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Chapter 4

SOLAR POWERED SORPTION REFRIGERATION AND AIR CONDITIONING

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ABSTRACT

The majority of the refrigeration and air conditioning systems produce the cooling effect through an electricity-driven mechanical compression cycle. Because the operation of these systems are responsible for 10 to 20 % of the worldwide electricity consumption, and because the production of electricity by thermal plants causes air pollution and green house effect, there is a growing interest on other types of refrigeration system that can use more environmentally friendly sources of energy. In sorption refrigeration, the cooling effect is obtained with a heat-driven cycle, which can operate with relative low-grade heat sources like waste heat or solar energy. Moreover, sorption refrigeration uses natural refrigerants like methanol, ammonia and water; and thus, it does not contribute to the ozone layer depletion. Hence, this chapter presents the principles behind the operation of the sorption refrigeration and air condition systems, the types of sorbents and refrigerants commonly used in these machines, and report the experimental results of some of the machines developed and tested all over the world. The sorption processes discussed are solid-vapor physical adsorption, solid-vapor chemical adsorption, and liquid-vapor absorption. These processes can occur either in single stage or in multiples stages, with single or multiple cooling effects per cycle. The machines analyzed can operate in closed cycle, where the mass of refrigerant inside the system is constant, or in open cycle, where the refrigerant is usually water from air. Most of the solar-powered icemakers designed can achieve a daily production of ice between 4 to 6 kg per m^2 of solar collector, with a typical solar coefficient of performance between 0.10 and 0.15. The most common type of sorption system available in the market is the LiBr-water absorption chiller and the ammonia-water refrigerator; however, recent developments on composite solid sorbents may result in solid sorption machines cheaper, and more competitive than the liquid-vapor absorption machines. Double stage adsorption chillers can be powered with hot water at temperatures of at least 55 °C, which can be easily achieved with flat plate solar

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collectors, whereas single stage chillers need heating sources with temperatures from 65 °C. The coefficient of performance of these machines is typically between 0.2 and 0.6, but it can reach 0.7 in some commercially produced machines.

1. INTRODUCTION

Nowadays, the majority of the refrigeration and air conditioning systems operate under a mechanical compression cycle powered by electricity, and according to the International Institute of Refrigeration [1], these systems are responsible for 10 to 20% of the electricity consumption worldwide. The production of electricity by thermal plants causes air pollution and green house effect, and the growing concern about these issues in the recent years had triggered the interest on other types of refrigeration system that can use more environmentally friendly sources of energy.

Sorption refrigerators are similar to mechanical-compression refrigerators in utilizing a condenser, an evaporator, and in certain machines, an expansion device. The difference is related to the way that the refrigerant vapor that leaves the evaporator at low pressure achieves high pressure to enter the condenser. In sorption systems, thermal power is the driving force, instead of a work-driven compressor of mechanical refrigerators. The heat supplied to the sorption systems can be from the combustion of natural gas, industrial waste heat, geothermal sources, or solar energy collection.

Moreover, sorption refrigerators use natural refrigerants like methanol, ammonia and water; and thus, they do not contribute to the ozone layer depletion.

The interest in sorption system was firstly renewed at the end of the 1970s, and beginning of the 1980s, due to the second oil crisis. For instance, Tchernev [2] and Guilleminot and Meunier [3] studied solar powered refrigerators with the working pair zeolite-water, whereas Worsøe-Schmidt [4] preferred to use the working pair $CaCl_2$-NH_3. The efficiency of these systems was around 10 to 15 %, which was enough to produce 6 kg of ice per m^{-2} of collector area, in a bright day, with irradiation around 20 MJ day^{-1}.

Since then, much research has been focused in the development and improvement of the solar powered sorption systems. Currently, there is about 9 MW of cooling produced by sorption systems, which are powered by the solar energy collected in 23,720 m^2 of solar panels distributed in more than 10 countries [5].

Although solar electric and solar thermo-mechanical systems could also be employed to produce cooling effect, the total cost of these systems is higher than that of sorption systems[6]. Hence, this chapter shows the state of art of the solar powered sorption cooling systems.

The operation principle, the similarities and the differences of the distinct types of sorption systems are presented in the sections two, three and four. Section five presents the main working pairs, whereas sections six and seven present the machines tested in laboratories, and machines operating in occupied buildings.

The types of sorption processes in the machines are the physical solid-vapor adsorption, the chemical solid-vapor adsorption (or absorption), and the liquid-vapor absorption. All these sorption processes can occur in either single or multiples stages, with single or multiple cooling effects per cycle. The sorption cooling machines can operate in closed cycle, where the mass of refrigerant inside the system is constant, or in open cycle, where the refrigerant is usually water from air. Some adsorption and absorption chillers can effectively use hot water at temperatures of at least 55 °C as main source of energy, and have a typical efficiency between 20% and 80%, depending on the working pair, type of sorption process, and operation conditions. Most of the sorption system installed in industries or in commercial buildings are based on the liquid-vapor absorption process; however, due to the recent developments in composite solid sorbents, solid-vapor sorption system may become an option more attractive due to the simpler design and manufacturing.

2. DIFFERENCES AND SIMILARITIES AMONG SOLID-GAS PHYSISORPTION, SOLID-GAS CHEMISORPTION AND LIQUID-GAS ABSORPTION

In most of the literature about solid-gas sorption refrigeration, physical adsorption is simply named as adsorption, whereas chemisorption and liquid-gas sorption are known as absorption. However, according to the International Union of Pure and Applied Chemistry (IUPAC) [7][1], adsorption can be either physical or chemical, and the main distinction between the former and the latter are the nature of the forces involved in the adsorption process. Valence forces similar to those operating in the formation of chemical compounds are involved in chemical adsorption, whereas intermolecular forces (e.g. Van der Waals forces) similar to those responsible for the condensation of vapors are involved in physical adsorption. In practical terms, the thermodynamic equilibrium is the main feature to distinguish between physical and chemical adsorption. Physical adsorption has divariant equilibrium, and the concentration of fluid in the solid (x) is a function of both pressure and temperature. Thus, at constant pressure, the concentration of fluid in the solid decreases an amount Δx, for every increment of temperature ΔT. If there is no severe mass transfer resistance within the sorbent, the equilibrium is reached almost instantaneously.

Chemical adsorption has monovariant equilibrium, and each reaction has a unique equilibrium condition. At constant pressure, the concentration of fluid decreases an amount equal to the stoichiometric coefficient of the reaction, if the temperature of the sorbent is higher than the equilibrium temperature. The rate of fluid desorption from the solid is related to the equilibrium drop, and the desorption can last several hours if the sorbent temperature is too close to the equilibrium temperature.

Regardless the nature of the adsorption process, the solid can be referred as adsorbent, whereas the fluid or the refrigerant of cooling systems can be referred as adsorbate. Ponec et al. [8] mentioned that the term absorption is better applied when the penetration of the particles of one phase into the other phase resembles dissolution. This definition can be easily applied in the liquid-vapor sorption, but the dissolution is less clear in the case of sorption of a vapor into a chemical compound. The IUPAC [7][2] defines that absorption is the transfer of a component from one phase to another, and that the structure of the sorbent and/or the

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[1] Available at http://www.iupac.org/reports/2001/colloid_2001/manual_of_s_and_t/manual_of_s_and_t.html

[2] Available at http://www.iupac.org/reports/2001/colloid_2001/manual_of_s_and_t/manual_of_s_and_t.html

chemical nature of the sorptive may be modified. However sometimes it is difficult or even impossible to discriminate experimentally between adsorption and absorption. Hence, it is convenient to use the term sorption, and its derived terms sorbent, sorbate, sorptive. Sorption can also be used as a general term to cover both adsorption and absorption when both occur simultaneously. Therefore, in this chapter, we will refer to adsorption as synonym of solid sorption (both physical and chemical) and absorption as synonym of liquid sorption. Sorption will be used to refer to both adsorption and absorption, in a general way, or to the cases where it is well know the existence of both adsorption and absorption.

3. CLOSED SORPTION CYCLES

All sorption refrigeration cycles consist of at least one positive sorption (enrichment of the sorbent with sorbate), which is also known by sorption, and one negative sorption (depletion of sorbate from the sorbent), which is also known as desorption. In conventional cycles, the cooling effect is usually obtained during the sorption process, because this process reduces the pressure inside the system, and causes evaporation of refrigerant in the evaporator. Alternatively, in machines using two types of sorbent, but no evaporator and condenser, the cooling effect can be obtained during the desorption process of the sorbent with the lowest equilibrium temperature.

3.1. Solid-Vapor Physisorption

Solid-vapor physisorption can occur in single-stage, double-stage or multi-stage, with usually, one or two cooling effects per cycle, depending on the number of reactors involved.

A single-stage cycle can be followed in the Clapeyron diagram presented in Figure 1, and consist of two phases. The first phase starts with the sorbent usually at ambient temperature ($T_{Ad.}$) and low pressure ($P_{Evap.}$). Once the sorbent inside the reactor is heated, and its temperature rises, the pressure also rises. The desorption process starts when the sorbent pressure reaches the condensation pressure, and continues until the sorbent reaches the maximum temperature ($T_{Gen.}$). During this period, the refrigerant flows from the sorbent to the condenser, and it is transferred to the evaporator or accumulates in a reservoir, depending on the design of the system. In the second phase, the process is reversed, and while the sorbent is cooled back to the ambient temperature, its temperature and pressure drop. When the sorbent pressure becomes smaller than the evaporation pressure, the sorption process starts to occur, and continues until the sorbent reaches its minimum temperature, which is usually related to the ambient temperature. During this phase, refrigerant vapor is formed in the evaporator, and flows to the reactor.

Compared to the single-stage cycle, the double- or multi-stage cycle can have higher cycled mass, at a specified generation temperature ($T_{Gen.}$) (Figure 2a), or the same cycled mass using lower generation temperature (Figure 2b). A system operating with double stage cycle needs at least two reactors operating out of phase. While the top reactor is heated, and desorbs to the condenser, the bottom reactor is cooled, and adsorbs from the evaporator. In the next phase, the top reactor is cooled, and adsorbs from the bottom reactor, which is being heated.

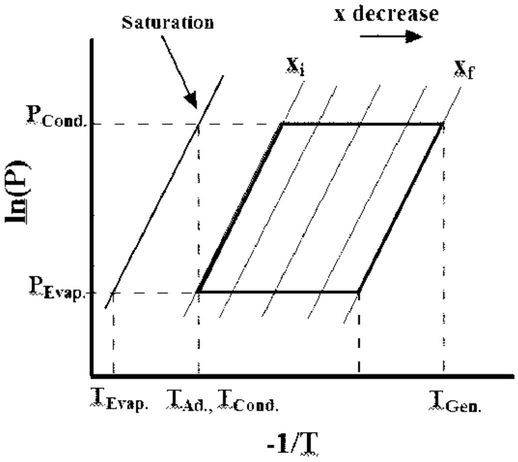


Figure 1. Clapeyron diagram for a single stage physisorption refrigeration cycle.

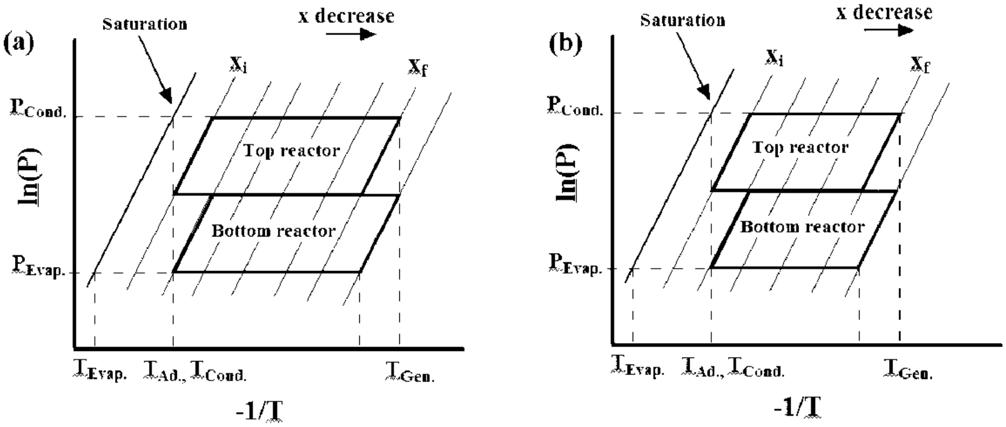


Figure 2. Clapeyron diagram for double-stage physisorption refrigeration cycle. (a) Increase of the cycled mass when compared to a single stage cycle with same generation temperature. (b) Reduction of the generation temperature, when compared to a single stage cycle with the same cycled mass.

The biggest advantage of the double-stage cycle, when compared to the single stage, is the possibility to have a sorption machine operating with relative low generation temperatures. Saha [9] used this cycle to operate an adsorption chiller with a generation temperature of 55 °C. However, the specific cooling power (SCP, eq. 1) and the coefficient of performance (COP, eq. 2) of the machines operating in double stage cycle is smaller than those of a machine operating in single stage because only one cooling effect ($Q_{Ev.}$) is obtained for each two heat input (Q_{Source}). The variables $m_{Sorb.}$ and Δt in eq. 1 are respectively, the sorbent mass and the cycle length of time.

$$SCP = \frac{Q_{Ev.}}{m_{Sorb.} \Delta t} \tag{40}$$

$$COP = \frac{Q_{Ev.}}{Q_{Source}} \tag{41}$$

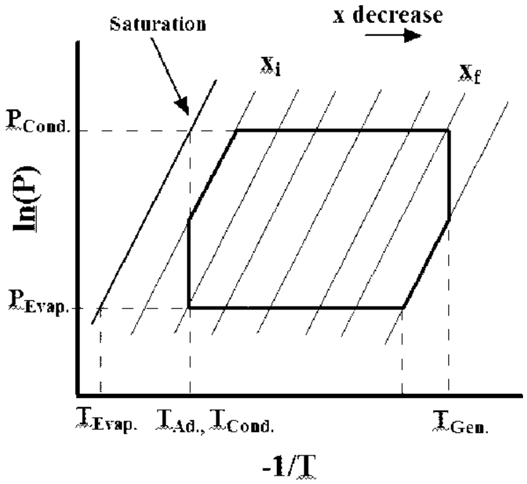


Figure 3. Clapeyron diagram for a mass recovery physisorption refrigeration cycle.

Alternatively, the mass recovery cycle [10] can overcome the drawbacks of double stage cycle, while keeping its advantage. This cycle is represented in the Clapeyron diagram of Figure 3, and it is similar to the conventional single-stage cycle, except that it needs at least two reactors operating out of phase. The desorption and adsorption phases in both reactors should last the same period, and before the reactors switch their phases, the reactor at high pressure sends refrigerant vapor to the reactor at low pressure.

Compared to the conventional single-stage cycle, the mass recovery cycle can enhance the adsorbed mass between 37 and 42 % [11], the SCP in about 20% [10], and the COP between 10 to 100 %[12], depending on the operation conditions. The biggest improvements were obtained at lower generation temperatures.

The mass recovery cycle can also occur in double-stage, and adsorption machine operating under such a cycle can produce ice, if the generation temperature is at least 75 °C [13]. The double stage mass recovery cycle is depicted in the Clapeyron diagram in Figure 4, and requires two pairs of reactors.

In the double stage mass recovery cycle, the bottom pair (reactors *B* in Figure 5) operates at low (evaporation) and medium pressures, and the top pair (reactors *A* in Figure 5) operates at medium and high (condensation) pressures. In the first phase of the cycle, one top reactor desorbs refrigerant to the condenser, while one bottom reactor adsorbs refrigerant from the evaporator. The remaining reactors of each pair exchange refrigerant vapor at medium pressure. At the end of this phase, the mass recovery occurs when one of the reactors at medium pressure receives refrigerant from the reactor at high pressure, while the other reactor at medium pressure sends refrigerant to the reactor at low pressure. In the second phase of the cycle, the process is repeated; however, the reactors in the same pair swap roles.

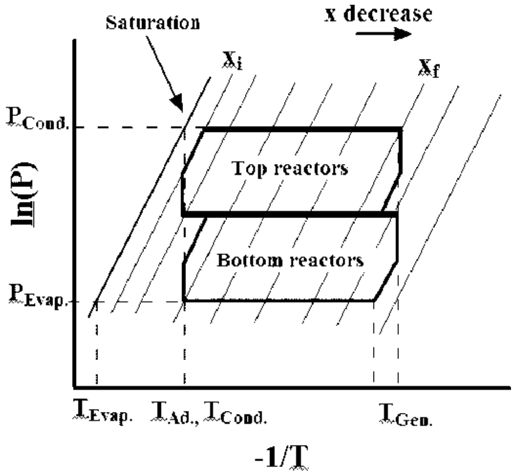


Figure 4. Clapeyron diagram for a double-stage mass recovery physisorption refrigeration cycle.

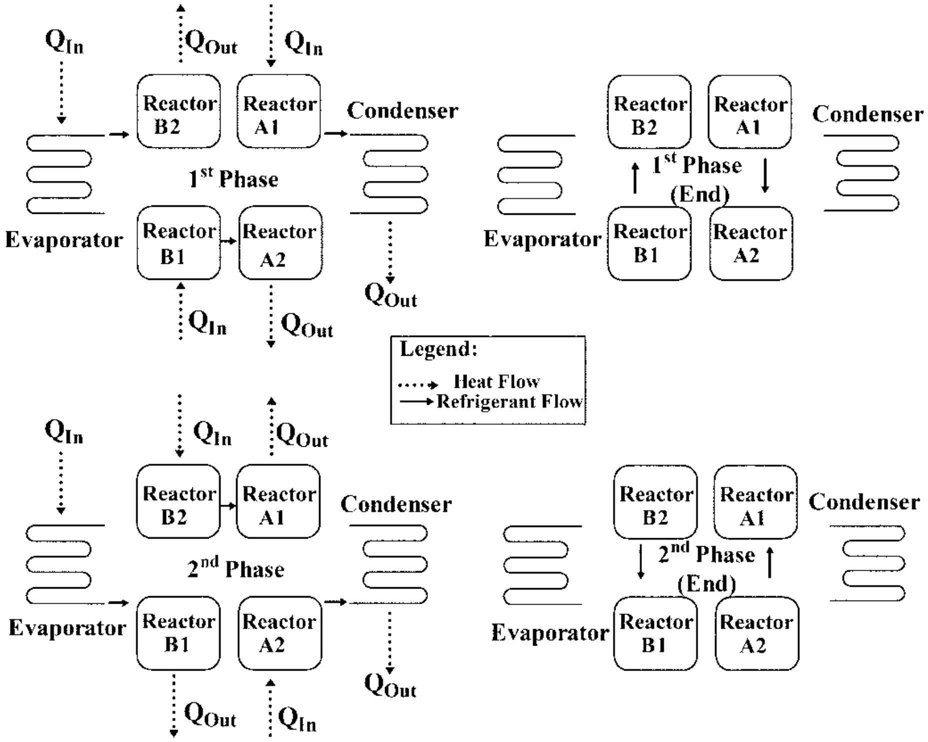


Figure 5. Scheme for the heat and mass transfer processes in a double-stage mass recovery physisorption refrigeration cycle.

The COP of an adsorption system operating under any of the cycles described above can be increased with a heat recovery scheme between the reactors operating out of phase. In a solar powered system, higher COP results in less area of solar panels per unit of cooling. In a cycle with heat recovery, the reactor at the beginning of the adsorption phase releases heat to the reactor at the beginning of the desorption phase. Theoretically, this process can last while the temperature of each reactor is different, but for practical reasons, the process finishes when the temperature difference between the reactors is between 5 °C and 15 °C. Once the heat recovery is concluded, one reactor starts releasing heat to a heat sink, whereas the other reactor starts receiving heat from a heat source, to complete the adsorption and the desorption processes, respectively. About 35% of the total heat transmitted to each reactor can be internally recovered, due to this heat management [14].

3.2. Solid-Vapor Chemisorption

Similar to the physisorption cycle, the chemisorption cycle can also occur in single-stage, double-stage or multi-stage. However, due to the nature of the chemisorption equilibrium, which is monovariant, there is little gain with the mass recovery process.

The chemisorption is usually described by an equation of the following type:

$$S.nR + mR \Leftrightarrow S.(n+m)R + m\Delta H \tag{42}$$

Where n is the number of moles of refrigerant adsorbed before the synthesis reaction, m is the number of moles of refrigerant adsorbed during the synthesis reaction, and ΔH is the reaction enthalpy.

The equilibrium pressure ($P_{Eq.}$) and the equilibrium temperature ($T_{Eq.}$) can be obtained with the Clapeyron equation, in the following forms:

$$\ln(P_{eq}) = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \tag{43}$$

$$T_{eq} = \frac{\Delta H}{\left(\Delta S - R\ln(P)\right)} \tag{44}$$

Where ΔS is reaction entropy, and R is the ideal gas constant.

A single-stage cycle with heat recovery between two reactors operating out of phase can be visualized in the Clapeyron diagram presented in Figure 6a and 6b.

Figure 6a shows the phase where the salt at temperature $T_{Gen.1}$ desorbs refrigerant to the condenser, while the other salt at temperature $T_{Ad.2}$ adsorbs refrigerant from the evaporator. The maximum amount of refrigerant desorbed or adsorbed by each salt is defined by the stoichiometric coefficient m, according to eq. (3), and which can be achieved if $T_{Gen.1}$ is higher than the equilibrium temperature $T_{Eq.}(P_{Cond.})$, or if $T_{Ad.1}$ is lower than the equilibrium temperature $T_{Eq.}(P_{Evap.})$. However, differently from physisorption which occurs almost instantaneously, the rate of reaction in chemisorption is related to the equilibrium drop ($\Delta T_{Eq.}$), and reactions carried out too close to the equilibrium can last for so long that an adsorbed or desorbed amount equal to the stoichiometric coefficient cannot be achieved in a practical time. The heat recovery occurs when the reaction in each salt is reversed, and it is represented schematically in Figure 6b. The heat released during the adsorption in the *Salt* 1 is the source of thermal energy for the desorption in the *Salt* 2. The COP with heat recovery is higher than the COP without this process because it is possible to obtain two cooling effects at the expense of a single heat input.

A different approach to increase the COP consists in replacing the evaporator and the condenser by a secondary reactor, which contain a salt with lower equilibrium temperature, a.k.a. low temperature salt (LTS). In this kind of arrangement, which is named resorption [15, 16], the cooling effect occurs when the LTS desorbs refrigerant to the salt in the main reactor. Because the reaction enthalpy of the LTS is higher than the evaporation enthalpy of the refrigerant, the COP can be higher, too.

The different equilibrium temperatures that different salts have when reacting with a certain refrigerant at a certain pressure can be used to design a system with multiple heat recovery schemes. Li et al. [17] proposed a sorption cycle that combined refrigerant vaporization and condensation, the resorption process and the heat recovery scheme. The system operating under such a cycle could have four cooling productions at the expense of only one heat input, and an ideal COP higher than 2.0 was predicted.

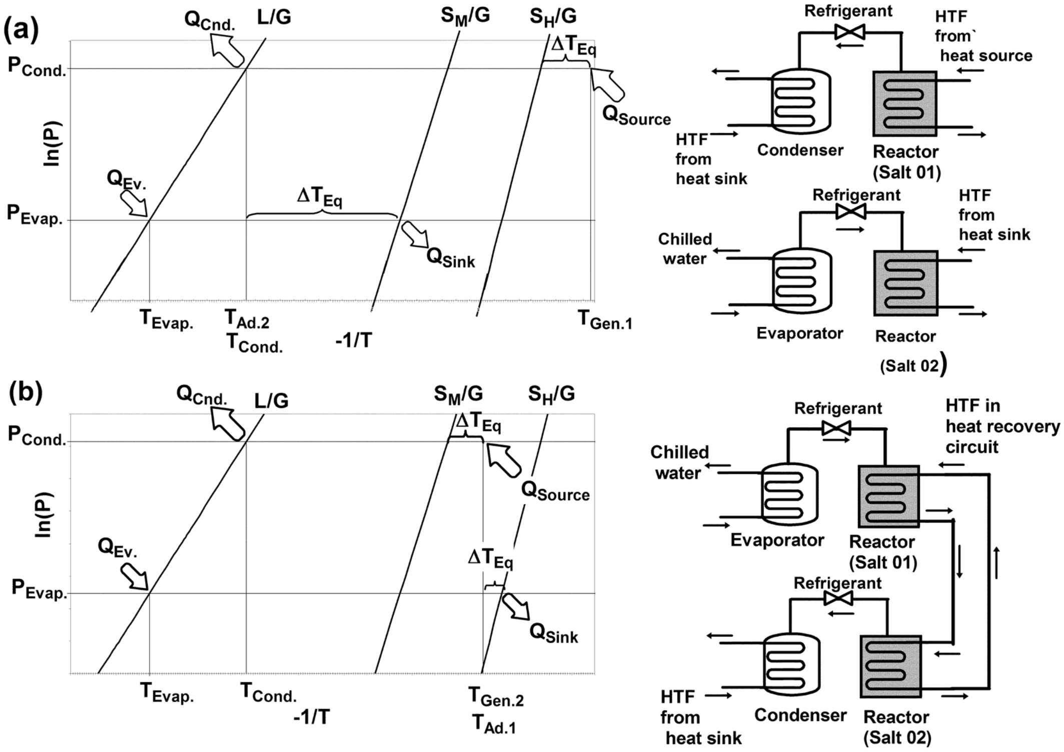


Figure 6. Clapeyron diagram for a heat recovery single stage chemisorption cycle.

Despite the possibility of COP enhancement, the combination of different kinds of cycle and heat recovery scheme may lead to a reduction in the cooling power because there is a reduction in the freedom to choose the temperatures of the heat source and the heat sink, in the heat recovery phase. Moreover, under a specified temperature and pressure constraint, the matching of the reactions in the different salts might not occur, and the reaction in one of the salts can finish much earlier than the reaction in the other salt. When the reaction in the salt with the highest equilibrium temperature finishes before the reaction in the salt with the lowest equilibrium temperature, the gain in the COP will not be as high as expected in a perfect match. According to Oliveira et al. [18], a system using $NiCl_2$, $MnCl_2$ and $BaCl_2$, and operating with the cycle proposed by Li et al. [17] could reach a COP of 1.10, and develop a cooling power density of 21.51 kWm^{-3}, whereas a system only using resorption and heat recovery would reach a COP of 0.72, with a cooling power density of 47.2 kWm^{-3}.

3.3. Liquid-Vapor Absorption

One of the most important difference between solid-vapor sorption and liquid vapor sorption is the possibility to run a steady state cycle in the latter type of process because the sorbent can circulate between the heat sink and the heat source continuously. In solid sorption, although it is possible to obtain a continuous cooling production when two reactors work out of phase, the process inside the rectors never reaches steady state. Figure 7 shows schematically a typical single stage absorption system, without heat recovery. Whereas in solid sorption, each reactor operates as generator and as absorber, depending on the phase of the cycle, in liquid sorption one reactor operates only as generator, and continuously receive strong solution from another reactor that acts only as absorber.

A relatively low-power liquid pump, which the electric power consumption is typically below 1 % of the chiller´’s rated cooling capacity, raises the pressure of the strong solution before it enters the generator. Then, the weak solution leaving the absorber is throttled in an expansion valve to maintain the pressure difference between the generator and absorber [19]. Besides the devices shown in Figure 7, systems using NH_3-H_2O as working pair, must have a rectifying column and a dephlegmator, combined to the generator, to separate the water vapor from the ammonia vapor.

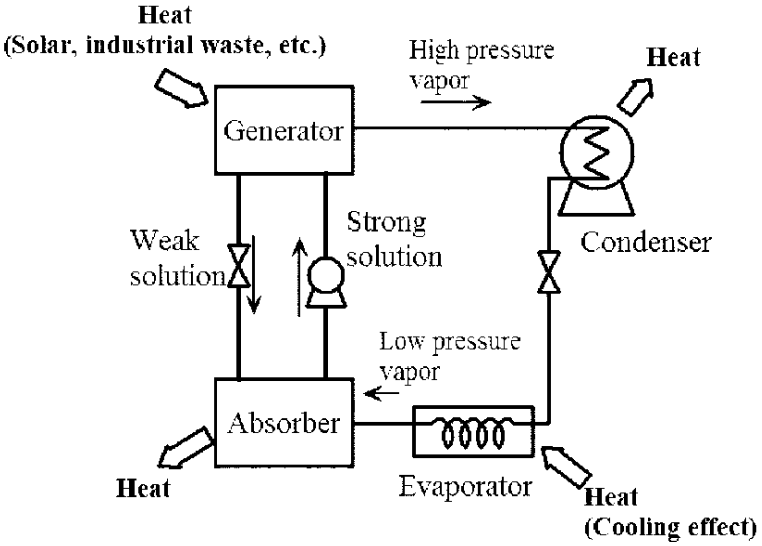


Figure 7. Scheme of a typical single-stage absorption refrigerator.

An absorption system operating with the pair NH_3-H_2O requires generation temperatures above 125 °C, and this level of temperatures cannot be obtained with flat-plate collectors. Alternatively, a system using the pair LiBr-H_2O could be powered by a flat plate solar collector, but because water is the refrigerant, the evaporator cannot operate at temperatures much below 5 °C [20].

Heat recovery and multiple stage schemes can be used to increase the COP of an absorption machine. The heat recovery between the strong and the weak solutions can be accomplished by passing both solutions through the same heat exchanger. In a double stage scheme aimed to increase the COP, the condensation heat from the refrigerant vapor at high pressure from the top generator can be recovered to generate refrigerant vapor at the bottom generator. However, this type of multiple stages arrangement requires higher generation temperatures than that used in single stage, which limits the application of non-concentrated solar energy. Alternatively, multiple-stages can be used not only to increase the COP, but also to reduce the generation temperature. In this case, the top stage operates between saturation pressure at ambient temperature, and intermediate pressure, whiles the bottom stage operates between intermediate pressure and evaporation pressure.

4. OPEN SORPTION CYCLES

Air conditioners have to handle the sensible heat load and the latent heat load to maintain a desired indoor condition. The latent heat load is removed by cooling the air below the dew point to condense part of the water vapor from the air. The dehumidified air has a temperature below the comfort temperature, and must be heated to meet the required indoor condition. If the latent load can be handled without cooling the processed air below the comfort temperature, the air conditioner can operate with higher evaporation temperature and thus, with higher efficiency.

Open sorption systems employ the humidity of air as refrigerant, and can be used to remove its latent load. A typical system designed to operate continuously has a desiccant wheel that turns continually to promote desorption and adsorption simultaneously, at different parts of the wheel. The desiccant wheel is formed by a supporting material, which can be coated or impregnated with the desiccant. The cross section of the wheel is divided into a process-air side and a regeneration-air side. Water vapor can be adsorbed in the process-air side when fresh air passes through this part. The moisture of the wheel is removed when hot air coming from a heater or from a heat exchanger flows through the regeneration side.

A system designed to operate intermittently can have the sorbent inserted in a fixed bed. Solar heated air can be blown in the sorbent during the day to promote desorption, and dehumidified air can be obtained in the evening through adsorption of water vapor from fresh air. The intermittent arrangement can be used to cool grain, as proposed in the literature [21, 22].

A scheme of a desiccant cooling system with evaporative cooling, thermal wheel, desiccant wheel, and solar heated regeneration is presented in Figure 8. The variation of air temperature and humidity through this system can be followed in the psychrometric chart presented in Figure 9.

Humidity and latent load decrease when air pass through the desiccant material (point 1 to 2), but its temperature increase, because adsorption is exothermic. The heated air (point 2) flows through a thermal wheel to exchange heat with colder air (stream at point 6), and its temperature is reduced (point 3). Then, it flows through a humidifier for a further temperature reduction, due to the evaporative cooling, before enters the building (point 4). The air leaving the building (point 5) is humidified (point 5 to 6) before enters the thermal wheel. The warmer air that leaves the thermal wheel is heated in an auxiliary heater (points 7 to 8) before enters the desiccant wheel (point 8 to 9), where it promotes desorption of moisture, and regenerate the desiccant material.

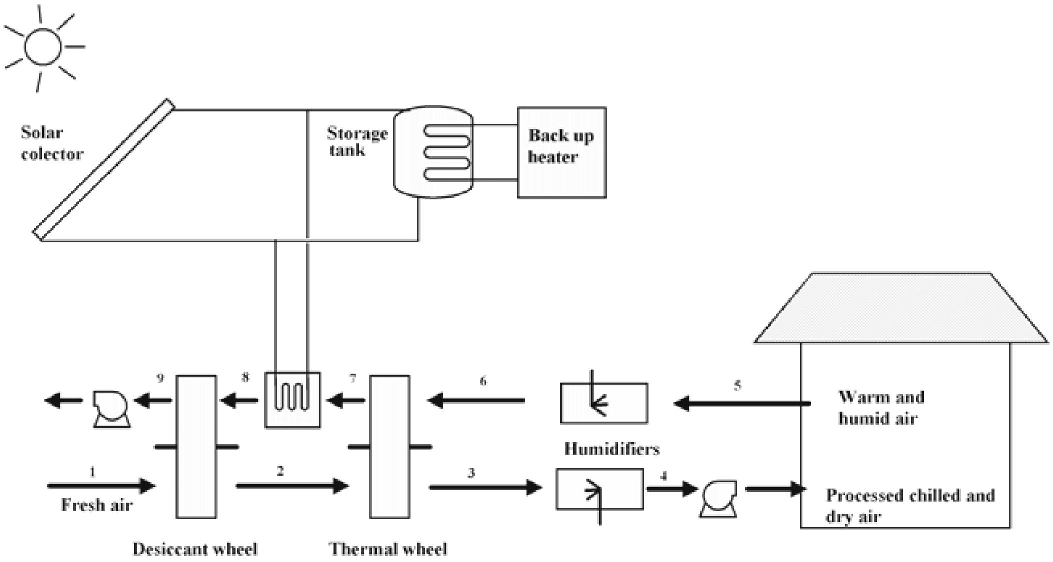


Figure 8. Scheme of a desiccant cooling system.

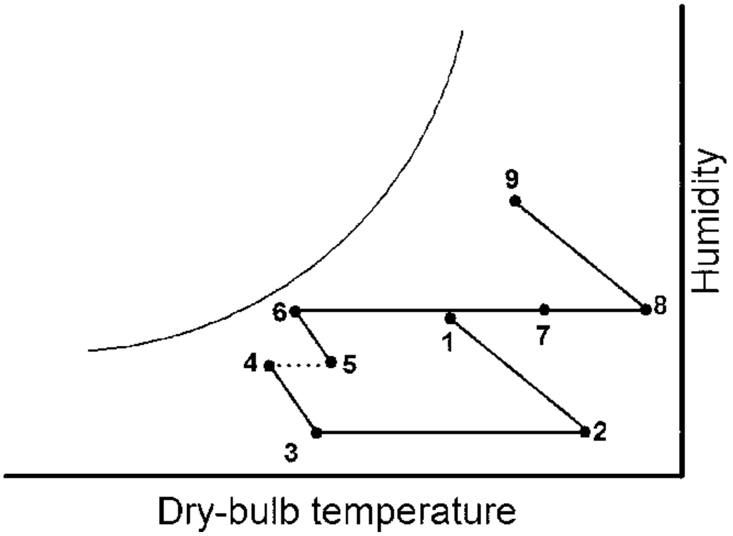


Figure 9. Variation of air temperature and humidity through the desiccant system presented in Figure 8.

5. SORBENTS AND REFRIGERANTS

Regarding operational conditions, environmental consideration and safety aspects, the ideal refrigerant for a sorption system should have the following characteristics:

1. low ozone layer depletion potential (ODP);
2. low global warming potential (GWP);
3. operation pressure close to atmospheric pressure;
4. high density (physisorption) or high molar mass (chemisorption);
5. high vaporization enthalpy;
6. non-toxic or very low toxicity;
7. non-flammable.

The first two characteristics are related to environmental aspects, due to the great concern about the ozone layer depletion by CFCs and HCFCs, and the increase of the greenhouse effect, mainly by gases like CFCs, HCFCs, HFCs, methane and CO_2.

The third characteristic was included because a system working with pressure much above or below atmospheric pressure will have its construction cost increased. High pressure systems must be designed to avoid explosion or any leakage that could contaminate the surroundings, whereas sub-atmospheric pressure systems must be designed to avoid air infiltration, which would cause malfunction of the system. Leak detection in sub-atmospheric system is usually difficult, and requires appropriate equipment and technology. For such a reason, high pressure refrigerants, like ammonia, are more suitable for machines designed to operate in remote areas, with lack of qualified assistance.

High density for physisorption systems, and high molar mass for chemisorption systems, and high vaporization enthalpy are important because the cooling effect is produced in batch operation, and high cooling capacity in each cycle leads to smaller machines.

Non-toxicity and non-flammability are especially important characteristics for refrigerants with high pressure, because any leak could put in danger the users or the operators or both.

Unfortunately, there is no refrigerant with all desirable characteristics, and the most employed refrigerants are water, methanol and ammonia, mainly due to their high enthalpy of vaporization. Water is the safest one, but its application is limited to systems with evaporation temperature above 0 °C. Moreover, due to its extremely low working pressure, the sorbent bed must be designed to minimize any mass transfer resistance. Methanol also has sub-atmospheric pressure under usual working condition, but it can achieve evaporation temperatures below 0 °C. However, Hu [23] reported that methanol in contact with copper or aluminum alloys starts decomposing in dimethyl ether and in methoxymethyl methyl ether at temperatures above 110 ºC, and this degradation reduces the performance of the system. Thus, the generation temperature must be controlled to do not exceed this value.

Ammonia does not have vaporization enthalpy per volume unit and per mol as high as methanol or water, and is incompatible with copper and its alloys, but it has working pressure above atmospheric pressure, and it achieve evaporation temperatures as low as -25 °C [24].

Water is employed as refrigerant of sorbents like silica-gel [9, 25-27], silica-gel impregnated with metallic salt [28-34], zeolite [2, 3, 35-40], and LiBr [41-43]. Methanol was traditionally used with activated carbon [44-53], but recently, Gordeeva et al. [54, 55] showed that “silica-gel impregnated with LiCl and LiBr can lead to adsorption refrigerators with better performance than those using activated carbon. Ammonia can be used with activated carbon [11, 56, 57], with water, in absorption systems [58-60], and with metallic salts as $CaCl_2$, $BaCl_2$, NaBr, $MnCl_2$, $SrCl_2$, $CoCl_2$, etc. These salts were mixed with activated carbon [61], impregnated in expanded graphite [24, 62-65] or in carbon fiber [66] to avoid the formation of impermeable lumps during the synthesis reaction.

The working pair (silica-gel impregnated with LiCl)-methanol [54], (expanded graphite impregnated with NaBr)-ammonia [62], and LiBr-water [67] are the most promising for solar powered sorption air conditioners due to the relative low generation temperatures required to regenerate these sorbents. A machine using the first pair had a SCP of 210 $W/kg_{sorbent}$ and a COP of 0.32 when desorption occurred at 80 °C, adsorption and condensation occurred at 30 °C, and the evaporation temperature was 10 °C.

A machine using the second pair can achieve a SCP of 129 $W/kg_{sorbent}$ and a COP of 0.46, at the same heat sink temperature, but with heat source temperature at 65 °C, and cold production at 15 °C, whereas a machine using the latter pair operating in double stage can deliver chilled water around 7.0 °C with a COP of 0.37, when the heat source temperature is 62 °C, and the heat sink temperature is 28 °C.

Regarding ice production, a simulation work presented by Maggio et al. [68] indicated that the pair (silica-gel impregnated with LiCl)-methanol could lead to a solar powered ice maker with coefficient of performance reaching up to 0.33, and daily ice production as high as of 20 kg/m^2.

6. ICEMAKERS AND REFRIGERATORS

Certain types of food, drugs and vaccines need to be stored at temperatures bellow 0 °C to prolong their shelf-life. Areas with high insolation which could employ solar energy efficiently for such purposes could minimize their dependence on electricity to accomplish such a goal. Attempts to use solar energy for refrigeration are reported in the literature since the 1950s, when Trombe and Foex [69] presented their studies with an intermittent water-ammonia absorption refrigerator directly heated by solar energy. In the 1960s, Chinnappa [58] compared the experimental and theoretical performance of a water-ammonia absorption refrigerator that could produce daily 1.43 kg of ice per m^2 of flat-plate collectors. The oil crisis in the 1970s motivated further research in refrigeration cooling. Swartman et al. [70] compared solar powered absorption systems using water-ammonia and using NaSCN-ammonia, and concluded that the latter pair leaded to higher performance, and to a simpler and cheaper machine, because there was no need of a rectifying column to prevent the absorbent from being carried over to the condenser. Worsøe-Schmidt[4] tested a $CaCl_2$-ammonia solar icemaker which had a COP of 0.10 and produced up to 6 kg of ice per m^2 of collector area. Several studies on solar refrigeration developed at the end of the 1970s and beginning of the 1980s were presented in the conference of the International Institute of Refrigeration, that happened in Jerusalem, in 1982 [71]. Among these studies, there were two sorption machines with zeolite-water as working pair, in which ice was formed inside the evaporators [72, 73]. This working pair was also employed in the solar powered cold store developed by Grenier et al. [74]. The COP of the system was 0.10, with a net daily cold production of 550 kJ/m^2. Sloetjes et al. [59] reported the experimental results of a 13kW and 50 m^3 solar-powered cold store, with 80 m^2 of evacuated tubes solar collectors. The generator of the water-ammonia absorption system was integrated to the solar collector. The electricity for the pump, fans and valves was provided by a photovoltaic system. The COP varied with the heat sink temperature, but remained below 0.12.

In order to obtain evaporation temperatures below 0 °C, Pons and Guilleminot [75] developed an ice maker prototype with the pair activated carbon-methanol, that have a solar COP of 0.12 and produced about 6 kg of ice per m^2 of solar panel when the insolation was about 20 MJ/day. The activated carbon was placed inside two 1.5 m^2 solar collectors, which had inner fins 5 cm apart to reduce the thermal resistance. The machine was tested with carbon bed thickness of 5 cm and 6 cm, which represented 20 $kg_{A.C.}/m^2$ and 24 $kg_{A.C.}/m^2$, respectively. The surface of the collector was covered with a selective surface (Maxsorb), and placed under a single sheet of glass, inside an insulated case. The case had dampers in the bottom and top side, which were open during the night to enhance the natural cooling of the sorbent. The machine was equipped with air cooled condenser made of cooper, with 23 m^2 of external aluminum fins. The evaporator was designed as a series of 24 trapezoidal cells, 3 cm high, 1 m long, with total heat transfer area of 2.5 m^2. The methanol evaporated inside the cells, which were placed inside a tank with water, to produce ice during the night.

Activated carbon/methanol was also the pair chosen by Li et al. [48] to manufacture a flat-plate icemaker that had its design very similar to the design proposed by Pons and Guilleminot [75], but with smaller solar collectors. The solar collectors had an area of 0.75 m^2 and were charged with 22 kg of carbon. The COP ranged from 0.12 to 0.14, and produced between 5 and 6 kg of ice per m^2 of collector.

Li et al. [76] improved and simplified the previous prototype by removing the valves, and manufacturing the reactor with stainless steel, instead of cooper and aluminum alloy. The reactor was a flat plate collector that was placed inside an insulated case, covered by two transparent plastic sheets with high transmissivity. The stainless steel fins inside the reactor were 10 cm apart, and the adsorbent layer thickness was 4 cm. These dimensions were chosen based on previous experimental results and optimization studies. This prototype was tested under indoor conditions (insolation simulated with quartz lamp) with insolation between 17 and 20 MJ/m^2 and produced around 6.0 to 7.0 kg of ice per m^2 of solar collector, with a COP between 0.13 and 0.15. When tested under outdoor conditions of insolation between 16 to 18 MJ/m^2, the ice production was 4.0 kg per m^2, and the COP was about 0.12. Further improvements in this prototype were achieved by reducing from 1.5 mm to 1 mm, the thickness of stainless steel plate used to produce the reactor, by reducing the thickness of adsorbent layer to 3.5 cm, and by decreasing the distance between the fins to 5 cm. The new prototype, which is shown in Figure 10, produced between 4.0 and 5.0 kg of ice per m^2, with a COP from about 0.12 to 0.14, when the daily solar radiation was between 18 and 22 MJ/m^2. The authors estimated the cost of this machine in about US$ 250 per m^2 of solar panel.

The solar powered icemaker developed by Buchter et al. [45] and tested in Burkina Faso also had ventilation dampers above the adsorbent bed to improve the cooling of the adsorbent bed during the night. The machine used the pair activated carbon-methanol, and had a COP between 0.09 and 0.13 when the insolation ranged from 22 to 25 MJ/m^2. The ice produced by the machine during the night was not removed from the cold box, and it was used to maintain the temperature inside the box at about 5°C, during the daytime.

Figure 10. No valve solar ice maker [76].

Figure 11. Solar refrigerator tested in Rabat, Morocco [77].

Lemmini and Errougani [77] designed and tested for 13 consecutive days an activated carbon-methanol flat plate refrigerator (Figure 11). The tests occurred in the city of Rabat, Morocco, which has a temperate and humid climate. The minimum evaporation temperature and the COP were very sensitive to the daily insolation. The machine had evaporation temperatures below 0 °C only in the days with insolation above 23.8 MJ/m^2. COP higher than 0.05 needed a daily insolation above 24 MJ/m^2.

Hildbrand et al. [78] developed an adsorption icemaker (Figure 12) with silica-gel as sorbent, and water was both the refrigerant and the cooling storage medium. The sorbent was inside a 2 m^2 solar collector. The ice was produced inside the evaporator, and the daily ice production was not measured. The experiments occurred with a constant load of 4.1 MJ/day inside the cold box where the evaporator was located, and the evaporator temperature was constant during a period of 30 days. The machine was tested over a period of 68 days and the COP varied according to the environmental conditions (insolation and outdoor temperature). The COP was between 0.12 and 0.23; when the mean outdoor temperature was between 12 and 25 °C, and the daily insolation higher than 20 MJ/m^2. COP higher than 0.15 were obtained when outdoor temperatures were below 20 °C.

Khattab [46] designed and tested a modular icemaker with the adsorbent placed in a glass container, which acted as solar collector and was positioned between reflector panels. The glass container diameter was 0.2 m^2, and each panel had an area of 0.04 m^2. The author tested the panels at different inclinations, as presented in Figure 13, to assess which configuration produced higher temperatures in the adsorbent. Moreover, four types of adsorbent bed were tested to idenfy which one yielded the best performance. Two beds were filled only with granular carbon, but one of them had black metallic meshes on both faces of the glass container, whereas the other one had black metallic plates. The other two beds had blackened steel together with the granular carbon, but in one of them, the steel was only mixed, and in the other one, it was bounded to the carbon. The adsorbent received solar energy directly, on both sides, and it was uniformly heated during daytime. According to the author, this kind of construction, where the adsorbent, the condenser and the evaporator are inside a single glass unit, eliminates possible sites for air infiltration, and reduces the necessity of maintenance.

The experimental set-up using granular carbon bonded with blackened steel had a COP of 0.16 and a daily ice production of 9.4 kg per m^2 of glass container when the daily insolation was 20 MJ/m^2, the mean outdoor temperature was 29 °C and the reflector panel was in position (c). At this same position, the COP dropped to 0.14, and the daily ice production was 6.9 kg/m^2, when the daily insolation was 17 MJ/m^2 and mean outdoor temperature was 20 °C.

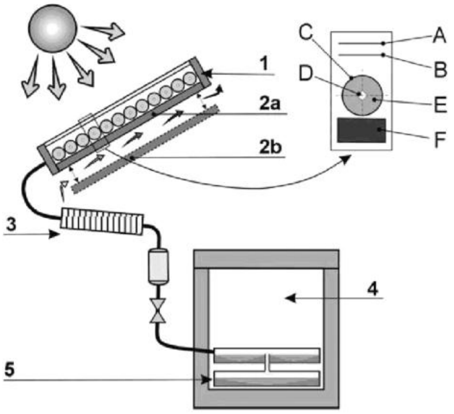


Figure 12. Solar collector/adsorber. 1) with detail: glass cover (A); Teflon film (B); tube covered with selective surface (C); central tube for vapor transport (D); silica gel bed (E); thermal insulation (F); 2) ventilation dampers (a - closed; b - open); 3) condenser; 4) cold box; 5) evaporator and ice storage [78].

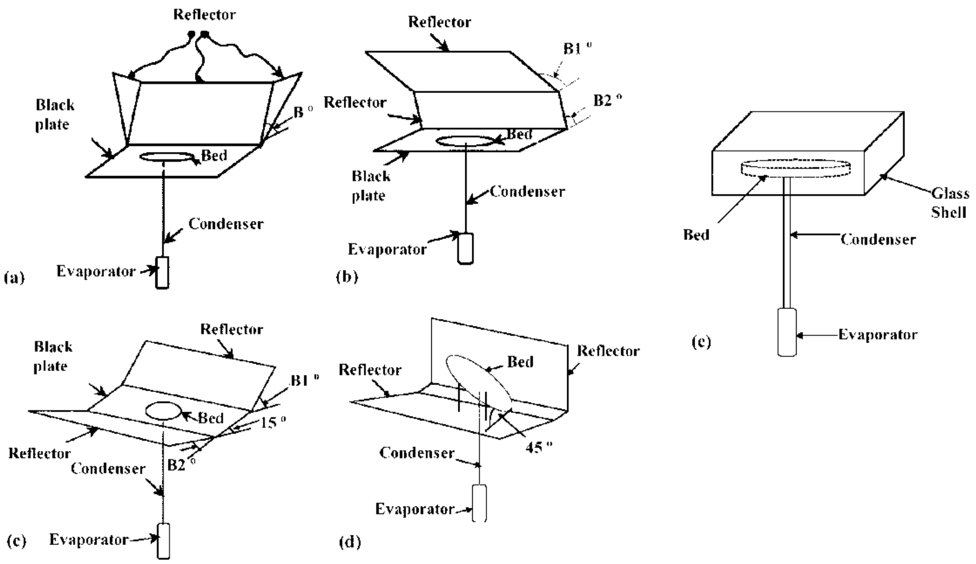


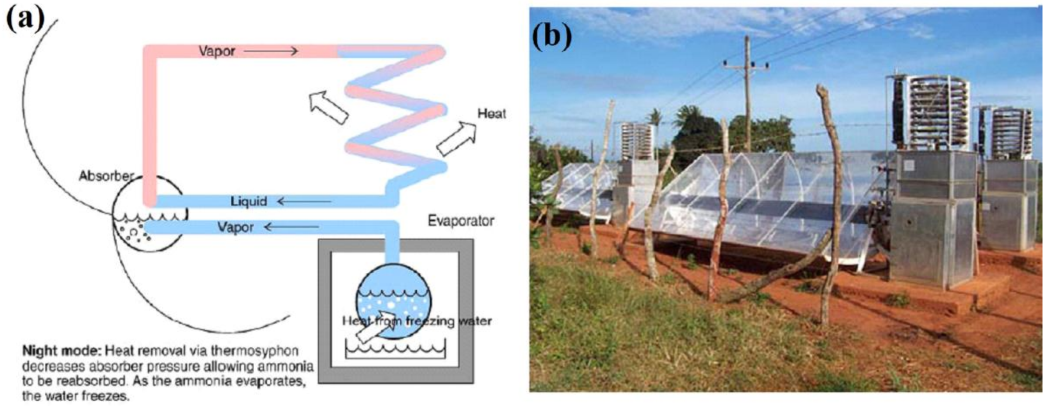
Figure 13. Reflector arrangements [46].

Headley et al. [79] used a compound parabolic concentrating solar collector (CPC) to increase the generation temperature of a activated carbon-methanol solar icemaker. The collector had a concentration ratio of 3.9 and aperture area 2.0 m^2. The system was charged with 2.5 kg of carbon, and yielded up to 1 kg of ice per day, with a COP of 0.02. The major advantage of the utilization of CPC is the possibility to produce ice even on low insolation days (about 10 MJ/m^2).

A solar powered cooling machine with no moving parts was built by Erhard et al. [80], for demonstration purposes. The working pair was SrCl$_2$-ammonia, and the salt was impregnated in expanded graphite to enhance the heat transfer within the sorbent. The reactor was mounted inside a concentrating solar collector, and the enthalpy of reaction was transported out of the solar collector by means of two horizontally positioned heat pipes. The COP was between 0.05 and 0.08, and the evaporation temperature was below -5 °C.

Bansal et al.[65] also used SrCl2-ammonia in their 5.4 MJ/day sorption refrigerator. The generation energy was obtained through 2.1 m^2 of heat pipes vacuum tubes solar collectors. Although a COP of 0.143 was predicted, the maximum COP obtained by the machine was 0.081, when the daily insolation was 27.4 MJ/m^2.

In Kenya, rural communities and dairy cooperatives are using 12 water-ammonia absorption icemaker for milk preservation [60]. The project was funded by the World Bank's Development Marketplace program, in partnership with the Solar Ice Company and the Heifer Project International. The machines operate intermittently, and their generator is placed in the focus of a parabolic solar collector to receive heat during the day. The absorption process occurs in the evening when the generator, acting as absorber, releases heat to the ambient through a heat pipe arrangement (Figure 14a). The system, which is shown in Figure 14b, can produce up to 4.2 kg of ice per m^2 of solar collector.



Night mode: Heat removal via thermosyphon decreases absorber pressure allowing ammonia to be reabsorbed. As the ammonia evaporates, the water freezes.

Figure 14. (a) Scheme of the absorption arrangement of the solar powered icemaker. (b) Photo of the solar powered icemaker in a dairy cooperative in Kenya [60].

Vasiliev et al. [81] developed a 150-200 W sorption refrigerator that used carbon fiber as sorbent, and could run in with a short cycle (15 minutes). The refrigerator (scheme in Figure 15) could be powered with solar energy or electricity. It used heat pipes to heat and cool the sorbent. The cooling effect was obtained by evaporation of ammonia inside another heat pipe, which was inserted in the walls of the cold box.

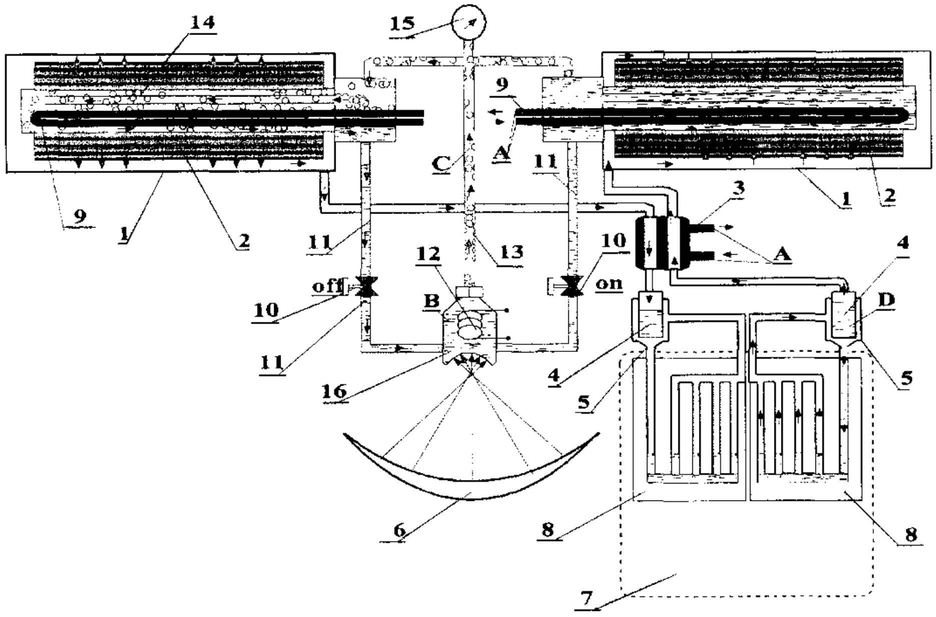


Figure 15**.** Scheme of the solar and electric powered sorption refrigerator. 1) reactors; 2) reaction beds; 3) condenser; 4) porous evaporators; 5) condensers of spaghetti-type heat pipes; 6) parabolic solar concentrator; 7) cold box; 8) spaghetti-type heat pipes; 9) cylindrical condensers; 10) electrical valves; 11) flexible pipes for liquid flow; 12) electric heater; 13) pipe for vapor flow; 14) vapor channel; 15) pressure gauge; 16) boiler - evaporator. Circuits: A) heat sink; B) heat source (liquid); C) heat source (vapor); D) NH_3 [81].

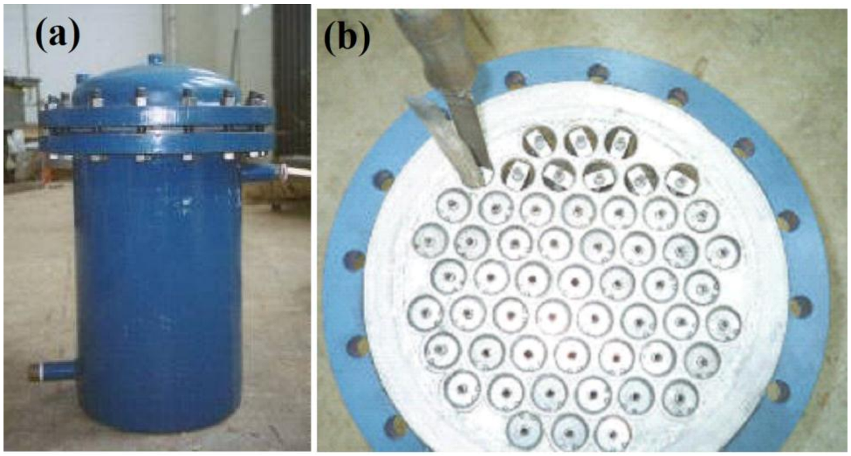


Figure 16. Tube and shell reactor. (a) Side View. (b) Tubes filled with activated carbon.

Oliveira [82] designed an icemaker with the pair activated carbon-ammonia that operated with refrigerant mass recovery. Tube and shell heat exchangers (Figure 16) were used as reactor, and the adsorbent was placed inside the tubes. The daily ice production was 1.2 and 1.6 kg per kg of adsorbent when the generating temperatures were 75 °C and 85 °C, respectively. Reduction of heat transfer resistance in the evaporator, and in the length of the mass recovery process could increase the daily ice production. The COP at these temperatures was about 0.08.

In order to increase the overall efficiency of a solar-heated refrigerator, Wang et al.[83], designed and tested a system that combined a solar water heater and an adsorption icemaker (Figure 17).

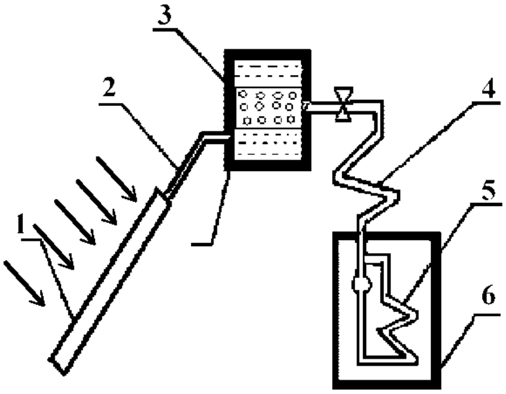


Figure 17. Scheme of the solar-powered water heater and refrigerator. 1) Solar collector; 2) water pipe; 3) reactor; 4) condenser; 5) evaporator; 6) refrigerator (with cold storage); 7) storage tank for hot water [83].

The working pair was activated carbon-methanol. The system had 2 m^2 of evacuated tube collectors, which were used to warm 60 kg of water up to 90 °C. The reactor remained immersed in the storage tank, and while the water was being heated, the desorption process occurred. During the night, the hot water from the storage tank was drained from the storage tank to be used for domestic or sanitary purposes, and the tank was refilled with water at ambient temperature. The water reduced the temperature of the reactor, and promoted the adsorption process. The system produced 10 kg of ice with a COP of 0.14 and water heating efficiency of 79.7 %, when the insolation during the day was about 22 MJ/m^2.

With the current technology on solar-powered sorption icemakers, it is possible to achieve a daily ice production of at least 5 kg/m^2, with a solar coefficient of performance (COP) of 0.12; although, these figures may vary considerably with the solar radiation and ambient temperature. Systems with flat plate and intermittent operations are simpler and cheaper than other types. Systems with parabolic concentrator collector are advised in areas with irregular insolation, because they can be used to produce ice even if the insolation is as low as 10 MJ/m^2.

7. AIR CONDITIONERS

The use of solar-powered air conditioners seems to be an attractive solution to avoid intense use of electricity during peak hours, because the highest demand for air conditioning usually coincides with the periods with higher insolation.

In the 1960s, Farber et al. [84] described an water-ammonia absorption system with flat-plate collectors that was installed in the University of Florida. The system operated continuously over long periods during the day, and produced about 84 kW of cooling, with a COP of 0.57.

According to Thevenot [85], in his *HISTORY OF REFRIGERATION THROUGHOUT THE WORLD*, a solar air conditioning system was installed experimentally in a house at the University of Queensland, Australia in 1966. This author also mentioned that in the following years, several systems based on solar energy were built in many parts of the world, and in 1976, there were about 500 solar absorption systems in USA. Most of the systems had LiBr-water as working pair, and they could run 75 to 80% of their time on solar energy.

At the beginning of the 1980s, an absorption system with LiBr-water was tested to produce 4 kW of cooling, with a COP of 0.11, in northern Italy [86]. Thirty six square meters of flat plate collectors with a black chrome selective surface were used to supply the heat consumed by the absorption chiller. Flat-plate collectors were also used by Yeung et al. [87] who studied the feasibility of obtain solar powered air conditioning in Hong Kong, with a 4.7 kW LiBr-water absorption chiller. The system had an auxiliary electrical heater, and an average solar energy utilization of 55%.

Saha et al. [9] designed and tested a double-stage, four-bed adsorption chiller that could be driven by solar energy or waste heat. When the heating source and the heat sink of the prototype had temperatures of 55 °C and 30 °C, respectively, it produced cold water at 10°C, with a cooling power of 3.2 kW and a COP of 0.36.

The 3.8 kW sorption air conditioner studied by Wang et al. [88] achieved an evaporation temperature of 10 °C, when powered by a heat source at 100 °C. The COP at this condition was 0.4, if the heat sink was at 24 °C. The machine used the pair activated carbon-methanol. The reactors were tube and plate heat exchangers, and the carbon was placed around the tubes, between the plates.

Machines operating under vacuum may have their performance reduced if there is any air infiltration. To avoid such a problem, and also to reduce the total cost of the system, Liu et al. [89] developed and tested a valveless silica gel-water adsorption chiller that worked with regeneration temperatures from 75 °C. The chiller had 52.8 kg of silica gel divided between two adsorbent beds, which operated out of phase to produce constant cooling. The machine had a cooling power of 3.56 kW and a COP of 0.26 when evaporation temperature was 7 °C, heat sink temperature was 28 °C, and heat source temperature was 85 °C. Figure 18 shows the scheme of this chiller integrated to a solar water heater.

Further improvements of this chiller, which is shown in Figure 19, included the reduction of the number of non-continuous and movable pieces to keep at minimum, the possible places for air infiltration. The improvements also included a modification of the adsorbent bed to enhance heat and mass transfer, and a modification in the condenser to avoid undesirable refrigerant evaporation. Such changes leaded to a COP of 0.5, and a cooling power of 9 kW, when the generation temperature was 80 °C and the evaporation temperature was 13 °C.

The pair silica gel-water need relative low regeneration temperatures, and were also used in the 3.5 kW adsorption chiller developed by Nuñez et al. [91]. This machine had two reactors; each one filled with 35 kg of adsorbent. The regeneration temperature had to be at least 75 °C, the heat sink up to 35 °C, and minimum evaporation temperature was 10 °C. The COP varied between 0.4 and 0.6, depending on the operation conditions. The authors compared the performance of this chiller to that of the commercially produced Nishiyodo NAK 20/70 adsorption chiller and to that of the Yasaky WFS SC-10 absorption chiller. The absorption chiller had the highest COP (about 0.7), but the cooling power of the adsorption chiller was less sensitive to the operation conditions.

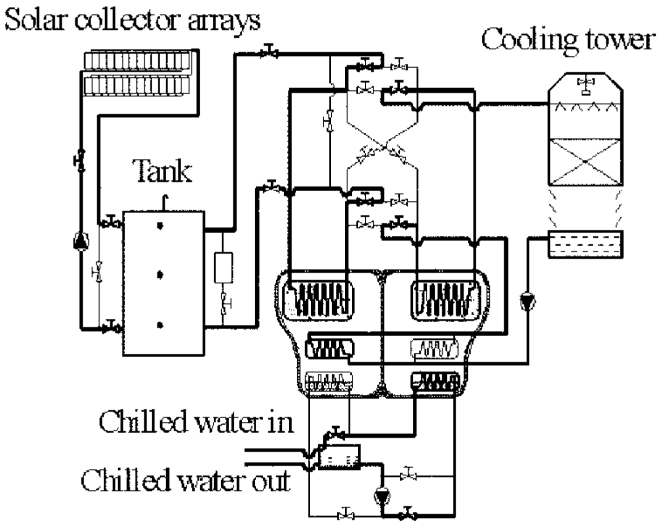


Figure 18. Scheme of the silica gel-water adsorption chiller powered by the solar water heater [90].

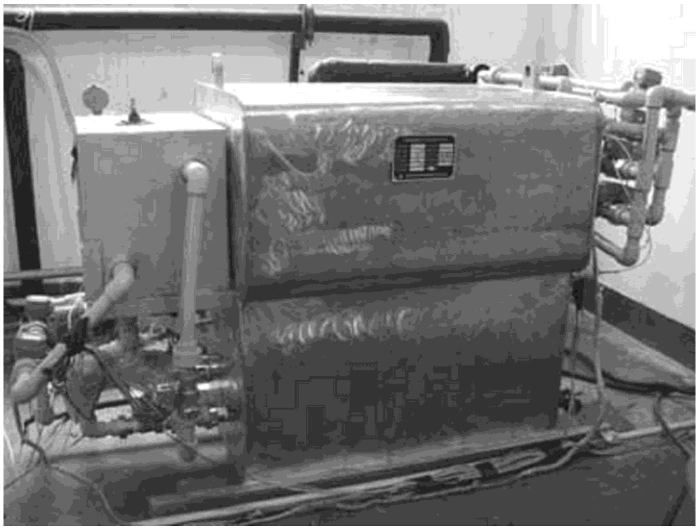


Figure 19**.** Prototype of a silica gel-water adsorption chiller [89].

The impregnation of $CaCl_2$ in silica gel enhances the absorption capacity of up to 0.7 kg of water per kg of dry sorbent; thus, Restuccia et al. [33] tested the feasibility to use this compound in an adsorption chiller. The COP of the chiller was close to 0.6, when the condensation temperature was 35 °C, the evaporation temperature was 10 °C, and the generation temperature was between 85 and 95. The increase of the condensation temperature to 40 °C reduced the COP to values between 0.3 and 0.4, depending on the generation temperature.

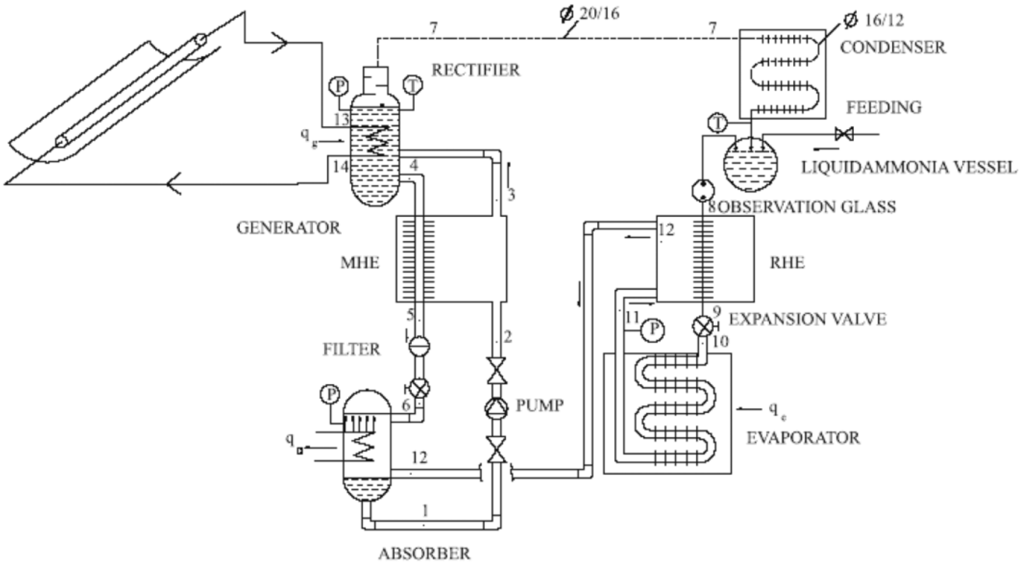


Figure 20. Scheme of parabolic through Water-ammonia solar refrigerator [92].

Absorption systems using the pair water-ammonia need generation temperatures higher than those that can be provide by flat-plate collectors; thus, Sözen et al. [92] used a parabolic trough collector with 2 m^2 of surface area to achieve temperatures around 100 °C inside the generator. The machine had a COP between 0.70 and 0.75, when the evaporation temperature was 10 °C, and the condensation temperature varied between 28 °C and 34 °C. The Figure 20 shows the scheme of the machine, which consisted of a condenser, an evaporator, an absorber, a generator, a pump, expansion valves, a refrigerant heat exchanger (RHE), and a solution heat exchanger (MHE). The heat exchangers were used to increase the performance of the machine.

Air conditioning can also be obtained through open cycle sorption systems, where water from air is the refrigerant. Ismail et al. [21] developed a desiccant system that was employed in a grain storage room. During the night, fresh air flew through two silica gel beds and through two heat exchangers. The absolute humidity and the enthalpy of air were reduced, and the processed air was blown into the grain storage room. During the day, fresh air with low relative humidity was heated by solar energy in the heat exchangers, and used to regenerate the silica gel beds. This system maintained the grain temperature about 5 °C lower than the usual grain temperature without ventilation. The COP of the system based only on the electricity consumption of the fans was greatly influenced by the airflow rate, and ranged from 3.9 to 30.3 for airflow rates between 0.065 kg/s and 0.021 kg/s.

Lu and Yan [93] studied a solar desiccant enhanced radiative cooling system (SDERC) that also used silica gel as adsorbent. The system was installed on the ceiling and side walls of a building at the Industrial Technology Research Institute, in Taiwan. The scheme of the installation is shown in Figure 21. The panels at the ceiling and those on the side walls covered an area of 6.7 and 4.5 m2, respectively, and they operated out of phase to produce dehumidified air continuously.

The dehumidification performance of the system was not constant during the day, due to the variation of the operation conditions of the beds. The authors estimated that a mechanical compression air conditioner would consume 9 to almost 25 times more energy than the SDERC to achieve similar dehumidification performance.

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Since 2003, the liquid desiccant system shown in Figure 22 is in operation in the Energy Research Center building at the Technion – Israel Institute of Technology (Haifa, Israel). Gommed and Grossman [94] reported the performance of this system, which was monitored in the summer of 2003. The system is driven by 20 m^2 of flat-plate solar collectors, and has a dehumidification capacity of 16 kW. The absolute air humidity can be reduced from 16 $g/kg_{dry\ air}$ to 8 $g/kg_{dry\ air}$ in a typical August day. Solar energy was stored in 120 L of 43% LiCl solution and 1000 L of hot water to allow the operation of the system during 4 h, without insolation. The mean thermal COP was 0.81, with parasitic losses of 10%.

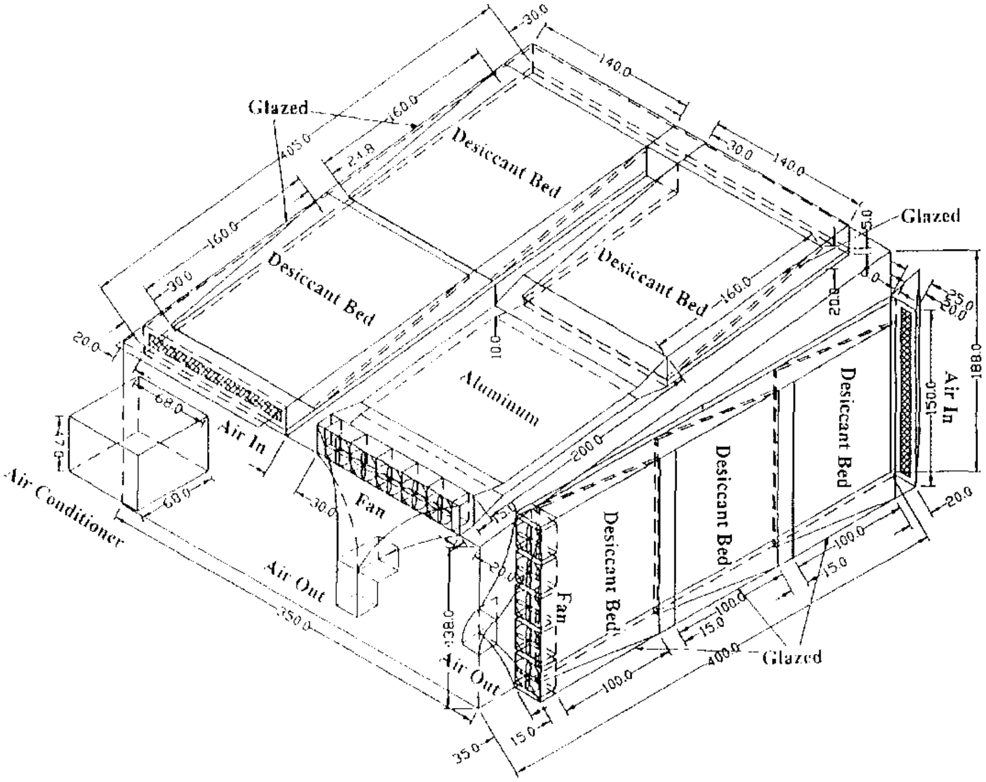

Figure 21. Scheme of the solar desiccant enhanced radiative cooling system [93].

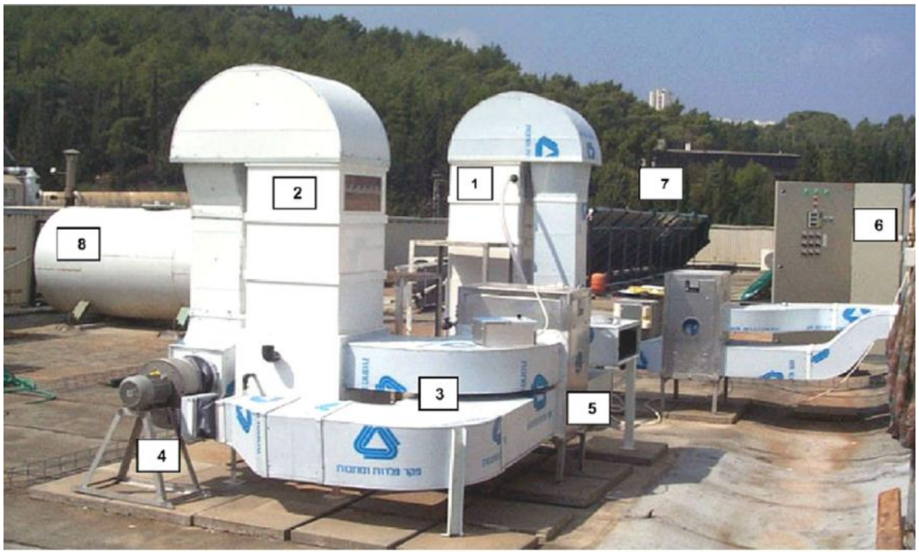

Figure 22. Photograph of the liquid desiccant system: 1 – absorber/dehumidifier; 2 – desorber/ regenerator; 3 – air ducts; 4 – fan; 5 – rotary air/air heat exchanger; 6 – control cabinet; 7 – solar collector field; 8 – hot water storage tank [94].

Desiccant systems can boost the performance of evaporative cooling systems, due to the dehumidification of the air by the sorbent, and Henning et al.[95] studied the combination of these systems. The combined system was able to produce inlet room air at 19 °C, when the ambient temperature was as about 31 °C. The solar energy used to regenerate the sorbent was around 76 % of the total input energy, and the COP of the system was 0.6.

Several other examples of buildings using solar powered are conditioning were presented by Wang and Oliveira [90]. Some of these buildings are facilities from the partners of the European project Climasol[3], and included a university hospital and the Chamber of Commerce in Freiburg, Germany, a cosmetic company in Greece, and the Renewable Energies Department building, in Lisbon, Portugal.

The system installed in 1999 in the Freiburg hospital has 230 m^2 of evacuated tube collectors. The collectors produce hot water, which is used, during summer, to drive a 70 kW adsorption chiller, and in winter, to pre-heat air. The chiller has a COP of about 0.6 and the solar collectors have a mean efficiency of about 32 %, which gives a solar COP of almost 0.2. The total investment in the whole system was € 353,000, and the annual operation cost is about € 12,000.

The cosmetic company in Greece uses air conditioning for an area of 22,000 m^2 (130,000 m^3). The solar powered air conditioner installed in this company utilizes 2,700 m^2 of flat plate collectors to increase the water temperature to about 70 to 75 °C. During the summer, the warm water is used to regenerate the bed of two 350 kW adsorption chillers. In winter, the warm water is used for heating purposes inside the buildings. Solar energy accounts to 66% of the total energy used by the adsorption chillers, and oil burners provide heat during periods of low insolation. Three 350 kW mechanical compression chillers were also installed to meet the cooling demand in peak hours. The total cost of the machinery was € 1,300,000 and such a combination of adsorption chiller and mechanical compression chiller can reduce the CO_2 emissions by about 5,100 tons/year.

The Chamber of Commerce, in Freiburg, has 100 m^2 solar heated desiccant panels, which are responsible for the production of 60 kW of cooling. The desiccant system cools the air of two rooms (total volume of 815 m^3) during summer, and pre-heats the air, in winter. The investment in the system was € 210,000, which was designed to save around 30,000 kWh/year, and to avoid the emission of 8.8 tons/year of CO_2.

A desiccant system is also used for air conditioning the offices on the first floor of the Renewable Energies Department, in Lisbon. The system cost € 75,000, and can provide 36 kW of cooling with a COP of about 0.6. Forty four percent of the energy used by the system is provided by 48 m^2 of the flat plate collectors. The system can avoid the emission of 3.5 tons/year of CO_2, and save around 7,000 kWh/year.

Best and Pilatowsky [96] reported that an international collaboration program between the Mexican and the Federal German Republic governments installed a solar powered air conditioning system in six residential facilities. The houses incorporated passive elements for reducing the cooling load, and had a machine tower with the components of the active solar system. The 316 m^2 of flat plate solar collectors were installed in the roof of the houses. The typical cooling load of a house in the location where the system was installed was 18 kW, but the passive elements reduced it to 7 kW. Then, the total cooling load was provided by a 90

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[3] http://www.raee.org/climatisationsolaire/gb/index_gb.htm

kW ARKLA-WFB 300 LiBr-water absorption chiller. The chilled water was sent to a cold-water storage tank and then, distributed to air handling units installed in each house.

The houses were occupied between 1984 and 1986, and the indoor conditions were kept regularly within a comfortable range of 26 °C to 28 °C, and 50% relative humidity, when the outdoor temperatures were as high as 42 °C to 48 °C. The efficiency of the chiller varied between 53 % and 73%, the overall solar collector efficiency was about 29%, and the yearly solar fraction utilization was around 75%.

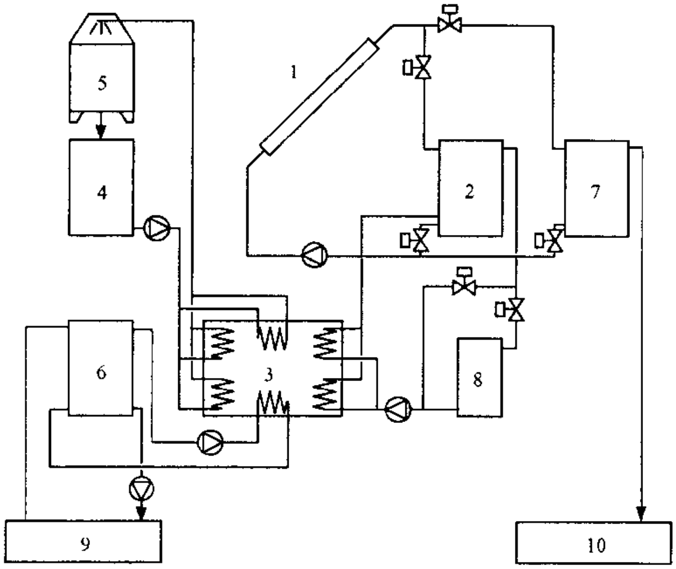
In the city of Shenzhen, China, an integrated solar powered air conditioning and hot water system was installed in a hotel, in 1987 [67]. The system provided cooling to an area of 80 m^2, in summer, and hot water in other seasons. The main components of the system were 38 m^2 of evacuated tube collectors, 38 m^2 of heat pipe tube collectors, 41 m^2 of flat-plate collectors, two 7 kW single-stage lithium bromide absorption chillers (WFC-600, Yazaki Co.), and two 5 m^3 storage tanks for hot and cold water. This system operated for two years, and in clear sunny days, the air conditioner could operate all day, except, during the first morning hours. The main obstacle for the widespread utilization of such a system was the requirement of costly high-grade solar collectors, which are necessary to produce hot water at about 90 °C. Another problem of such a system was the requirement of cooling water below 32 °C, which was not always possible to obtain at this city, during the summer.

Sumathy et al. [67] suggested that the utilization of a double-stage LiBr could overcome the disadvantages of the single-stage system described above. An integrated solar powered air conditioning and hot water system with a 100 kW two-stage absorption chiller was installed on the roof of a building in Jiangmen City, China. The building comprised hotels, business centers, entertainment places and an education center. The solar system had 500 m^2 of flat plate solar collectors, and it supplied 30 m^3/day of hot water which was distributed to the building, and also used to drive the absorption chiller. The chiller provided air conditioning for the education center, with an area of 600 m^2. The scheme of this system is shown in Figure 23.

The collectors provided hot water between 70 °C and 75 °C to the storage tank (2), and hot water at 60 °C to the storage tank (7). The water from tank (2) was used to drive the chiller, whereas the water from tank (7) was employed for daily use. During periods of high insolation, the chillers had the priority to receive the hot water from the collectors, but when the insulation is not high enough, the collector circulation was directed to the tank (7). The oil burner (8) ensured the operation of the chiller during periods of low insolation. The chiller had a COP that varied between 0.37 and 0.44, when the inlet hot water was around 62 °C, and the outlet chilled water was between 7 °C and 10 °C.

Alternatively, adsorption chillers can be used to provide cooling for food preservation. In Jiangsu province, China, a silica gel-water adsorption chiller was part of a solar powered system utilized to cool grain in a depot [90]. This chiller, which is shown in Figure 24, was patented by Xia et al. [97]. It has two identical chambers and a second stage evaporator with methanol as working fluid. Each chamber comprises one adsorber, one condenser and one evaporator (the first stage evaporator), and the whole refrigeration system used in the grain depot is shown schematically in Figure 25. It consisted of four subsystems: (i) solar-powered water heating unit, (ii) adsorption chiller, (iii) cooling tower, and (iv) fan coil unit.

The solar-powered water-heating unit had around 50 m^2 of evacuated tube collectors, a water pump and a storage tank for hot water. The heating unit delivered hot water to the adsorption chiller. The cooling tower was the heat sink for the condensers and for the reactors. The fan coil unit was responsible to deliver the cooling effect from the chiller to the grain depot. The hot water used by the chiller had a temperature between 60 and 90 °C. In a day with insolation between 16 and 21 MJ/m^2, the chiller could supply processed air with temperatures from 14 to 22 °C. The cooling power of the chiller was close to 5 kW and the COP was around 0.32, when the chiller was fed with hot water at 85 °C. However, these figures were reduced to around 3 kW and 0.23, respectively, when water at 65 °C were used.



1. Solar collector; 2. Hot water tank for cooling; 3. Two-stage absorption chiller;
4. Cooling water tank; 5. Cooling tower; 6. Chilled water tank; 7: Hot water for daily life;
8. Oil burner; 9. Air conditioning user; 10. Daily life hot water user.

Figure 23. Scheme of the integrated solar cooling and hot water system [67].

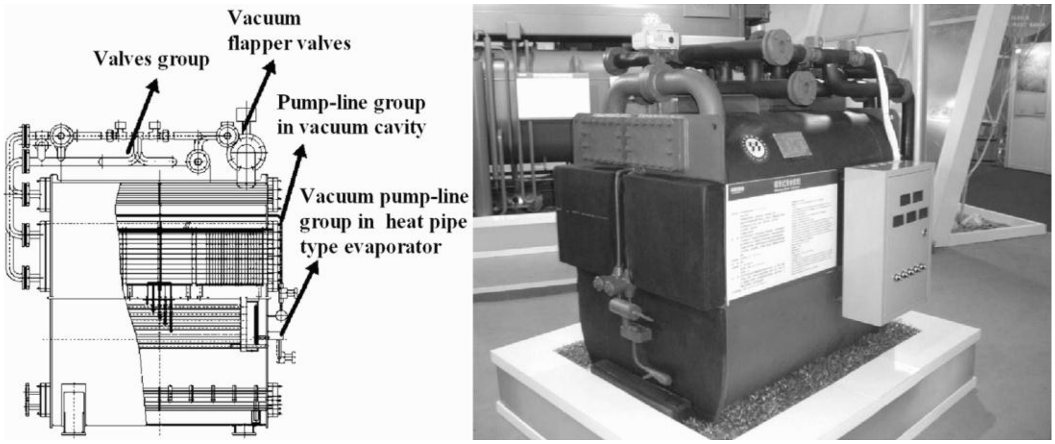


Figure 24. Silica gel-water adsorption chiller with secondary evaporator [90].

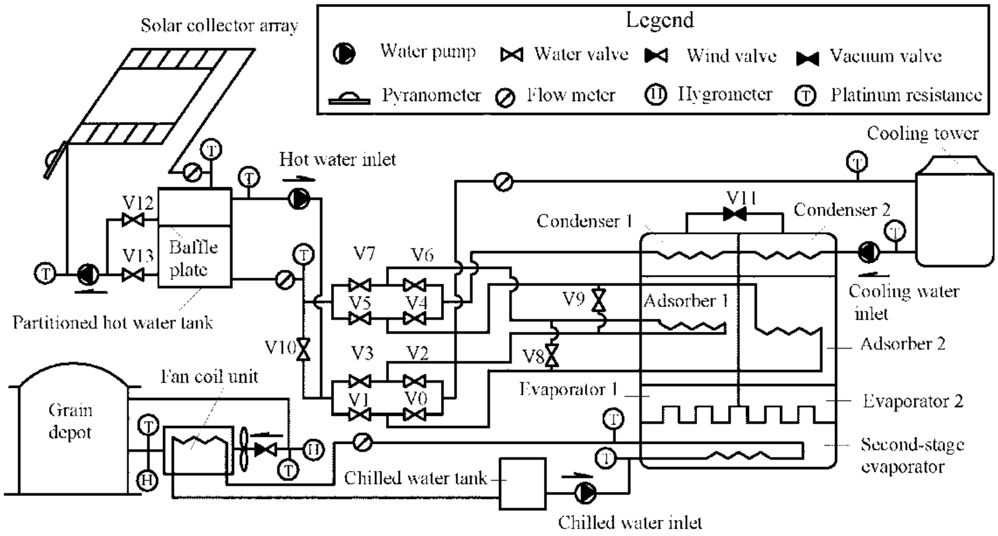


Figure 25. Scheme of the solar-powered system used for cooling a grain depot [90].

The Shanghai Research Institute of Building Science in China also has a solar powered air conditioning system with chillers similar to those described previously, but with higher nominal cooling capacity [90]. The installation has 170 m^2 of U-type evacuated tube collectors, which have mean efficiency of 36 %. The chillers operate between 9:30 AM and 4:30 PM, and they are located in an equipment room on the top floor of the building. Under solar radiation of 19.2 MJ/m^2.day, the chillers could be fed with hot water at 65 °C, and deliver a mean cooling power around 12 kW, with cycle COP of 0.28, and solar COP of 0.09.

8. CONCLUSION

Sorption systems are one of the alternatives for solar powered cooling, and this chapter presented an overview of the operation principle of this type of system. The similarities and differences among the different types of sorption process were discussed, and followed by the presentation of the most common sorption working pairs. Water, ammonia and methanol are the most used refrigerants. Activated carbon and silica gel are the most used physical adsorbents, metal chlorides are the most used chemical sorbents, and water and LiBr are the most used liquid sorbents.

In the past 30 years, several machines have been designed and tested for either ice making or air conditioning, and some of the most representative efforts are shown in sections six and seven.

The technology of solar powered ice makers allows daily ice production of at least 4 kg per m^2 of solar collector, but this figure can be at least 50 % higher in conditions of high insolation.

The ice makers can have continuous or semi-continuous operation, if the reactor is heated by a hot fluid, which was heated in the solar collectors, or intermittent operation, if the reactor is directly heated by solar energy. Intermittent systems are usually cheaper, but are inoperable in low insolation days or rainy days. Systems that are indirectly heated by solar energy can be designed to have an auxiliary heater, which can provide heat to the reactor, when solar energy is not available.

The solar powered sorption air conditioners are usually indirectly heated by hot water. The single stage systems can operate with hot water from 65 °C, whereas double stage systems can use water with temperature from 55 °C. The COP of silica gel-water chillers are usually below 0.5, but this figure can reach values close to 0.7 in LiBr-water chillers.

Solar powered sorption air conditioners are commercially available, but they are still not competitive with conventional electricity driven systems due to their high initial cost. However, solar powered air-conditioning has the advantage that both the supply of solar energy and the need for cooling reach maximum levels at the same time of the day, and in the same period of the year. Moreover, since the 1980s, the research on these systems has increased, and several technical problems associated with the design and construction of sorption machines has been successively resolved. Thus, with the continued development of research in this field, and the popularization of solar water heated systems, the total price of a solar powered air conditioning installation tends to fall, and these systems may become more economically attractive in a close future.

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