{-4.439E-3}\ Z^{-2.615}\ Ra_b^{0.283} \\ \eta &= 10^{8.203}\ Z^{*30.27}\ Ra_b^{*-1.501E-3} \end{aligned}$$

The regeneration efficiency, η , is defined as the ratio of the energy required to evaporate water from the absorbent solution to the solar energy incident on the C/R minus the sensible heat gain of the solution. For the unglazed C/R, an average value of 0.466 was obtained for conditions described in reference [19, 27]. For the glazed C/R, operating under similar environmental conditions, an average efficiency of 0.39 was obtained [19, 27]. Similar results were obtained by Mullick and Gupta [32] with $CaCl_2$ solution. The efficiency values reported by Hollands [4] with LiCl solution in a solar still were considerably lower.

Novak [17], Stack and Wood [27], and Hawlader et al. [19] reported the results of a simulation study, which was conducted to identify the important variables affecting the rate of evaporation from the C/R. The variables considered in these studies were as follows:

i) ambient temperature and humidity ratio;
ii) inlet solution temperature, concentration and flow rate;
iii) solar irradiance;
iv) wind velocity; and
v) collector geometry (length, width and glazing height).

The results presented here are based on those reported by Stack and Wood [27], where two collectors/generators, one glazed and the other unglazed, were tested under identical environmental conditions. The experiment was performed in Tempe, Arizona, where very low relative humidity and high solar irradiation were considered to be the main features of the meteorological conditions, as shown in Table 1. The working fluids were water (the refrigerant) and lithium chloride (the absorbent).

For the unglazed collector, Fig. 5(a) shows greater change in the evaporation rate with the variation of ambient temperature. With the increase in ambient temperature, the evaporation rate for the glazed collector went through a maximum and then declined. When the ambient temperature increased, the driving potential for heat transfer decreased and the solution temperature rose since less energy was lost to the surroundings. The warmer fluid had a higher driving potential for mass transfer, leading to an increase in evaporation rate with the increase in ambient temperature. For the glazed C/R, the buoyancy driven internal flow decreased due to a reduction in heat transfer from the solution to the ambient air. As a result, evaporation rate increases with temperature, passes through a maximum and then declines.

The evaporation rate was affected by the changes in humidity ratio, as shown in Fig. 5(b). The unglazed and glazed collectors/regenerators responded similarly to increases in ambient humidity ratio, the glazed C/R showing less sensitivity. The driving potential for mass transfer decreased with the increase in humidity ratio and the solution left the C/R with greater amount of sensible heat due to the available solar irradiation.

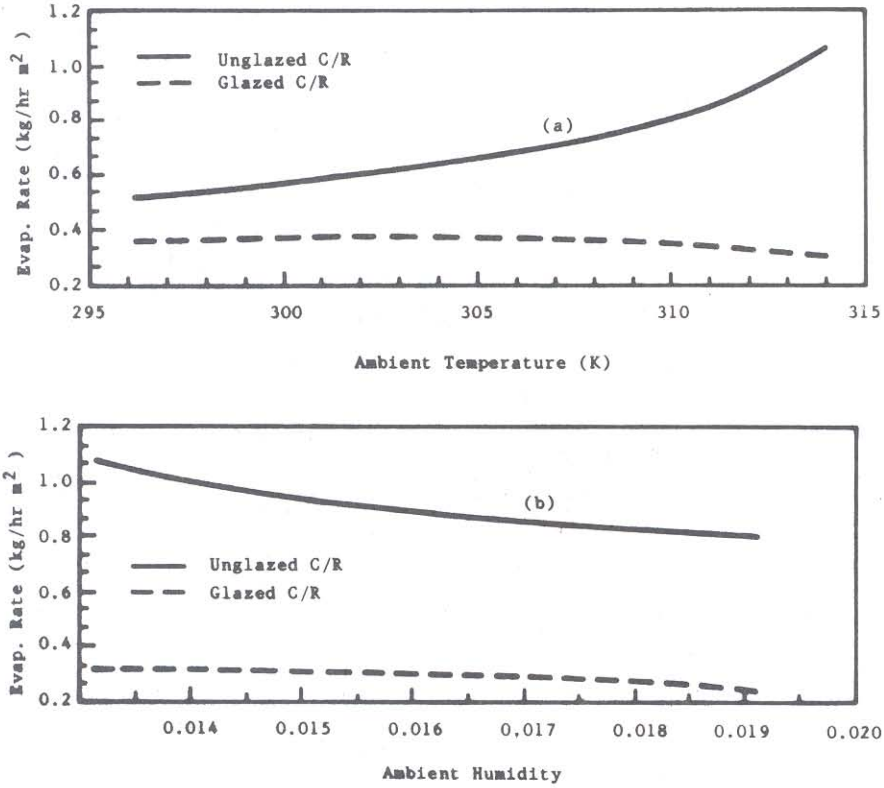

Fig. 5. Variation of evaporation rate with (a) ambient temperature (b) ambient humidity.

A warmer solution at inlet to the C/R had greater driving potential for heat and mass transfer producing an increased evaporation rate for glazed C/R and a mixed effect for unglazed C/R, as shown in Fig. 6(a). The evaporation rate for the unglazed C/R went through a maximum and then declined with the increase in solution temperature. The concentration of solution at inlet had a similar effect on the evaporation rate as that of ambient humidity. As shown in Fig. 6(b), the evaporation rate for the glazed C/R was much less sensitive to the concentration of solution at inlet. The vapour pressure decreases with the increase of concentration of the solution of lithium chloride. This lead to a decrease in driving potential and, consequently, a decrease in evaporation rate for the unglazed C/R. For glazed and unglazed C/Rs, the mass flow rate affected the evaporation rate differently, as shown in Fig. 6(c). The evaporation rate for the unglazed C/R increased with the increase in flow rate, whereas for the glazed C/R, it decreased. The change in solution concentration decreased with the increase in flow rate resulting in an overall increase in evaporation rate for the unglazed C/R. The changes in outlet temperature and concentration were less dramatic than the unglazed C/R, and there was slow decline in evaporation rate for the glazed C/R.

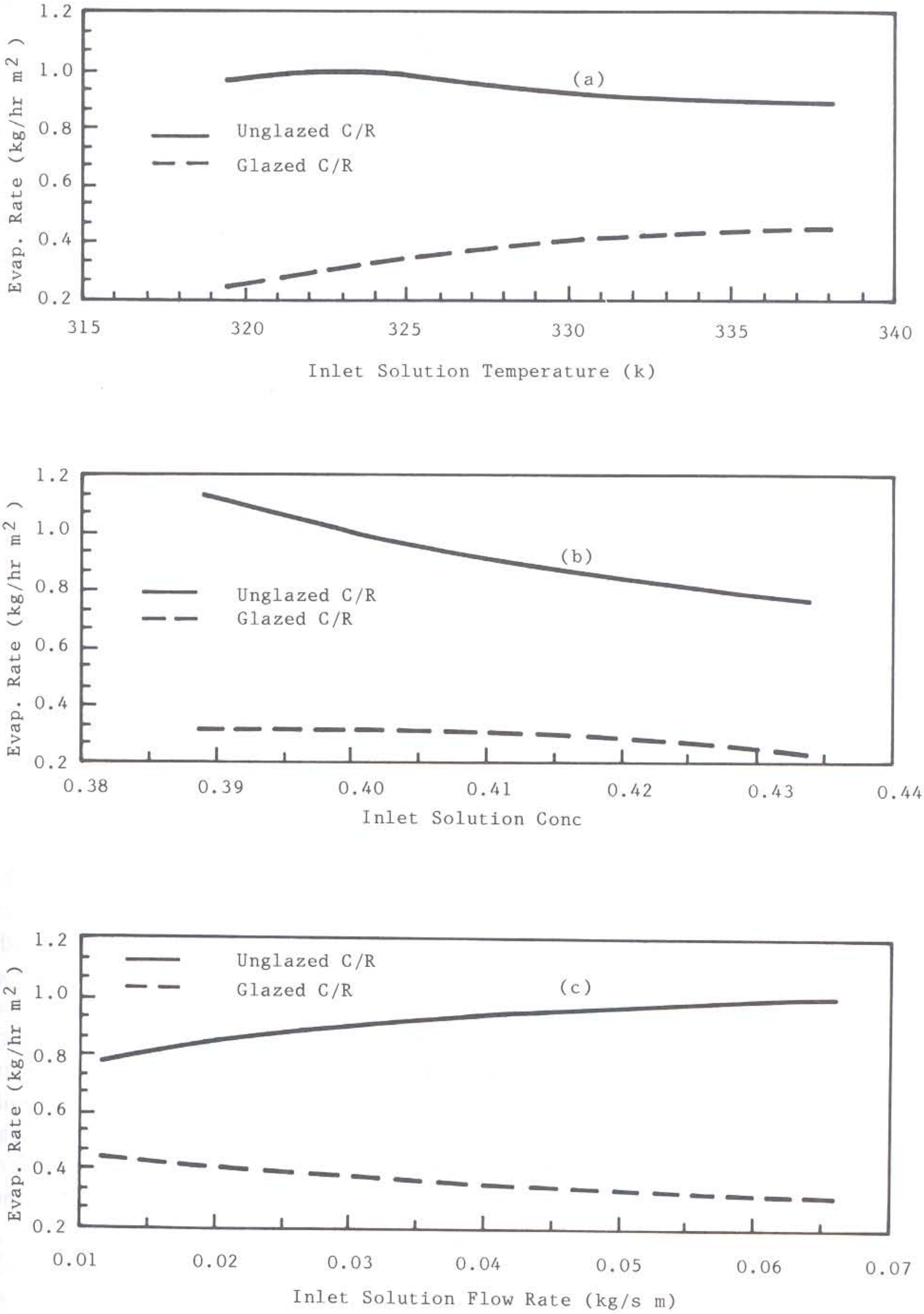

Fig. 6. Variation of evaporation rate with changes in (a) inlet solution temperature, (b) inlet solution concentration, and (c) inlet solution flow rate.

Figure 7 shows the effects of solar irradiation on evaporation rate for glazed and unglazed collectors/regenerators. For the glazed C/R, the evaporation rate increases almost linearly with the increase in solar irradiance. The evaporation rate for the unglazed C/R went through a maximum and then declined. Increased evaporation rate for the unglazed C/R led to a lower temperature and higher concentration, which might have contributed to a decline in evaporation rate for further increase in irradiation. For the meteorological conditions, the absorbent solution for the glazed C/R left the C/R at higher temperature and at a lower concentration than the unglazed C/R. This could be attributed to the nature of the design of the glazing, where air enters the C/R at the inlet and travels a long distance before it reaches the outlet. The air becomes fully laden with water vapour within a short distance from the inlet and, thereafter, it travels the remaining path without absorbing additional water vapour.

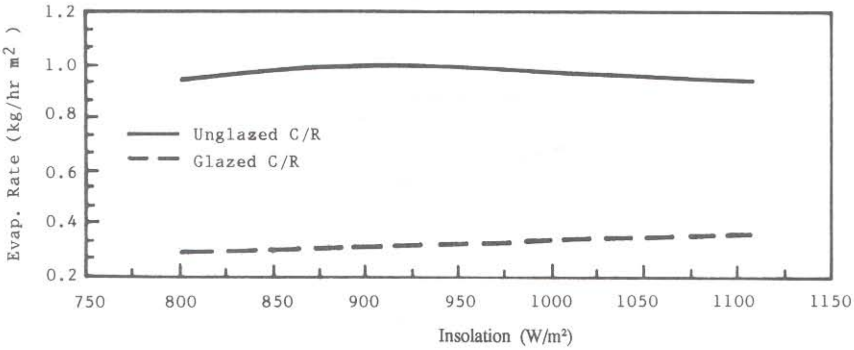

Fig. 7. The influence of solar irradiation on evaporation rate.

Figure 8 shows the effects of wind speed on the evaporation rate. The performance of the glazed C/R was essentially unaffected by the wind speed. The evaporation rate for the unglazed C/R increased slightly with the increase in wind speed. The heat and mass transfer coefficients increased due to a thinner boundary layer at higher wind speed. Increase in heat transfer reduces solution temperature causing a reduction in mass transfer and an increase in mass transfer also reduces solution temperature causing a reduction in heat transfer. In these two opposing forces, the mass transfer effects dominate.

The effects of aspect ratio, the ratio of height to C/R length, on the performance of glazed C/R are shown in Fig. 9. The evaporation rate for the unglazed C/R is included for comparison only. The evaporation rate increased slightly with the increase in plate height. Nelson [18] predicted a better performance of glazed C/R than the unglazed one. However, this study indicates a better performance for unglazed C/R than the glazed C/R under the meteorological conditions of Arizona, where the relative humidity is very low.

CONCLUSIONS

The research and development activities in the area of SAOCAC have been reviewed showing the current state-of-the-art. The open-cycle absorption cooling shows good potential and is considered to be environment friendly.

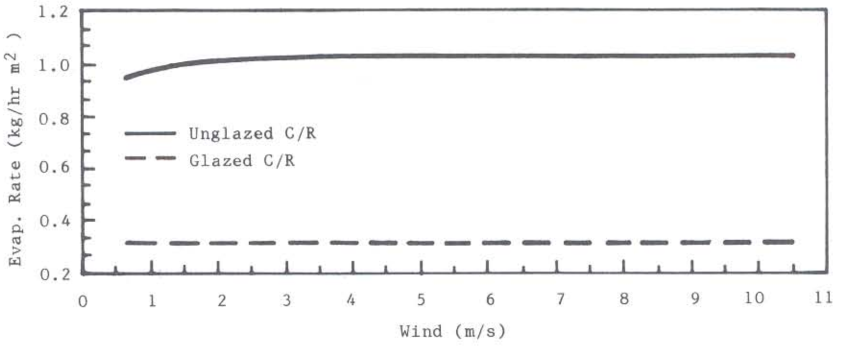

Fig. 8. The effect of wind on the rate of evaporation.

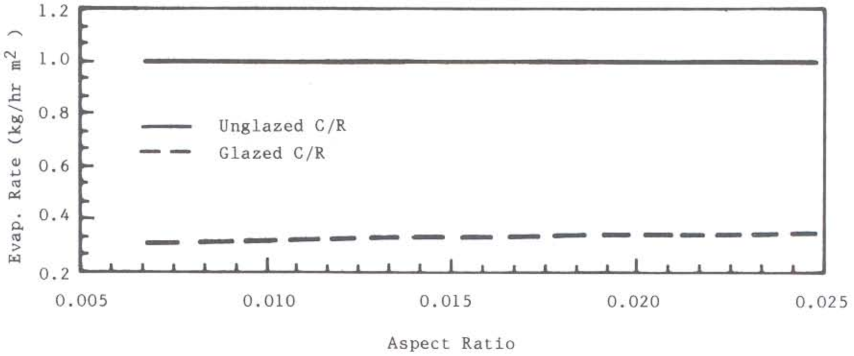

Fig. 9. Effects of glazing height on the rate of evaporation.

The performance of SAOCAC has been studied by many investigators and the important variables that influence the performance of regenerators have been identified. Although the simulation study indicates a better performance for glazed regenerators, experimental results consistently show a better performance for unglazed regenerators operating under arid weather conditions.

NOMENCLATURE

b	Glazed C/R channel height (m)
L	Characteristic length of C/R (m)
Gr	Grashof number
N	Ratio of mass to heat transfer Grashof Numbers
Nu	Nusselt number
Ra	Rayleigh number
Sh	Sherwood number
Z	Scaling factor
*	based on uniform heat and mass flux boundary condition

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