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Solar Cooling Technologies: Current Status and Recent Developments

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Abstract

The energy demand for air-conditioning has increased continuously throughout the last decades especially in developed countries. This increase is responsible for a large rise of the electricity demand and a sharp increase in peak demand due to the use of electrically driven vapour compression machines. The substitution by thermally driven cooling systems using renewable energy or waste heat is a promising alternative to save fossil fuel and reduce greenhouse gas emissions. The paper presents the available options for solar cooling. A review of the current status is given as well as examples and recent developments and pilot plants .A system, being developed at the Sustainable Energy Centre of the University of South Australia, is also presented.

1. INTRODUCTION

The energy demand for air-conditioning to control temperature and humidity and for the provision of fresh air has increased continuously throughout the last decades especially in developed countries. This increase is caused amongst other reasons by increased thermal loads, occupant comfort demands, and architectural trends. This has been responsible for the escalation of electricity demand and especially for the high peak loads due to the use of electrically driven vapor compression machines. The provision of reliable supply to meet this demand requires huge electrical generation, transmission and distribution infrastructure. Additionally, the consumption of primary energy and the emissions of greenhouse gases associated with electricity generation from fossil fuels lead to considerable environmental consequences and monitory costs.

In order to reduce the electricity consumption, the substitution of vapor compression machines by thermally driven cooling systems using renewable energy or waste heat is a promising alternative. The utilisation of solar energy for space cooling captured the imagination of many pioneering workers in solar energy (eg. Sheridan, 1972, Ward et al, 1976, Conway and Löf, 1978) as the demand for comfort cooling is generally in phase with solar energy availability. However, solar cooling is one of the more complex solar applications. A considerable number of solar cooling demonstrations built in the nineteen seventies and eighties suffered from serious problems, mainly due to low net conventional energy savings or maintenance requirements. In this case it is not sufficient to collect heat, store and distribute it. The energy must be used to generate cold air or chilled water by means of a device capable of absorbing heat at low temperature from a conditioned space, and rejecting it into the higher temperature of the outside air with an acceptable coefficient of performance.

According to Figure 1, thermally driven cooling principles can be divided into thermo-mechanical systems and systems using heat transformation. For the latter, closed cycle systems produce chilled water, and open cycle systems directly treat the air, which is entering or leaving the building. Both system types can either be operated with solid or with liquid sorbents. The systems underlined in Figure 1 are already market available and suitable for use with solar thermal energy, e.g. desiccant wheel systems for open cycles or absorption machines for closed cycles, whereas systems written in italics are still in the phase of research and development, e.g., liquid desiccant systems and fixed bed sorption systems.

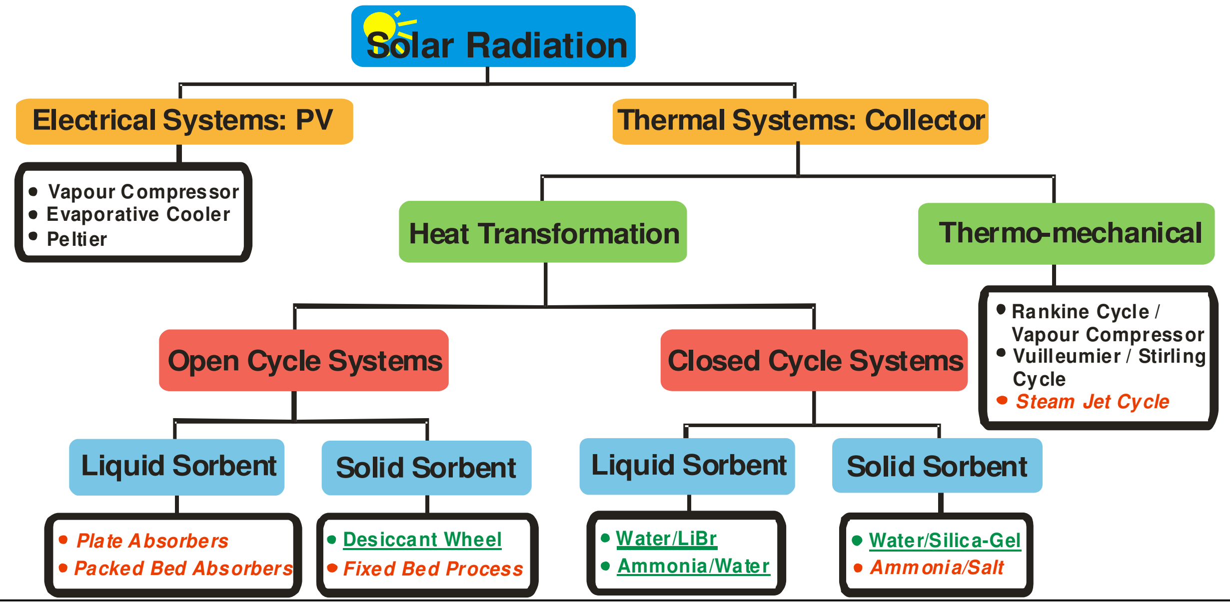


Figure 1: Classification of solar cooling technologies. Underlined systems are market available and suitable for the use with solar collectors, systems in italics are still in the R&D phase.

However, the intention of including solar energy into the cooling cycle requires new system concepts and cooling machines with high coefficients of performance and low driving temperatures. When solar energy is also used for hot water and space heating, the whole system becomes very complex. Consequently, no system suitable for a single family house has been introduced to the market so far. Thus, the main research effort in these areas is focusing on the reduction of investment costs and system sizing.

From the thermo-mechanical systems, the steam jet cycle represents a practical opportunity for solar air-conditioning as it requires temperatures of about 200℃, which can be reached by concentrating collectors like parabolic troughs. Beside the thermally driven systems, the direct coupling of a conventional cooling system with photovoltaic panels seems an additional solution for applying solar energy to space cooling. As evaporative cooling requires considerably less energy than vapour compression systems, it is more practical to use in areas where water is available. However, since it is more convenient to deliver photovoltaic electricity to the grid without any need for storage devices, this possibility seems to be realistic only for rural applications.

This paper will focus on systems which are classified under “Heat transformation”. The overview also contains recent research activities, and demonstration units of solar cooling technologies including their performance behavior, advantages and disadvantages. The available alternatives aim to provide thermal comfort in both hot dry and hot humid climates by using solar energy. The paper will also describe the liquid desiccant system being developed at the University of South Australia and current collaborative activities in its development.

A detailed description of the different cooling concepts, the requirements for the solar collector field and the interaction with the building load can be found in (Henning, 2003). A comprehensive list of installed solar assisted air-conditioning systems in Europe can be found in (SACE, 2003).

2. CLOSED CYCLE ABSORPTION SYSTEMS

Figure 2 shows a schematic of a single effect absorption chiller. Solar energy is used in the desorber (4) to drive a refrigerant out of a solution at a high temperature and pressure. The refrigerant vapour is condensed (3) afterwards using cooling water and evaporated (2) again, brought to a low pressure level. Thus, chilled water to drive the air-conditioning process can be produced in this evaporator. Afterwards, the refrigerant vapour is delivered back to the solution in the absorber (2), where it condenses again.

For such a process, a combination of water and Lithium-Bromide has been widely used since the 1950's (Herold et al, 1996). As water is used as the refrigerant, the system is limited to refrigeration temperatures above 0°C. If temperatures below 4°C are required, absorption systems utilizing Ammonia/water as the working pairs with Ammonia as the refrigerant can be used. Thermal coefficients of performance (COPs) of single effect systems are typically between 0.7 and 0.8.

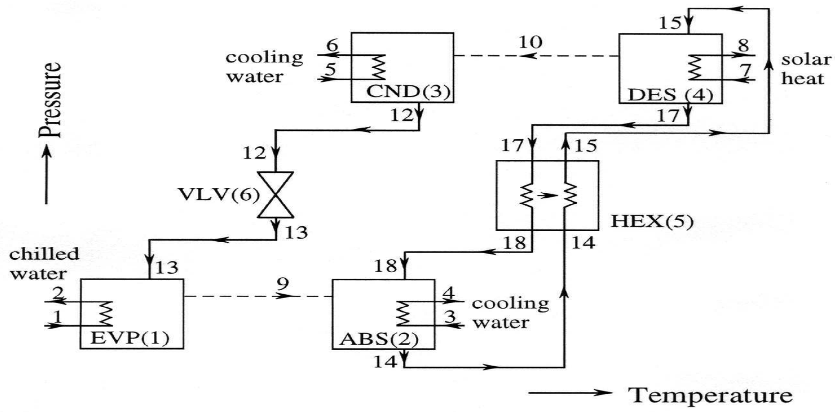


Figure 2: Single effect solar absorption systems.

The nineteen seventies and eighties saw a number of solar absorption cooling demonstration systems in operation in many parts of the world. The systems generally used flat plate collectors with selective surfaces or evacuated tube collectors to produce hot water at 70 to 85°C. The hot water was used to fire water/ Lithium Bromide absorption chillers, with natural gas or kerosene used as auxiliary sources for heating the water. A number of these systems were monitored. The monitoring results demonstrated varying degrees of success in saving energy. In the light of experience gained in the operation of a number of these systems, the main drawbacks in their performance is summarised as follows (Saman, 1995):

- High system cost, particularly of the solar collection systems.
- Lower solar contribution than generally expected due to system losses.
- Lower system COP mainly due to the unsteady operation.

Absorption cooling technology has recently experienced a resurgence of interest in a number of countries around the world. This has been mainly due to the high electricity costs at peak demand periods and partly due to the growing awareness of global warming. The gas companies have been active in marketing gas-powered absorption cooling systems in large buildings and other applications.

The relatively low COP of single effect absorption systems and corresponding need for large collector areas may be improved by using the double and triple effect chillers. A single stage absorption system is not suited to utilise a heat source at a temperature higher than 100°C. To take advantage of a higher temperature heat source, absorption systems must be configured in stages. The principle of operation is to utilise the heat rejected from the absorber to power additional desorbers, thereby approximately doubling or tripling the amount of refrigerant extracted from the solution with no extra heat input.

Developments in gas fired absorption systems in recent years, mainly in the USA and Japan, have made double effect chillers available on the market with COP in the range 1.0 to 1.2 with supply temperatures of around 150°C. Triple effect systems, with a COP of around 1.7 have also been developed. These require heat supply temperatures of about 200°C. Although these systems have been developed for use with gas as a fuel; they can be adapted for use with high temperature solar collectors. However, overall costs of such systems remain uncompetitive in comparison with current electricity and gas tariffs (Grossman, 1999).

Figure 3 shows a design of a recently developed absorption chiller with a small capacity. Table 1 lists some manufacturers of absorption cooling machines suitable for solar assisted air-conditioning.

Figure 3: Small size single effect absorption cooling machine, developed by the Company EAW and the ILK Dresden, Germany (Safarik, 2003). The specifications are: 15 kW cooling power, driving temperature 85°C, COP>0.75.

Manufacturer	Cooling load, type
Broad Air	20 kW LiBr/H_20 single and double effect
Colibri/Stork	100 kW NH_3/H_2O single effect
EAW	15 kW LiBr/H_20 single effect
Robur Corporation	17 kW- 88 kW LiBr/H_20 single effect
Yazaki	35 kW LiBr/H_20 single effect
York	420 kW LiBr/H_20 double effect

Table 1: Examples of commercially available absorption chillers.

In addition to developing more efficient multi effect absorption chillers, current research is mainly focusing on the development of cost-effective absorption chillers with low capacities down to 10 kW and high COPs even at part load, cf. (Storkenmaier, 2003) and (Afonso, 2003).

3. CLOSED CYCLE ADSORPTION SYSTEMS

Instead of absorbing a liquid refrigerant with a solution, the refrigerant can also be adsorbed to a highly porous solid. Different working pairs are suitable with these adsorption systems: water/silica gel, water/zeloite, ammonia/activated carbon, etc.(Critoph, 2003). Figure 4 shows a schematic of an adsorption chiller. The refrigerant, e.g. water, which was previously absorbed in one chamber, is driven out of its porous solid using solar energy. Using cooling water, the refrigerant is condensed at the top of the machine. Under low pressure, the condensate is sprayed into the evaporator and evaporates again producing the chilled water to drive the air-conditioning process. Afterwards, the vapor is absorbed in the second chamber in a water cooled process. In order to guarantee a continuous operation of the adsorption machine, the functions of the chambers are changed after all refrigerant has been transported from one chamber to the other.

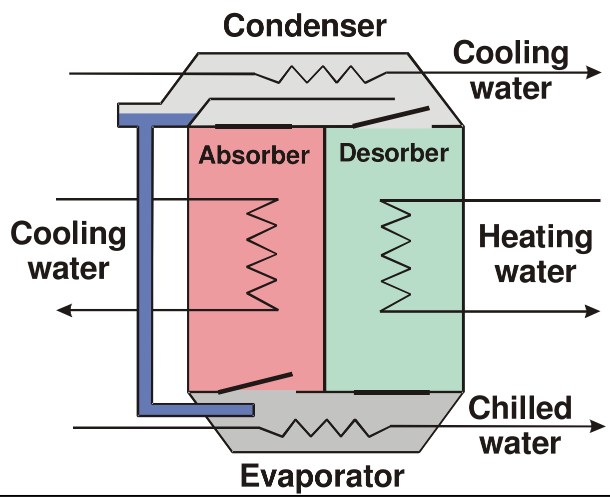


Figure 4: Schematic of an adsorption chiller. In order to enable a quasi continuous operation, two similar chambers filled with adsorption material are necessary. At the working state shown in the schematic, the left compartment is used as the absorber, the right side as the desorber. After one cycle, the functions of the chambers are switched.

Adsorption chillers can operate from a heat source at temperatures as low as 55°C and reach at those temperatures higher COPs than absorption systems. However, at higher driving temperatures, the COPs are lower than those of multi stage absorption chillers. Adsorption systems are only available from a few manufactures. All commercially available systems utilise water and slica gel as the working pairs, Figure 5 shows a picture of a system installed at a hospital in Germany. The largest solar cooling installation in Europe (2700 m² flat plate collectors) uses two adsorption machines with a total cooling power of 700 kW is located in Greece (Henning, 2003).

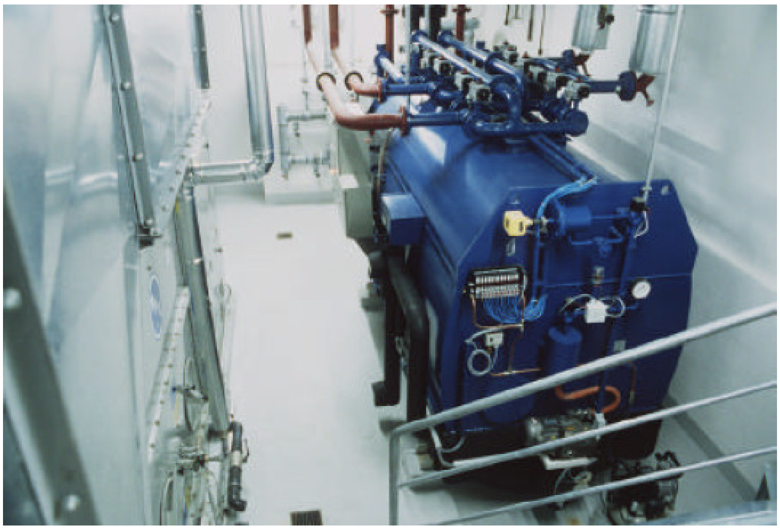


Figure 5: Mycom adsorption chiller with a cooling capacity of 70 kW, installed at a hospital in Germany.

Table 2 lists some manufacturers of adsorption machines, which have been introduced to the market. However, especially small scale adsorption chillers are more expensive than absorption machines.

Manufacturer	Cooling load, type
Mycom	70 kW H_20/silica gel
Nishiyodo	105 kW H_20/silica gel
Takeshima	176 kW H_20/silica gel

Table 2: Examples of commercially available adsorption chillers.

4. OPEN CYCLE DESICCANT SYSTEMS

Desiccant systems are essentially open sorption cycles, utilising water as the refrigerant in direct contact with air. The desiccant (sorbent) can be either solid or liquid and is used to facilitate the exchange of sensible and latent heat of the conditioned air stream. The term “open” is used to indicate that the refrigerant is discarded from the system after providing the cooling effect and new refrigerant is supplied in its place in an open-ended loop. In both types of systems the process air is treated in a dehumidifier and goes through several additional stages before being supplied to the conditioned space. The desiccant is regenerated with ambient or exhaust air heated to the required temperature by the solar heat source.

Desiccants have been used for many years to control humidity in process industries where high or varying humidity levels are detrimental to the manufactured product. The basic technology for both solid and liquid desiccants has been well proven over many years and is now available for incorporation into air conditioning systems. Humidity control can be achieved by using desiccant dehumidification to remove the moisture and then cooling, if required, to attain a suitable supply temperature.

Desiccant systems possess several advantages relative to their closed-cycle counterparts: They operate at ambient pressure, and not in a vacuum or at an elevated pressure; heat and mass transfer between the air and the desiccant take place in direct contact; both cooling and dehumidification of the conditioned air may be provided, in variable quantities, to fit the load in the conditioned space. Disadvantages are the low COP, due to inherently inefficient regeneration; relatively large air volumes must be pumped, leading to potentially high parasitic losses; contamination of the desiccant by dirt and dust contained in the air may require its replacement after some period of operation.

This technology is now being applied in buildings and spaces where humidity levels are critical such as supermarket frozen and cold food areas, hospital operating theatres, nursing homes, schools, hotels, convention centres and theatres. The technology is also applicable to buildings requiring a high fresh air intake in humid climate zones.

Removing moisture from the air can be a substantial part of the work performed by any cooling system. Condensing moisture from the air by chilling is relatively expensive and inefficient compared with using desiccant materials that soak up humidity and release the water vapour when subjected to heat.

4.1. Solid Sorbents

In solid desiccant systems, the desiccant is commonly deposited onto a ‘honeycomb’ wheel that is rotated between two air streams. One half of the wheel dries an indoor supply air stream and the other gives up moisture to the exhaust air. With an efficient desiccant, super-dried air can be cooled by evaporative cooling or other means. Separate controls for cooling and dehumidification can improve comfort and may reduce energy costs substantially. Alternatively, the sensible heat is removed using an external mechanical chiller, an absorption system, or indirect/direct evaporative cooling.

Gas fired solid desiccant dehumidification systems are now being specified into many supermarkets, ice arenas, and cold warehouses in the USA. Their cost effectiveness is due to the economic benefits from improved refrigeration processes resulting from the introduction of drier air. Desiccant dehumidification is also being used to solve indoor air quality. Minimum ventilation air requirements have increased significantly in response to the sick building syndrome. So air handling systems in many building types today are processing large percentages of outside air. These moisture laden outside air streams are requiring new equipment solutions, like desiccant dehumidification, to properly control humidity indoors (Kosar and Witte, 1998).

Figure 6 shows a typical arrangement for adding a solid desiccant system to conventional air conditioning systems for dehumidifying the required outdoor air. Ambient air is entering the unit from the left side. After drying (and heating) in the desiccant wheel, the air is cooled by the heat recovery wheel. Before entering, a direct evaporative cooler produces the required indoor conditions. The return air is in the first stage directly evaporatively cooled in order to cool the fresh air in the heat recovery wheel. Afterwards, the preheated air (in the heat recovery wheel) is heated by the heating coil, using solar energy, thus enabling the drying of the desiccant wheel. In addition to a multitude of installed systems, a thermally solar autonomous air conditioning system using desiccant wheels has been recently installed and monitored at an office building in Germany (Schnabel, 2003).

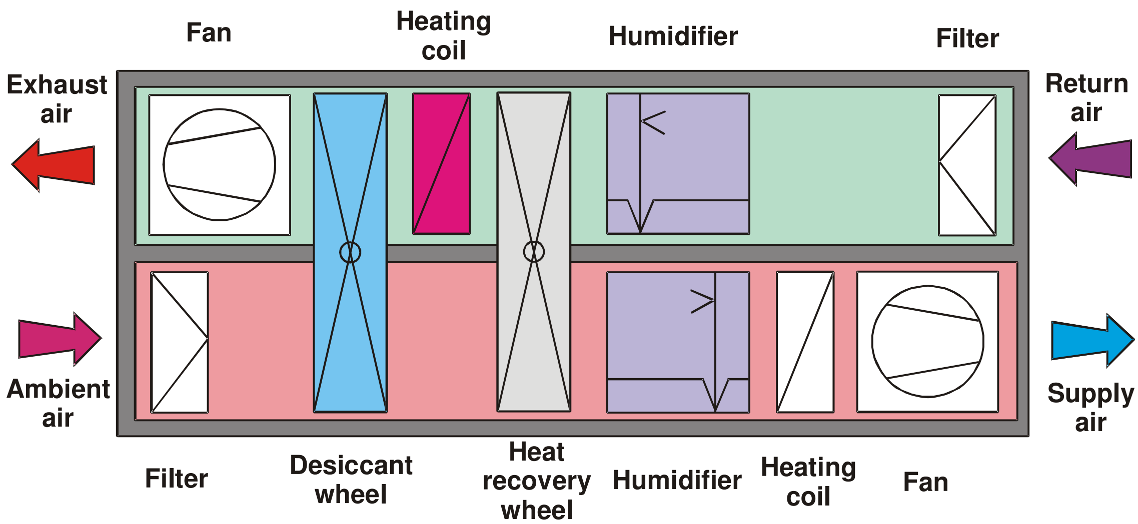


Figure 6: Desiccant heating and cooling unit using an open cycle systems.

However, one main drawback of these systems is that the desiccant wheel comes in direct contact with both the supply and the exhaust air streams. This may lead to hygienic problems, since with the supply of fresh air and the disposal of the exhaust air, hazardous particles may still remain in the system and thus in the building. A new approach, followed by the Fraunhofer Institute in Freiburg (Germany), uses solid desiccants in a fixed bed process, as shown in Figure 7. In such a system, the sorbent is coated on the surfaces of a plate heat exchanger. In the air-conditioning mode, the heat exchanger is operated with ambient air on one side and exhaust air on the other side. Hereby, the exhaust air, treated by a humidifier before entering the heat exchanger, provides internal cooling of the absorption process. For the regeneration, only ambient air, which is heated with solar energy before entering the heat exchanger, is used. Like in the closed cycle adsorption systems, two chambers are used to guarantee continuous operation.

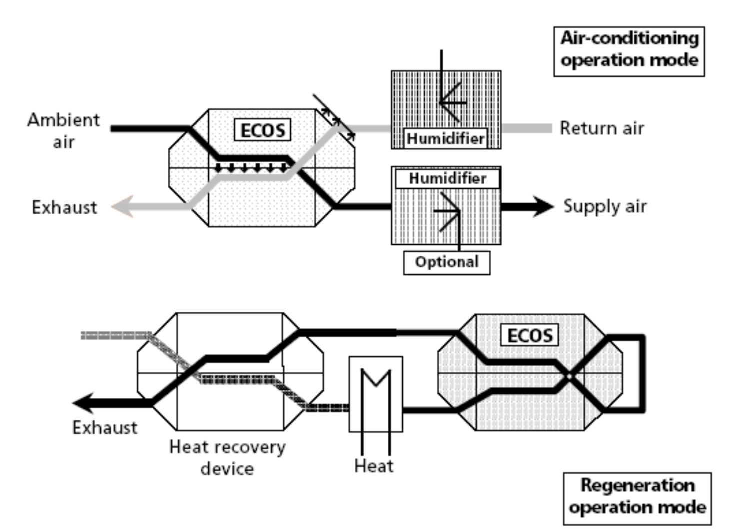


Figure 7: Schematic of a fixed bed process for the utilisation of solid desiccants in an open cycle process (Motta, 2003). The process is performed using an evaporatively cooled sorptive heat exchanger (ECOS).

However, the ECOS system is just in the laboratory stage, all commercial desiccant systems are rotary wheel systems using normally silica gel. Table 3 lists some desiccant systems available on the market.

Manufacturer	Wheel size
Klingenburg	0.6-5 m
Munters USA	0.25-4.5 m
Nichias	0.1-4 m
ProFlute	0.5-3 m

Table 3: Examples of commercially available desiccant wheel systems.

4.2. Liquid Desiccant Systems

Liquids which absorb water similar to those used in closed absorption systems (LiBr, LiCl) are employed in the open systems using a cycle similar to the one described in Figure 2. The net result of the operation of this device is the dehumidification of the conditioned air stream, which takes care of the latent load. To take care of the sensible load, the temperature of the conditioned air must be lowered either by an external cooling device or by evaporating water into the now dry air stream, using an evaporative cooler in place of the evaporator of Figure 2. Liquid desiccant systems have many of the same advantages of closed cycle absorption: They allow internal heat recovery from the strong and hot solution to the weak and cool solution by means of the recuperative heat exchanger; circulating the sorbent from one unit in the system to the next is easy, by pumping the liquid; pressure drop in the liquid-air direct contact – dehumidifier and regenerator – is relatively low, reducing parasitic losses. For solar-powered operation, desorption is possible in a special regenerating collector exposing the desiccant directly to the sun (Kakabaev and Golaev, 1971; Johannsen and Grossman, 1983) which can make the regeneration process simpler and more efficient. One disadvantage is the potential carryover of desiccant in the air, which may lead to desiccant loss and contamination of the air.

A schematic diagram describing the principal of operation of a liquid desiccant system is shown in Figure 8. In this case, the absorber and regenerator have similar constructions, the regenerator is operated using ambient air and solar energy, the absorber is internally cooled and uses either return air or also ambient air. For dehumidifying operation, the concentrated solution is pumped from the sump of the unit and sprayed over the contactor coils. Air to be conditioned is passed over the coils and comes in contact with the solution.

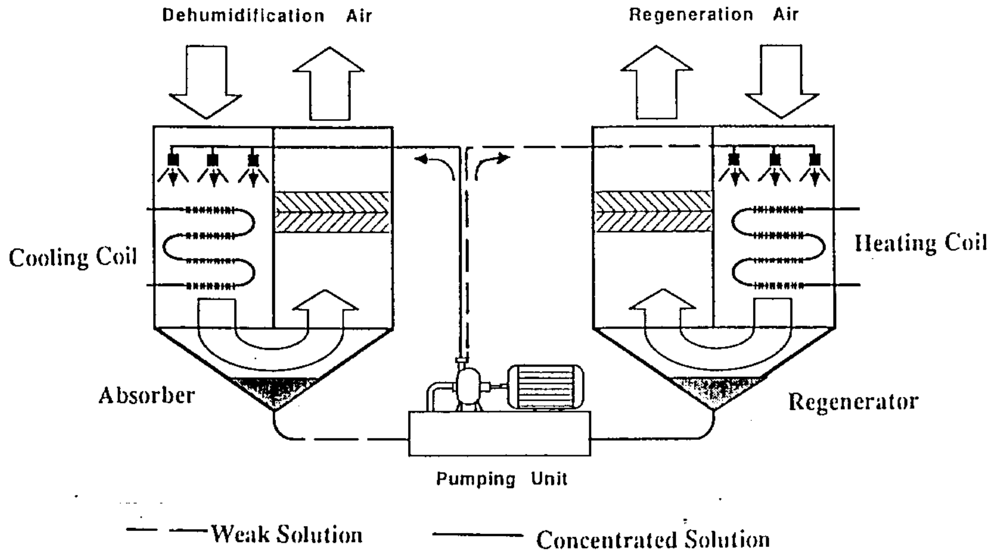
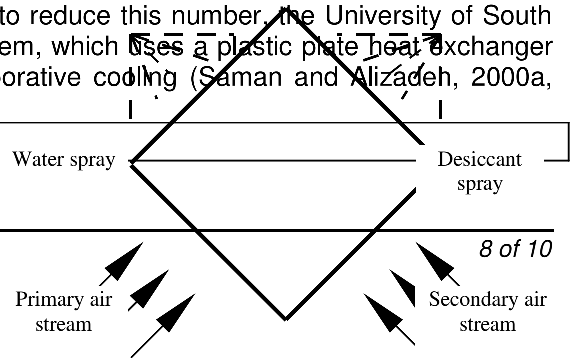


Figure 8: Schematic of a liquid desiccant system.

A limited number of solar-powered air conditioning systems employing liquid desiccants, mostly experimental, have been constructed over the past three decades, (Kakabaev et al., 1977; Lenz et al., 1985; Wood, 1986). Recently, (Biel and Röben, 2002) developed a compact cooling machine using liquid desiccants in a packed bed construction, which is now installed as a pilot plant in Freiburg (Germany). Gommed and Grossman, 2004 investigated a whole solar assisted liquid desiccant system in Israel. (Lävemann and Peltzer, 2003) installed and monitored a liquid desiccant system using a flat plate heat exchanger construction. However, there are no commercially available liquid desiccant systems for solar air-conditioning on the market.

One of the practical drawbacks associated with the manufacture and use of absorption and desiccant systems has been the number of components required in the real dehumidification/cooling systems with associated size and cost considerations. In order to reduce this number, the University of South Australia has been investigating a liquid desiccant system, which uses a plastic plate heat exchanger for the dual role of dehumidification and indirect evaporative cooling (Saman and Alizadeh, 2000a, 2000b), as shown in Figure 9.



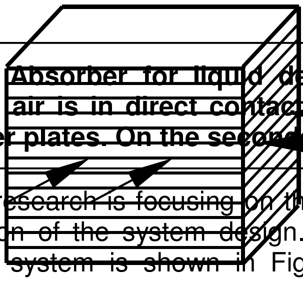


Figure 9: Absorber for liquid desiccants developed at the Sustainable Energy Centre. The incoming air is in direct contact with the desiccant solution on the primary side of the heat exchanger plates. On the secondary side, return air is directly cooled by a water spray.

Ongoing research is focusing on the development of a suitable regenerator design as well as on the optimization of the system design. One possible solution for a suitable system design for a liquid desiccant system is shown in Figure 10. Thus, in order to identify optimal designs, cooling and dehumidification demands as well as the solar thermal system have to be considered. For this, numerical models for all the different components have been developed and implemented into a TRNSYS system model offering the option of producing hot water, space heating and cooling using solar energy.

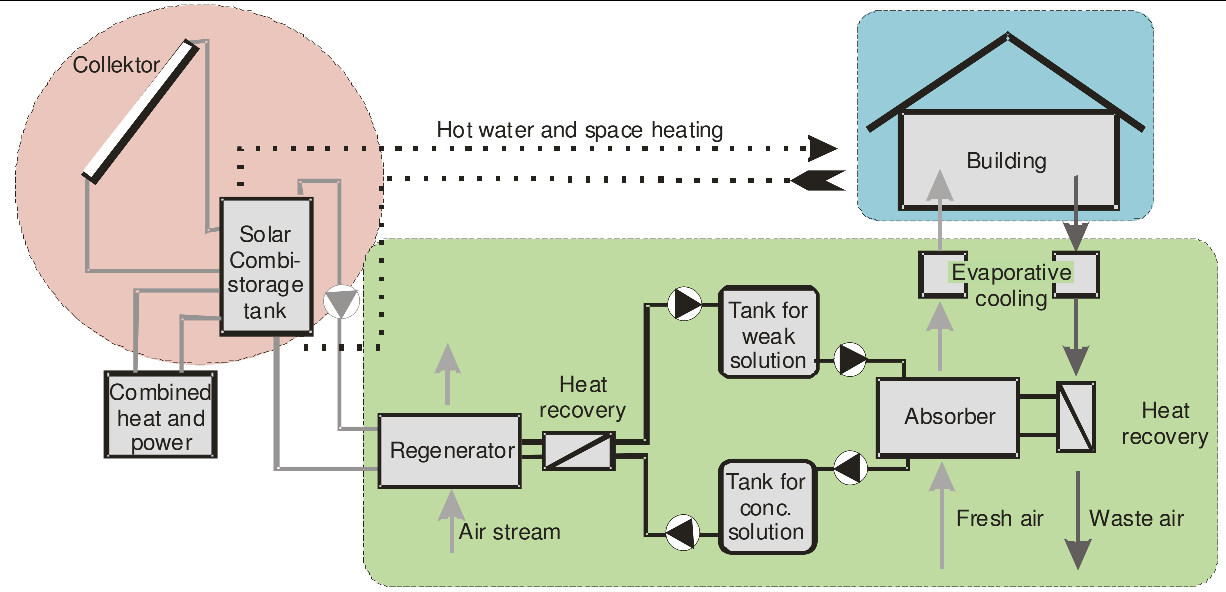


Figure 10: Possible system design for a combination of solar hot water preparation, space heating and air-conditioning.

5. ACKNOWLEDGMENTS

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