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Solar Cooling and Dehumidification Systems - a review

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Abstract— Recently, cooling system, especially air-conditioning system, cannot be absent in many fields such as appliances (homes, schools, shopping malls, factories, and theaters), food, agro-products and pharmaceutical storages, and so forth. Most of the conventional cooling systems driven by electrical power while solar energy, rather than a burning fuel, can provide the heat energy for these refrigeration processes. This paper reviews how, what, and where the solar energy can be applied for cooling systems. The types of sorption processes and the electrical and thermo-mechanical systems using solar energy have been analyzed. Many studies indicated that the absorption system is most suitable for solar cooling systems. Both theoretical and experimental results also showing that solar sorption refrigeration and air-conditioning are reasonable at present and for future applications. The cost of system, the simple and combine-system in designing, maintaining and controlling of system via using network and the simulation for the system are some perspectives need to study to develop the solar cooling systems.

Keywords—***solar energy, cooling systems, air conditioning, renewable energy***

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INTRODUCTION

In some last decades, there are many applications in a considerable number of fields of cooling in human life such as the air-conditioning sector, the food storage fields via freezing, the conservation of pharmaceutical products and so forth. Recently, almost cooling systems apply the vapor-compression refrigeration cycle which uses a circulating liquid refrigerant as a medium to absorb and move heat from the space to be cooled to another space and subsequently dump the absorbed heat out of the system. All such systems have four components: a compressor, a condenser, an expansion valve (sometime called a throttle valve), and an evaporator.

The air conditioner is an appliance, system, or mechanism designed to extract heat from an area using a refrigeration cycle. The purpose of air conditioning system, in the home, building, tower, or in the car, is to provide comfort during hot days and nights. Domestic air conditioning is most popular and ubiquitous in developed Asia-Pacific nations such as Australia, Japan, South Korea, Taiwan, Hong Kong, and Singapore, especially in the latter two due to most of the population living in small high-rise flats. In this area, with soaring summer temperatures and a high standard of living, air conditioning is considered a necessity and not a luxury. It is also increasing in popularity with the rising standard of living in tropical Asian nations such as India, Malaysia, and the Philippines and in some big cities in mainland China. In the United States, home air conditioning is more prevalent in the South and on the East Coast, in most parts of which it has reached the ubiquity it enjoys in East Asia. Central air systems are most common in the United States, and are virtually standard in all new dwellings in most states. In Europe, home air conditioning is less common in part due to higher energy costs and more moderate summer temperatures.

The freezing is the process whereby a liquid turns to a solid. The freezing point is the temperature at which this happens. All known liquids undergo freezing when the temperature is lowered with the sole exception of helium, which remains fluid at absolute zero and can only be solidified under pressure. The popular applications of freezing are food preservation and storage. A food refrigerator or freezer works to moves heat out of the interior into the room in which it stands. So this process can treat and hand food in such a way as to stop or greatly slow down spoilage. This also used to prevent food-borne illness while maintaining nutritional value, density, texture and flavor.

However until now, unfortunately, the refrigeration cycle has been used in almost cooling systems is driven by traditional vapor compression. In general, they have contributed significantly in an opposite way to the concept of sustainable development. In these refrigeration cycles the non-natural working fluids, like the chlorofluocarbures (CFCs), the hydrochlorofluorocarbures (HCFCs) and the hydrofluocarbures (HFCs) result in both ozone depletion potential (ODP) and/or global warming potential (GWP). The environmental impact of fluorocarbon traces in the atmosphere has shown that CFC emissions are responsible for about one third the global greenhouse effects (Dieng and Wang, 2001). For instance, the Regulation of European Commission name “2037/2000 Reg.”, which has been implemented on 1 October 2000, treats the whole spectrum of control and phase-out schedule of all the ozone depleting substances (table 1). This regulation has indicated that till 2015 all HCFCs will be prohibited for servicing and maintaining existing systems (Papadolous et.al, 2000).

Table 1 Time table for refrigerant phase-out in the European Union (Papadolous et al, 2000).

1/1/2001	CFCs banned for servicing and maintaining existing systems Recovered CFCs must be destroyed HCFCs banned in new systems > 100 kW cooling capacity
1/7/2002	HCFCs banned in new systems <100 kW cooling capacity 15% cut in supply of new HCFCs
1/1/2003	55% cut in supply of new HCFCs
1/1/2004	HCFCs banned in new reversible and heat pump systems 70% cut in supply of new HCFCs
1/1/2008	Review of alternatives to HCFCs—ban on HCFCs for servicing and maintaining existing systems might be brought forward 75% cut in supply of new HCFCs
1/1/2010	Virgin HCFCs banned for maintaining and servicing existing systems Total ban on supply of new HCFCs
1/1/2015	All HCFCs banned for servicing and maintaining existing systems

The other thing is these cycles are driven by electricity or heat, which strongly increases the consumption of electricity and fossil energy. Approximately 15% of total of electricity energy produce all over the world is employed for refrigeration and air-conditioning processes and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings (Santamouris and Argiriou, 1994). This situation would create the increasing of global energy consumption while the primary energy is limited.

Due to these problems, it is very important to find out the other energy can be used to drive the refrigeration cycles. Solar energy is huge and is free energy source with its capacity about E=3.8*1023 KW. Therefore, it can be applied to reduce energy consumption, to replace the primary energy, and to protect the environment has emerged in cooling and dehumidification engineering and technology. In the years of 1980s, many activities on solar energy developments in cooling fields have been performed. The most important in starting step is how to develop the components and systems have been achieved. However, these achievements were stopped due to the cost reasons. Coming up to recently, the topic has emerged again. Many new activities, both in research and demonstration projects, are carried out in many countries and international co-operations (Hening, 2007). This paper presents an overview of the principles of solar energy applying and developing for cooling and dehumidification systems.

SOLAR COOLING TECHNOLOGIES

The heat from a solar collector can be used to cooling fields. It may seem impossible to use heat to cooling a space or a building, but it makes more sense if we think of the solar heat as an energy source. By point of view of thermodynamic, there are many processes can be performed to convert of solar energy in cooling. Figure 1 presents an overview on physical ways to convert solar radiation into cooling or air-conditioning (Hening, 2007)

In the existing systems for producing cold using solar thermal energy are based mainly on the phenomena of sorption:

- The process by absorption liquid–gas,
- The process by adsorption solid–gas, and
- The process of desiccant dehumidification.

The other way can be used is transform solar energy to electricity (such as using photovoltaic) or heating energy (run Rankin engine) to drive a vapour compressor.

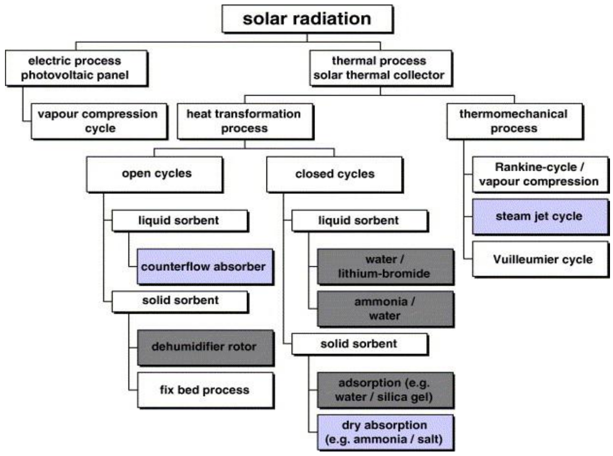


Figure 1. An overview on physical ways to convert solar radiation into cooling or air-conditioning (Hening, 2007)

Solar sorption refrigeration technologies

Solar sorption refrigeration technologies are the prevailing option for the utilization of solar energy in cooling and dehumidification. This applies to adsorption, and absorption. Sorption systems are referring either to open or closed cycles. Open cycles are mainly desiccant systems, while closed cycles are adsorption or absorption systems. The sorption refrigerator includes one or several reactors such as regenerator(s), absorber(s), adsorber(s), and generator(s) etc., depending on the specific cycle and the working pair, and of course the condenser and the evaporator, which exchange refrigerant vapour with the thermal compressor.

In general, the absorption systems are the oldest and most common heat driven systems. In this system, an evaporative refrigerant is absorbed by the absorbent formulating a weak absorbent solution on the low-pressure phase. The weak solution is directed to the generator where the pressurization takes place by de-sorption of the refrigerant. The refrigerant then undergoes a common cooling cycle, while the weak solution is directed to the absorber and the cycle is repeated. Figure 2 shows a typical single effect solar driven $LiBr–H_2O$ absorption refrigeration system. In this system solar radiation come to collector then supply heat for the generator to de-absorb the refrigerants.

The most important thing for an absorption system running is mixture of refrigerant and absorbent called the working pairs. For solar absorption refrigeration systems, there are two major working pairs have been used are

H_2O–LiBr and NH_3–H_2O. In the H_2O–LiBr systems, H_2O is refrigerant and LiBr is absorbent while in the NH_3–H_2O systems H2O is absorbent and NH3 is refrigerant. The H2O–LiBr system is more suitable for air conditioning application and the NH3–H2O system is mainly encountered in industrial applications, in chemical processes, in the food industry and in drying processes. Other working pairs have also been investigated such as NH3–CaCl2 and SrCl2. Each working pair has its advantages and disadvantages, as shown in Table 2.

Table 2. The advantages and disadvantages of two major working pairs (Fan et.al, 2007)

Working pair	Advantages	Disadvantages
NH_3-H_2O	Evaporative at the temperature below 0^0C	Toxic and dangerous for health
H_2O-LiBr	High COP Low operation pressures	Rick of congelation Relatively expensive (LiBr)

The adsorption system

Adsorption systems are based on a physical or chemical reaction process in which the molecules of one substance are adsorbed on the internal surface of another substance (Papadopoulus, et. al, 2000). This is the phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant).

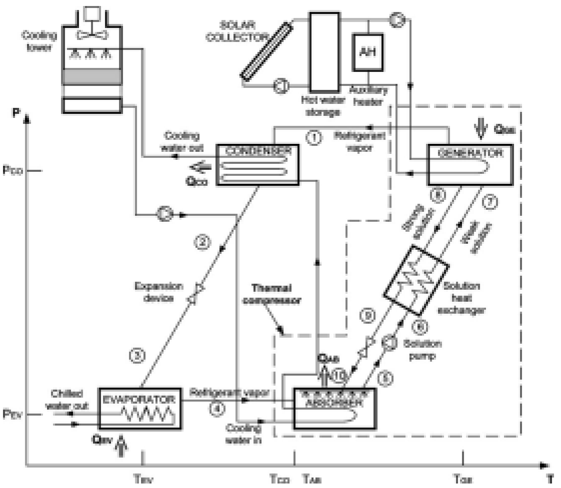


Figure 2. Schematic of a solar driven LiBr–water single effect absorption refrigeration system (Papadopoulus, et al, 2000).

It is generally consisted of a generator, a condenser, a pressure-relief valve and an evaporator. The generator consists of a solar plate containing the adsorbent, which is heated by the solar radiation, for desorption of refrigerants. The general operating principal of solar closed cycle sorption refrigerator is presented in Fig. 3. The process followed at the points from 1 to 9 of Fig. 3. Ambient air is heated and dried by a dehumidifier from point 1 to 2, regenerative cooled by exhaust air from 2 to 3, evaporative cooled from 3 to 4 and introduced into the building. Exhaust air from the building is evaporative cooled from 5 to 6, heated to 7 by the energy removed from the supply air in the regenerator, heated by solar or other source to 8 and then passed through the dehumidifier where it regenerates the desiccant (Florides et al, 2002).

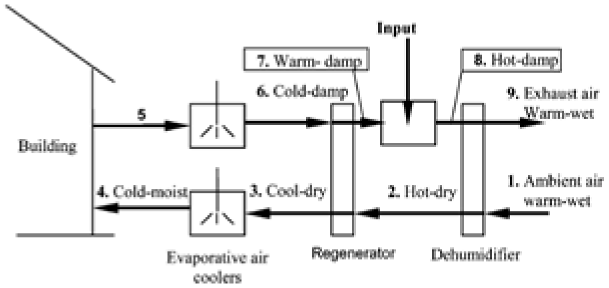


Figure 3. Schematic of a solar adsorption system (Florides, et al 2002)

For the working pair, the main adsorbents used for cooling are silica gel and zeolite, with water as refrigerant. It is noted that zeolite-water systems require the highly temperature of regeneration, is about 1700°C that is not suitable for flat plate of solar collectors. In contrast, the active carbon-methanol systems, and in particular the silica gel-water, can utilize heat at temperatures below 1000°C. As a result, for air-conditioning applications, the most common pairing is silica gel–water system. Figure 4 is a single stage silica gel–water adsorption chiller. Activated carbon-methanol systems can also serve for refrigeration purposes due to methanol can be cooled below 0^0C.

Finally, the main differences between absorption and adsorption sorption cooling systems are located in the nature of the sorbent, which in the latter case is a solid material, and in the duration of the cooling cycle, which is significantly longer for adsorption

The desiccant dehumidification system

The second class of solar cooling is based on open-cycle dehumidification-humidification processes as desiccant technology. This technology has become a valuable tool in the cooling industrial options. The desiccant cooling system provides advantages over the more common vapor-compression and absorption units. For example, desiccant units do not require ozone-depleting refrigerants, and they can use natural gas, solar thermal energy, or waste heat. For case of air conditioning, these systems take in air from outside, dehumidify it with a solid or liquid desiccant, cool it by exchange heat and then evaporative cool it to the desired state. In general, the solar-assisted desiccant cooling consists of the following major components (Dieng and Wang, 2001):

1. A rotary wheel impregnated with a nominal silica gel matrix rotating continuously between the process and regeneration air streams;
2. a sensible heat wheel (rotary regenerator) also rotating between the process and regeneration air stream (the wheel transfers heat from the process side to the regeneration side);
3. process and regeneration side evaporative air coolers;
4. a solar collector storage subsystem for supplying the required thermal energy for regeneration;
5. a gas fired auxiliary heater as a backup for the solar subsystem;
6. a liquid-to-air heat exchanger coil; and
7. two thermostats one for activating the desiccant system and the other for activating the vapor compression system.

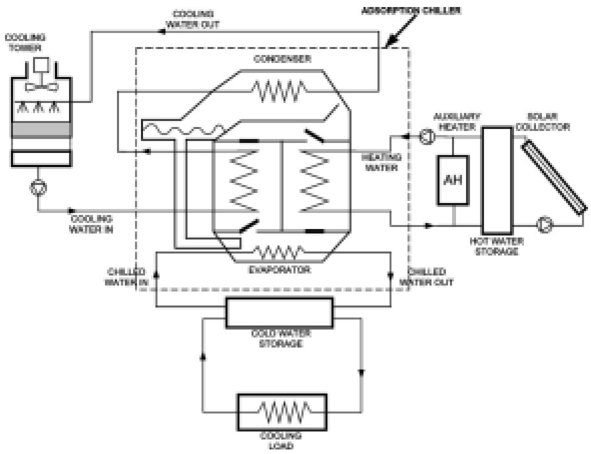


Figure 4. Schematic of a single stage silica gel–water adsorption chiller (Papadopolous et. al, 2000)

Recently, there are many researches in the development of a solar desiccant cooling system (Dieng and Wang, 2001). They have focused on the development of advanced desiccant materials that give improved sorption capacity, favourable equilibrium isotherms, and better moisture and heat rates. This creates the performance of these systems have been improved to get lower initial costs and also make these systems a more attractive alternative to existing vapor compression systems.

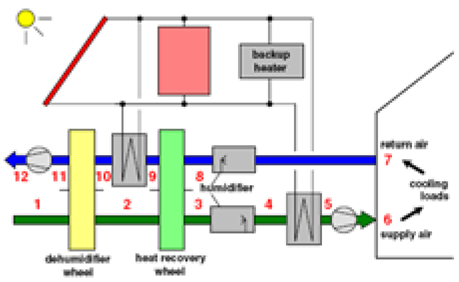


Figure 5. Standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy as driving heat input (Hening, 2007)

Figure 5 presents a standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy as driving heat input (Henning, 2007). In this system the air follows as the processes during the system: 1-2 is the sorptive dehumidification of supply air. This process is almost adiabatic and the air is heated by the adsorption heat and the hot matrix of the wheel coming from the regeneration side. 2 – 3: the pre-cooling of the supply air in counter-flow to the return air from the building. 3 - 4: evaporative cooling of the supply air to the desired supply air humidity by means of a humidifier. 4 – 5: the heating coil is used only in the heating season for pre-heating of air. 5 - 6 a small temperature increase is caused by the fan. 6 – 7: supply air temperature and humidity are increased by means of internal loads. 7 – 8: return air from the building is cooled using evaporative cooling close to the saturation line. 8 - 9 the return air is pre-heated in counter-flow to the supply air by means of a high efficient air-to-air heat exchanger. 9 - 10 regeneration heat is provided for instance by means of a solar thermal collector system. 10 - 11 the water bound in the pores of the desiccant material of the dehumidifier wheel is desorbed by means of the hot air. And 11 - 12 exhaust air is blown to the environment by means of the return air fan.

Figure 6 presents the other types of the desiccant cooling system. This is independent liquid desiccant dehumidification system. This system consists of two loops: the air dehumidification loop and the liquid desiccant dehumidification loop. These two loops are connected by two solution tanks which are specified as strong solution tank and weak solution tank. In the dehumidifier, the strong liquid desiccant solution absorbs water vapor from air at the surface of the packing materials. It is then diluted and pumped from the bottom of the dehumidifier to the weak solution tank waiting for regeneration. The flow rate of the strong desiccant solution varies with the outdoor air humidity ratio to meet the dehumidification task. In the regeneration cycle, the weak solution passes through the regenerative heat exchanger on its way to the solar collector/regeneration. The weak solution slowly flows down the collector's inclined surface where it is heated by solar radiation and water vapor is released into the air.

Figure 6. 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. (Gommed and Grossman, 2007)

Electrical and thermo-mechanical systems

The third class of solar cooling system can be considered by coupling solar heating energy with the heating – power converting equipment as Fig.7.

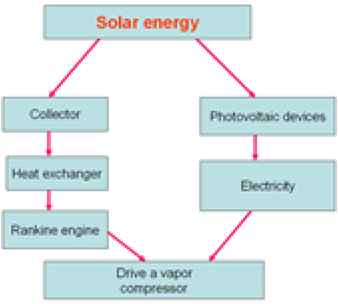


Figure 7. Solar energy can be converted to drive a vapor compressor.

These systems utilize a solar-powered prime mover to drive a conventional air conditioning system. Converting solar energy into electricity by means of photovoltaic devices, and then utilizes an electric motor to drive a vapor compressor. However, the photovoltaic panels have a low field efficiency of about 10–15%, depending on the type of cells used which result in low overall efficiencies for the system. The solar-powered prime mover can also be a Rankine engine. In a typical system, energy from the collector is stored, then transferred to a heat exchanger and finally energy is used to drive the heat engine. The heat engine drives a vapor compressor, which produces a cooling effect at the evaporator. The efficiency of the solar collector decreases as the operating temperature increases, whereas the efficiency of the heat engine of the system increases as the operating temperature increases. In order to find an optimum operating temperature for steady state operation in case of Rankine engine, it is noted that the two efficiencies need to meet at point A as in Fig.8. The combined system has overall efficiencies between 17 and 23%.

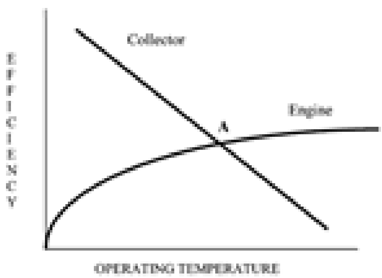


Figure 8. Collector and Power cycle efficiencies as a function of operating temperature (Florides et al, 2002).

Analysis solar cooling system

As above, three major solar cooling systems have been presented. Depending on what are the objectives we need to apply, we can choose a suitable system. Table 3 presents the main points of each system with its advantages and disadvantages. Basing on this table, designers can choose which is suitable for application.

Table 3. The main advantages and disadvantages of solar cooling systems (Florides et al, 2002)

Main advantages and disadvantages of low energy cooling techniques

Cooling method	Advantages and disadvantages
Solar sorption cooling:	Generator temperature must be 70 °C–95 °C with water cooling in absorber and condenser
Lithium bromide-water (LiBr-H_2O)	COP 0.6–0.8 for single effect systems Evaporator cannot operate at temperatures below 5 °C
Ammonia-water (NH_3-H_2O) systems	A rectifying column must be present Generator temperatures must be 125 °C–170 °C with air-cooled absorber and condenser and 95 °C–120 °C when water cooling is used COP 0.6–0.7 for single effect systems
Desiccant cooling	Independent control of humidity and temperature Removal of certain airborne contaminants Ability to use energy sources such as waste heat, solar power and natural gas COP around 1.0
Solar-mechanical systems	Efficiency of photovoltaic panels is very low, about 10% The solar-powered prime mover combined with a Rankine engine has low efficiency about 17–23%. Very expensive system viable for very large applications Difficulty into ensuring that only vapour enters the turbine, since the boiler temperature changes during the day Not steady output power
Heat pumps	COP (useful effect/work done), between 2 and 5 Heat pumps can be used in combination with solar energy for heating

DEVELOPMENT AND APPLICATION

Based on the cooling temperature demand, the developments and applications of solar cooling systems can be broadly classified into three categories: air-conditioning (16–25^{0}C) for spaces, refrigeration (0–8^{0}C) for food and vaccine storage, and freezing (< 0^{0}C) for ice-making or congelation purposes.

Air-conditioning

An air-conditioning system is used to control temperature and humidity for indoor thermal comfort for people. The demand of this application is high in populated place such as a big city. The first application of solar cooling was in the 1960s, in which it was considered to be used in the field of air-conditioning. After that, in *USA* around 500 solar-powered air-conditioning systems were installed at 1976 in which the LiBr was the most using in absorption systems. Meantime in *Japan*, a solar heating and cooling system with flat-plate collectors and absorption refrigeration machine was installed. In *Hong Kong*, a system consisted of a flat-plate collector array with a surface area of 38.2m2, and a 4.7kW nominal cooling capacity H_2O–LiBr absorption chiller had been investigated (Fan et al, 2007). In *Malaysia*, there was a research presented a H_2O–LiBr absorption unit using evacuated tube solar collectors carried out by the TRNSYS program. The results of this research displayed that with the Malaysia's climate a 3.5kW system consists of 35m^2 evacuated tubes solar collector sloped at 20^{0}C. In *China*, solar-powered sorption systems have been studied intensively during last several years. The institute of refrigeration and cryogenics in Shanghai Jiao Tong

University developed and tested different kinds of prototypes for practical purposes: air conditioning for bus and train locomotive. Figure 9 presents the schematic of this air-conditioner.

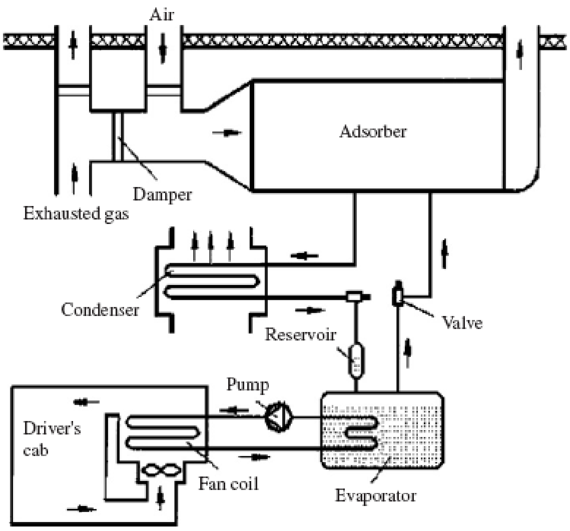


Figure 9. Schematics of locomotive air-conditioner applied in China (Fan et al, 2007)

In *Europe*, more close attention was paid to the research and application of solar powered sorption systems for air-conditioning. Figure 10 displays an overview solar cooling system installed in Europe with 70 systems. Two countries leading in this field are *Germany and Spain*.

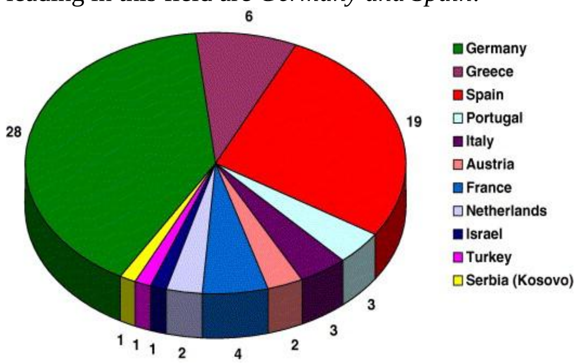


Figure 10. Overview about systems installed in Europe (Henning, 2007)

The International Energy Agency (IEA) set up the "Solar Heating and Cooling" program in 1977, which was actived up to 2005. The other is "Solar Assisted Air Conditioning of Building" project, which ended in 2004, focused on the use of solar energy for air-conditioning of buildings. The main objective of this project was to improve conditions for the market entry of solar-assisted cooling systems, mainly absorption and adsorption systems (Fan et al, 2007). EU project SACE (Solar Air Conditioning in Europe), aimed to assess the state-of-theart, future needs and overall prospects of solar cooling in Europe was done recently. The potential energy savings and limitations of solar thermal air-conditioning in comparison to conventional technologies are illustrated and discussed. The solar cooling system for typical Spanish houses in Madrid had been developed. This system consisted of a flat-plate collector array with a surface area of 49.9m^2, a 35kW nominal cooling capacity single-effect (H_2O–LiBr) absorption chiller. The measured maximum instantaneous, daily average and period average COP were 0.60 (at maximum capacity), 0.42 and 0.34, respectively.

Refrigeration

The low temperature application like food and vaccine storage can be used as sorption systems. These technologies are attractive for refrigeration purpose in some remote or rural areas of developing countries where the access to electricity is impossible. Various kinds of solar sorption refrigerators have been developed.

A small capacity (56 litters) solar-energy stimulated H_20-NH_3 absorption-type refrigerator has been developed to store vaccines in remote locations in the Third World. For this, conventional absorption-cycle and solar-energy systems have been modified and coupled in a novel way to produce a reliable and low-cost refrigeration unit (Uppal et al, 1986). In the *Danube Delta*, Solar refrigeration is especially attractive in isolated regions. An intermittent single-stage H_2O-NH_3 solar absorption system of 46 MJ/cycle had been developed for fish preservation in which solar collectors heat the generator. The system coefficient of performance $(COP)_{system}$ varies between 0.152 and 0.09 in the period of May–September. Actual $(COP)_{system}$ values of 0.25–0.30 can be achieved at generation and condensation temperatures of 80°C and 24.3°C respectively. For bigger capacities of 450–675 MJ/day, the pay-off period is estimated to be 6 and 4 years respectively and the life-time to 15–18 years (Staicovici, 1986).

In *India*, for the cold storage of agricultural products at temperatures of 2–4°C, a solar-hybrid cooling system has been developed. It uses solar energy from flat plate collectors and the waste heat of a gen set, operated with producer gas. A commercially available low temperature (80–90°C) adsorption cooling system for air-conditioning application had to be modified for operation at cooling temperatures below the freezing point of water. Methanol instead of water was investigated as a refrigerant. Because of the inferior thermodynamic properties of methanol and the lower operation temperature, the efficiency is reduced. Calculations showed that the *COP* for a commercial adsorption cooling system is about 30% when operating the system with methanol- silica gel at a chilled water temperature of T_0=−2°C, a heating water temperature of T_h=85°C and a condenser temperature of T_c=30°C (Oertel and Ficher, 1998).

Hammad and Habali (2000) designed a solar-powered absorption refrigeration cycle using NH_3 –H_2O solution to cool a vaccine cabinet in the *Middle East*. An insulated steel sheet cabinet of 0.6 × 0.3 m face area and 0.5 m depth was designed. The cabinet was intended to store vaccine in remote desert areas, away from the electrical national grid. The inside temperature of the vaccine storage cabinets is to the range of 0–8°C. A solar energy powered absorption refrigeration cycle using Aqua-Ammonia solution was designed to keep this cabinet temperature in the range of required temperatures, away from the outside temperature, which reaches about 45°C in August. Refrigeration cycle coefficient of performance ranged between 0.5 and 0.65.

In *Freiburg, Germany* a solar cooling system is operated by the University hospital (Henning, 2007). The system consists of an adsorption chiller with a capacity of 70 kW and a field using evacuated tube collectors with an aperture area of 170 m2 shown in Fig. 11. The project was monitored over a period of 4 years. Main results are: the solar collector works properly and the COP of the adsorption chiller seems acceptable after a series of improvements in control. The other experiment is set up as Fig.12 in which a solar powered adsorption refrigerator using the pair activated carbon AC35-methanol was studied in Rabat, Morocco (Lemmini and Errougani, 2005). It has been built and tested in the solar laboratory of the faculty of sciences of Rabat, Morocco with a Mediterranean climate. Experimental results show that the refrigerator gives good performances in Rabat. The unit can produces cold air even for rainy and cloudy days and the COP (cooling energy/solar energy) ranges between 5 and 8% for an irradiation between 12,000 and 27,000 kJ/m2 and a daily mean ambient temperature between 14 and 18 °C. The performance of the unit could be higher if the cold chamber is well insulated, which is the next objective of this work. The use of automatic valves for connections between the elements of the unit could also improve the efficiencies of the refrigerator. Even though the COP is low compared to the one given by conventional vapor compression refrigerator, the solar powered adsorption refrigerator is using free energy for its operation. It is also noiseless and environmentally friendly.

Figure 11. 70 kW adsorption-chillers in a hospital, in Freiburg, Germany (Henning, 2007)

Freezing - Ice maker

For freezing application that needs temperature below 0^0C such as icemaker or congelation storage. An absorption chiller, an adsorption chiller, or a chemical reaction chiller can also be used. Due to the temperature requires for this application is lower than free-temperature of water means the lower cooling temperatures demanded, the higher generation temperatures are needed for driving a sorption refrigeration system.

AIn 1991, there was a study for a non-valve solar adsorption ice maker with a 0.8m2 collection surface (Fan et al, 2007). The prototype employed an intermittent daily cycle with activated carbon AC35–methanol pair. The results showed that, with a collection efficiency of 0.41 and a thermal COP of 0.40, it is possible to obtain a gross solar COP of 0.15, and produced 4 kg of ice per day, during summer. In 1994, Critoph built a small solid adsorption solar refrigerator. The collector is 1.4 m^2 in area and contains 17 kg of active carbon. It uses transparent insulation to reduce collector heat losses. The cold box is remote from the collector, being linked to it by a flexible steel hose. It is possible to produce up to 4 kg of ice per day in a diurnal cycle. In 2000, an adsorptive solar refrigerator was built in *Switzerland* with the adsorption pair is silica gel and water (Hilbrand et. al, 2004). The machine does not contain any moving parts, does not consume any mechanical energy except for experimental purposes and is relatively easy to manufacture. Cylindrical tubes function as both the adsorber system and the solar collector (flat-plate, 2 m^2 double glazed); the condenser is air-cooled (natural convection) and the evaporator contains 40 litters of water that can freeze. This ice functions as a cold storage for the cabinet (320 litters).

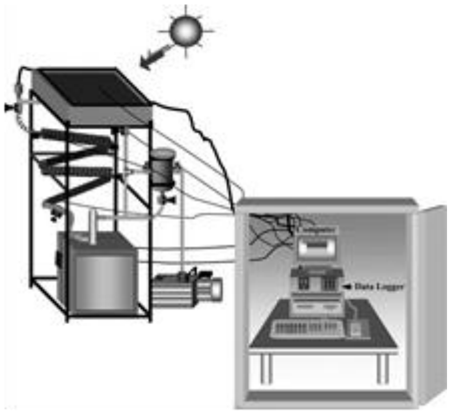
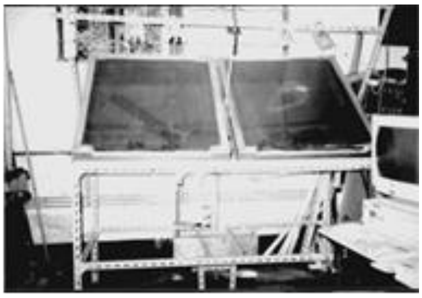


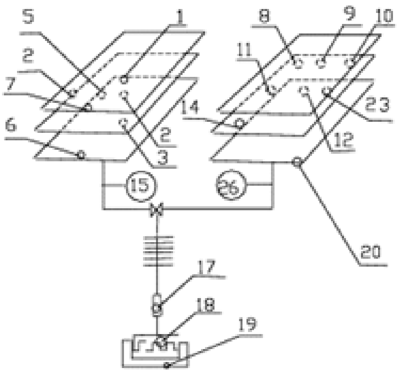
Figure 12. Layout of the experimental unit in Rabat Morocco (Lemmini and Errougani, 2005).

In China, a lot of research work on adsorption refrigeration has been done in *Shanghai Jiao Tong University* since 1993. Several prototype adsorption icemakers have been developed and tested in the past years. A flat-plate solid-adsorption refrigeration ice maker has been built for demonstration purposes by Li et. al (2002). The working pair consists of methanol used as the refrigerant and activated carbon as the adsorption medium. The adsorbent bed is constructed of two flat-plate collectors, with a total surface area of 1.5 m^2. Solar radiation can be simulated with quartz lamps and some important parameters such as temperature and pressure of each subsystem can be handled by a computer (Fig.14). The experimental results show that this machine can produce 4–5 kg of ice after receiving 14–16 MJ of radiation energy with a surface area of 0.75 m^2, while producing 7–10 kg of ice after receiving 28–30 MJ of radiation energy with 1.5 m^2. These are the most advanced results for a solar ice maker so far. All these successful achievements will speed up the commercial processing of a solar ice maker (Li et al. 2002).

After some improvements, these authors built a no valve solar ice maker on the basis of the previous research achievements (Li et al, 2004). The characteristics of the no valve solar ice maker appears to be reasonable application in west of China, where the solar radiation resource is abundant while the availability of electricity is relatively less in most villages (Fig.13). The price of the no valve solar ice maker can be expected no more than about US $250 for per solar ice maker with 1 m^2 collector. This solar ice maker (Fig.14) can produce about ice of 4–5 kg each sunny day under the condition of about 18–22 MJ/m^2 solar isolation. The no valve solar ice maker is expected to be economical in west of China in near future and fabricated for mass application in China.



a)



b)

Figure 13. **a)** Sketch of measurement distributing points for the solar ice maker: (1–7) temperature measurement points of the first adsorbent bed; (8–14) temperature measurement points of the second adsorbent bed; (20) compensate temperature point; (15,16) pressure measurement points; (18) temperature measurement point of refrigerant; (19) temperature measurement point of water in the ice box. **b)** Photograph of the solar ice maker (Li et al, 2004).

Though application of solar sorption refrigeration systems in the field of ice making has proliferated in recent years, effort in congelation, especially in low-temperature applications (such as $T<-18^0C$) is lacking. A review from Wang (2001) summed up an adsorption ice-making system driven by generation temperatures from 90 to 100^0C with activated carbon–methanol as working pair. *This system can reach an evaporation temperature as low as -15.5^0C.*

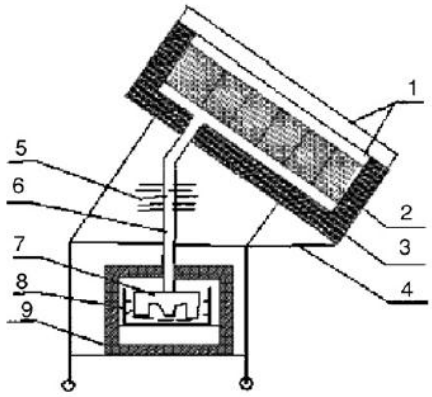


Figure 14. The sketch structure of the no valve solar icemaker: (1) cover plate, (2) adsorbent bed, (3) insulation materials, (4) ice frame, (5) condenser, (6) connecting pipe, (7) evaporator, (8) water tank, (9) insulation box (Li et al, 2004b).

DISCUSSION

The first thing need to focus is if *we think of the solar heat as an energy source*, solar energy can be applied to reduce energy consumption, to replace the primary energy, and to protect the environment has emerged in cooling and dehumidification engineering and technology.

The other is what type of solar energy cooling system technology can be applied popularly.

- The solar sorption refrigeration systems are suitable for air-conditioning due to the low installation cost and the high cooling capacity. In these systems, the H_2O–LiBr working pair is more suitable for air conditioning applications. Solar air conditioning has a strong potential for significant primary energy savings. In particular, for southern European and Mediterranean areas, solar assisted cooling systems can lead to primary energy savings in the range of 40–50%. Related cost of saved primary energy lies at about 0.07€/kWh for the most promising conditions (Balaras, 2007). The NH_3–H_2O system is mainly encountered in industrial applications, in chemical processes, in the food industry and in drying processes.
- In the solar desiccant systems, zeolite-water systems require the highly temperature of regeneration, is about 170^0C so it is not suitable for flat plate of solar collectors. If apply for air-conditioning applications, the most common pairing is silica gel–water system. Development of advanced desiccant materials is one of important thing for these systems become more attractive.
- With solar refrigeration system, ice can be made with about 4 kg per $1m^2$ of collectors per day. However the solar COP is not high, about 0.12 to 0.15.

Figure 15 displays the results of the solar cooling system installed in Europe (Henning, 2007) in which indicates that about 59% of systems use absorption chillers. In about 11% of the installations an adsorption chiller is installed. Only about 6% of all installations use liquid desiccant technology which shows that this technology is still less developed on a commercial level.

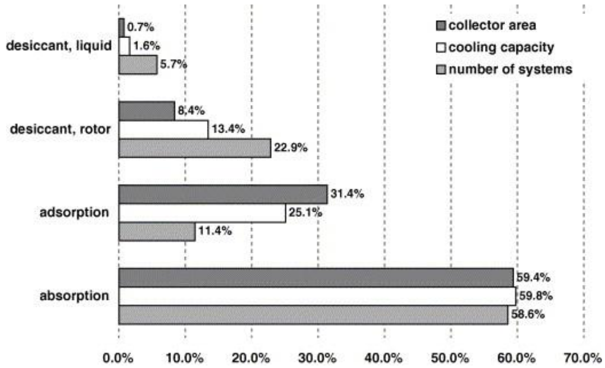


Figure 15. Distribution of systems in terms of number of systems, cooling capacity and installed collector area in Europe (Henning, 2007)

A distribution of the specific collector area defined as the collector area installed per kW of cooling capacity is shown in Fig. 16. The installed collector area for the water chillers (absorption, adsorption) is higher than for the desiccant systems. A typical value for water chillers lies in the range of 3m^2 per kW while for the desiccant systems a typical value is about 1.5 m^2 per kW which corresponds to about 10 m^2 per 1000 m^3 /h of nominal air flow rate.

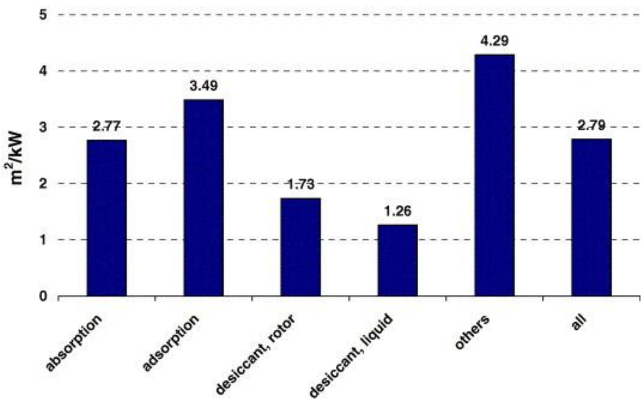


Figure 16. Distribution of the specific collector area (collector area in m2 of installed cooling capacity in kW) for the different technologies (Henning, 2007)

The last thing is how does develop the using solar energy in cooling fields. Some perspectives as follow need to study:

1. optimizing the economics by develop the small thermally driven chillers and open cooling cycles, and using the “solar combi-systems”,
2. needing the greater effort in design phase than a conventional system,
3. using computer simulation to identify the best energy-cost performance,
4. keeping the hydraulic design as simple as possible,
5. using Web-base or means of telecommunications networks for operation monitoring of the system as well as making this become simpler,
6. waste heat driven adsorption systems should be market-attractive for application in energy utilization systems, and
7. using and applying the adsorption heat pump for house hold application.

CONCLUSION

This paper has summarized the solar cooling systems both in researches and applications. Air conditioning is the first application of using solar energy. Several thermally driven air conditioning technologies are market available by today, which enable the use of solar thermal energy for this application. Based on current technologies, market available thermally driven cooling devices and market available solar collectors, solar assisted air conditioning can lead to remarkable primary energy savings. Various research aspects on adsorption refrigeration have been completed in many countries, and some new researches are still going on. Both experimental and research results show that solar sorption refrigeration and air-conditioning are reasonable at present and for future application.

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