A review of active solar cooling technologies

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ABSTRACT

In hot climate, passive cooling techniques will often be unable to provide all the cooling needs. In such situation, active cooling is needed to keep the temperature within the comfort zone. Nevertheless, this additional cooling can also comes from renewable energy sources. For this purpose, solar air conditioning represents a technical solution keeping the environmental impacts at minimum. A significant advantage of this technology it is the fact that summer peak cooling period is conveniently associated with a high level of solar radiation.
Development of this technology has been carried over the last 30 years with most work done in the last 10 years. It is now mature enough to show a strong potential for significant primary energy savings. In particular, for southern European and Mediterranean areas, solar assisted cooling systems can bring energy savings in the range of 40 to 50%. For more northern countries, where cooling loads are much lower, this technique can be coupled with more traditional solar applications like water and space heating. In this communication, we will review the state-of-the-art and potential of solar-assisted cooling and air conditioning technologies.

1. INTRODUCTION

At first glance, solar cooling is counter intuitive: how do you cool something by using a heat source, while not violating any laws of thermodynamic? Off course, there is the simple solution of using a photovoltaic solar panel to drive a classical heat pump or a thermoelectric cooler. Alternatively, one could use the heat to drive a thermal motor, which itself would drive the thermopump. If those techniques are possible, they tend to be ineffective. This is why, in most system, the functional principle is to emulate the classical heat pump evaporation-condensation cycle by replacing the compressor by a sorption cycle, which has the same function..

The cooling technologies based on this principle are quite old. In 1929, Miller (Miller 1929) described several systems, which utilized silica gel and sulfur dioxide as an adsorbent/adsorbate pair. During the 1930s and 40s, Thomas Midgley, jr. and co-workers,working for the Kinetic Chemical Company revolutionized the chemistry of operating fluids for refrigeration (Midgley et al, 1931, 1934). Simultaneously, Edmund Altenkirch and Francis Bichowsky (Bichowsky 1935, 1937, 1938; Bichowsky &. Kelley 1935) were putting forward concepts and technical solutions for open absorption systems that are still used today. Later, Alexis Berestneff (Berestneff 1951) was developing LiBr-H_2O systems for the Carrier Corporation. However, the development of cheap reliable compressors and electrical motors and the improvement in power station efficiency as the introduction of CFCs in the 1930s, sorption refrigeration became a niche technology (Zigler 1999).

In the 1960s, solar-powered absorption systems were considered for air-conditioning (Kapur 1960; Faber et al. 1966). The first large-scale experiment of their usage for air-conditioning can be traced to the 1970s. Indeed, in 1976, around 500 solar-powered air-conditioning systems were installed in USA, most of them were absorption systems using the LiBr-H_2O cycle (Fan et al. 2007). Meantime in Japan, a solar heating and cooling system with flat-plate collectors and absorption refrigeration machine was installed (Nakahara 1977).

In 1977, the International Energy Agency (IEA) started the "Solar Heating and Cooling" program. The Task 25 of this program "Solar Assisted Air Conditioning of Buildings", which ended in 2004, focused on the use of solar energy for air-conditioning of buildings. The main objective of the task was to improve conditions for the market entry of solar-assisted cooling systems (Henning & Albers 2004)

Following the second oil shock in 1979, many projects of solar cooling were developed; some of them were available on the market (Lamp, & Ziegler 1998). In the 90', the need to curtail the usage of the ozone depleting refrigeration fluid, following the introduction of the Montreal protocol in 1988, lead to a renewal in interest for the alternative cooling technologies (Stephan and Krauss 1992).

Solar cooling technology presents the great advantage of being well coupled with the thermal load, which attenuates the peak electricity demand driven by cooling needs in summer. As the planet warms and heat island increases, this problem will become more pressing in the future. The total energy consumption is also reduced. In southern European and Mediterranean areas, solar assisted cooling systems can lead to primary energy savings in the range of 40–50% (Baleras et al. 2007).

Today, the technology is relatively mature, and many commercial solar cooling systems are sold. These are essentially based on three technologies: absorption, adsorption and desiccant cooling. Recently, a few systems were also developed to provide both cooling and water heating (Aldhou et al. 2007).

2. ABSORPTION COOLING

The phenomenon of absorption is caused when a mixture of two fluids (gas or liquid) is present in a solution. For cooling purpose, this phenomenon must also be easily reversible. Absorption systems are similar to vapor-compression air conditioning systems but differ in the pressurization stage. Today, this technology is largely dominant for air conditioning applications.

The typical cycle follows this sequence (see Figure 1)

1. A mechanical pump brings the refrigerant enriched solution towards the high-pressure zone.
2. The mixture is heated in the generator; this allows the separation of the refrigerant from the absorbent.
3. The vapors of refrigerant are moved into of condenser, expansion valve and evaporator. Cooling is produced by the evaporation of refrigerant in the evaporator at low pressures.
4. The poor solution turns over in the absorber by moving trough a pressure-relief valve.
5. The vapors of refrigerant are absorbed by the poor solution of absorber coming from the generator, which then acts as a compressor.

It should be pointed out that a medium temperature cooling fluid must be provide for both the adsorber and the condenser to remove the latent and sensible heats. For this purpose, the cooling fluid is often water cooled into an evaporation tower. Since, water shortage might be an issue in some circumstances, air cooling can also be used but at the cost of degraded overall system performances (Helm et al. 2009)

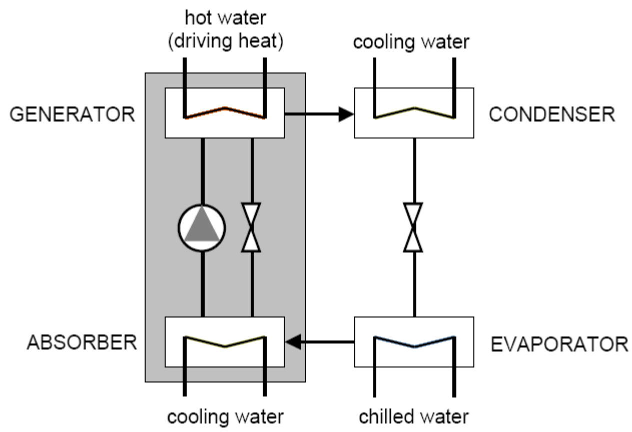

Fig 1: Absorption cooling cycle (adapted from ESTIF 2006)

The main advantage of this method is that refrigerant vapor is compressed with a minimal amount of mechanical energy. Overall, there is only one pump and a few valves that are moving parts. Two major working pairs used in the solar absorption refrigeration systems are H_2O–LiBr and NH_3–H_2O. Water being the refrigerant and LiBr the absorbent in the former system, while at the opposite NH_3 is the refrigerant and H_2O is absorbent in the latter case. Broadly, speaking, NH_3–H_2O systems are often used for refrigeration and in industrial applications, while H_2O–LiBr systems are more suitable for air-conditioning purposes (Desideri et al. 2009).

Most systems used today are single-effect cycle based on the H_2O–LiBr pair. The LiBr-H_2O system operates at a generator temperature in the range of 70°C–95°C, which allows the usage of simple flat solar collectors. Water is used as a coolant in the absorber and condenser (Duffie & Beckman 1991). A disadvantage of LiBr-H_2O systems is that their evaporator cannot operate at temperatures much below 5 °C since the refrigerant is water vapor and might freeze. This is why they are mostly used for climatisation. Their coefficient of performance (COP), which is the ratio between cooling power and heating and electricity power inputs is rather low with a typical value between 0.6 and 0.8 (Desideri et al 2009). This is very poor by any standard, but it is acceptable in this case since energy is in large part provide by the sun.

They are now double-effects systems available on the market. They use two generators working at different temperatures and operating in series. The latent heat of condensation of the refrigerant desorbed from the first generator is being recycled in the second generator. These systems are able to achieve a COP in the range of 1.0-1.2. Nevertheless, they require higher operation temperatures (≈140°C), which can only be provided by a solar concentrating system or an evacuated tube, both techniques being more expensive than flat plate collectors. This is an important factor since the solar collectors are the main cost driver in such system (Grossman 1992; Balaras, et al 2007). Their utilization also reduces the effectiveness of the solar energy capture efficiency due to higher heat loss.

The NH_3-H_2O system requires generator temperatures in the range of 125°C–170°C with air-cooled absorber and condenser and 95°C–120°C when water-cooling is used. Again, these temperatures cannot be obtained with flat-plate collectors. In addition, since NH_3-H_2O systems are mainly used for refrigeration application, they need a rectifying column that assures that no water vapor enters the evaporator where it could freeze.

3. ADSORPTION COOLING

Instead of using a liquid sorbent, some cooling systems are based on a solid sorption material. This process named adsorption is a phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant or adsorbate), based on a physical (Van der Waals interactions) or chemical reaction process (Critoph 1999). The utilization of this process for refrigeration was common in the first decade of the twentieth century (Plank 1960).

They use the properties that the typical heat of adsorption is 30-100% higher than the heat of condensation of the adsorbate. This has the consequence that vapor from a liquid will tend be concentrated in the adsorber. The exchange of heat due to evaporation and adsorption leads to a temperature increase in the adsorber and in a temperature decreases in refrigerant liquid. (Suzuki 1980), which is the basis of refrigeration system.

This approach as recently received more attention (Sumathy et al 2003; Alghoul et al. 2007; Yong & Wang 2007; Wang et al. 2010), since it needs no moving part, except valve, and hence is essentially noiseless. In addition, it can be powered by a low-grade heat source.

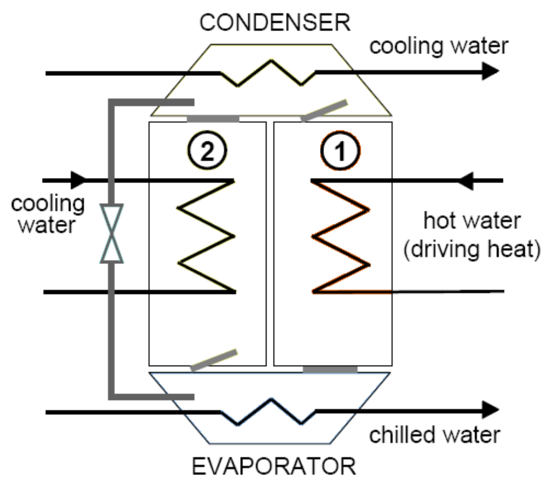

Fig 2: Adsorption cooling cycle (adapted from ESTIF 2006)

Activated carbon, silica gel and zeolite are most widely used adsorbents, while water, methanol (ethanol) or ammonia are most widely used adsorbates in solar-powered or waste heat-driven adsorption refrigeration systems. Still others materials could be used such as activated alumina and carbon, calcium chloride and metal hydrid as adsorbent, while ethylene, hydrogen or some salts can be used as an adsorbate (Dieng & Wang 2001)

For the successful operation of a solid adsorption system, careful selection of the working medium is essential. The ideal adsorbent posses a high adsorptive capacity at ambient temperatures and low pressures, but has also a low adsorptive capacity at high temperatures and high pressures. A large specific surface area is preferred since this increase the effectiveness of the adsortivity. Good thermal conductivity and a low specific heat capacity are needed to favors a rapid cycling between operation mode. For the adsorbates, the desired properties are a high latent heat and thermal conductivity, low specific heat and viscosity. Chemical compatibility between adsorbent and adsorbate and long-term stability in the operating conditions are also essential. In addition, both compounds must be cheap, non-toxic, non-inflammable and non-corrosive (Sumathy et al. 2003).

Off course, with a long wish list of contradictory properties no operating pairs are perfect. The main limitation is caused by the poor heat transfer characteristics of the adsorbents, like the activated carbon, the zeolites or the silica gel. This leads to bulky system and rather low thermal COP (Wang et al. 2005). To improve the thermal conductivity of adsorbent one can use metal fins (Munyebvu 1994) or consolidated adsorbent (Wang et al 2005).

The cooling system can be very simple when only one sorbent compartment can be used. This brings the benefit of silence, mechanical simplicity, high reliability and a very long lifetime at the price of intermittent operation. In addition, the shift from absorption to desorption creates a dead time, which leads to a drop of the COP.

Alternatively, two sorbent compartments working in parallel and sharing a common condenser and evaporator can operate continuously (Figure 2). In the evaporator, the solar heat regenerates the sorbent, while in the condenser refrigerant is adsorbed by the porous matrix of the sorbent. To do so, the sorbent needs to be cooled to remove the heat of adsorption. This is often done by water cooling but air cooling is also possible. Once the absorber is loaded with the refrigerant, sides are switched and the cycle can start again.

4. DESSICANT COOLING

Desiccant system is a different approach to cool the air based on the adsorption of water vapor. This adsorption itself is not cooling the air, quite the opposite since this process is exothermic. Indeed, the cooling is provided by evaporative cooling, which the prior drying boosts its effectiveness. The main advantage of this technology is it brings temperature needed for the desorption of water within a range, between of 55°C and 90 °C, achievable with a simple flat plate solar collector.

The most common desiccant systems use a solid rotating wheel for continuous removal of the moisture from air. This desiccant wheel rotates between the entrance and exit air stream. It captures the water vapor in the input air and is regenerated by solar heated air, before the exit. Most common desiccants are solid like silica gel or lithium chloride.

Alternatively, the drying agent can be a liquid, such as triethylene glycol. In that situation, the drying agent is sprayed into an absorber where it picks up moisture from the building air. Once it has absorbed the water, the desiccant is regenerated by spraying it in a stream of hot air, which removes the water. Heat exchanger are also used to heat the glycol before getting inside the regenerator and to cool it before getting inside the adsorber (Duffie & Beckman 1991)

The desiccant can be integrated to the air conditioning system in various configurations. In temperate climates, the process follows the following steps (Figure 3):

1.Outside air is dried by a desiccant wheel. The adsorption process, being exothermic, heats the air. The sensible heat of the desiccant wheel brought from the regeneration step amplifies this heating.

2. Air is then precooled by the action of a heat exchanger, typically a thermal wheel, using the relatively cold air exiting the building.

3. Air is then rehumidified, this lower further its temperature and brings its relative humidity to the comfort zone.

In the building, air is heated and humidified.

4.The return air is then humidified further, up to the saturation limit.

5.It is then preheated by the heat exchanger.

6.Solar heat is used to heat the air further for regeneration of the desiccant wheel (auxiliary heating power can be added if needed).

7.Water desorbed from the desiccant wheel is released in the open air.

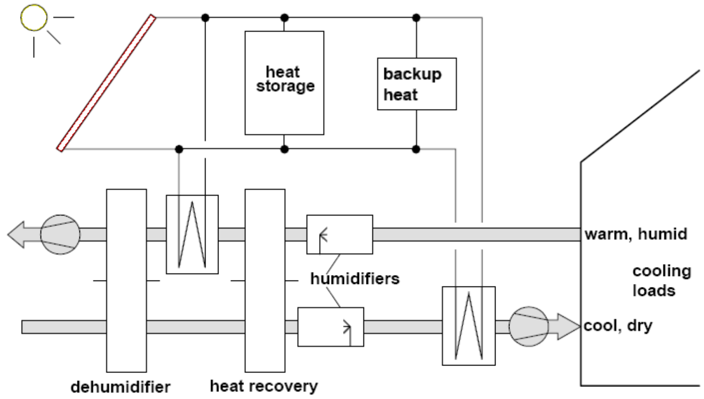

Fig 3: Desiccant cooling cycle (adapted from ESTIF 2006)

Application of this cycle is limited to temperate climates, since the possible dehumidification is not high enough to enable effective evaporative cooling when humidity of the ambient air is much higher. One approach is to use an enthalpy exchanger, a rotor that enables exchange of sensible heat and humidity, to precooled and pre-dehumidified the entrance air using the return air from the building (Figure 4a). This pretreatment allows the utilization of the desiccant cycle described previously (Hening 2007).

Another option is to precool outside air to the dew point with a cooling coil supplied with cold water from a conventional cooling system or a solar one as described previously. The following air treatment is essentially the same as previously but evaporative cooling done before the injection inside the building is replaced by a cooling coil. Relative humidity is controlled by the airflow through the desiccant wheel. The advantage of this method is its ability to work with relatively warm cold water, such as in a river or a lake (Figure 4b).

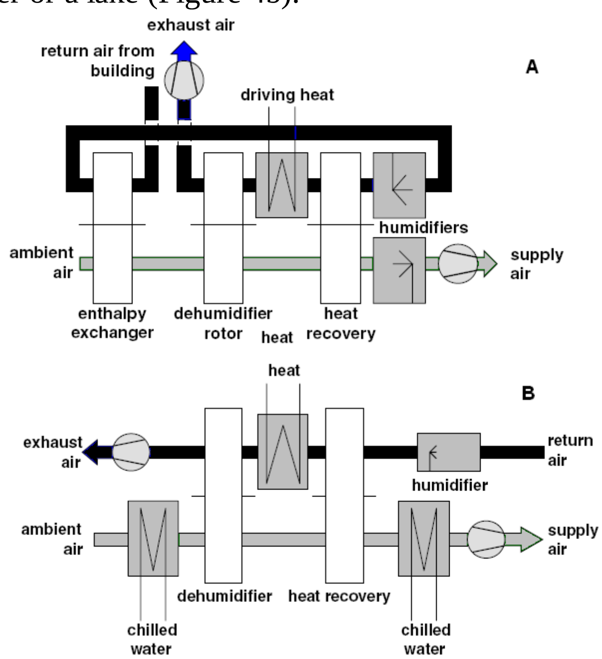

Fig 4: Alternate desiccant cooling cycle (adapted from Henning 2007)

Desiccant cooling system using rotary wheels shows some disadvantages: air leaks reduce the system efficiency, as the heat transported by the desiccant wheel. To address those issues, an advanced desiccant cooling system as been developed (ECOS: Evaporative COoled Sorptive heat exchanger; Henning 2004, Motta et al. 2004; Henning 2007). This design results in a far higher desiccation, which is intended for climates with high ambient air humidity (e.g., Mediterranean and tropical). In addition, this design is not using any moving component, which increases the reliability while opening the door to the development of smaller systems.

This process is based on simultaneous sorptive dehumidification and indirect evaporative cooling of the supply air stream. This is achieved with a counter-flow heat exchanger, where indirect evaporative cooling is obtained through a humidification on the return side of the heat exchanger. This configuration insures an efficient heat exchange between the two flows in a very compact configuration. After some time, the sorption process saturates and the system must be regenerated, by connected the two ends and flushing them first with hot air, then with colder air the remove the excess heat. As any adsorption cycle, a second system needs to be used in parallel to insure a continuous operation.

The overall performance of those systems depends of various factors including climatologic conditions. Nevertheless, as a rule of thumb the COP of this technology is close to one. It should be noted, that in very dry climate evaporative cooling could be used directly. However, this bring in mind that if in most cases, water could be considered as an acceptable consumable, in some case, its availability might be an issue.

5. DUAL USE SYSTEMS

In northern countries, where cooling needs are much smaller, it does not much make sense to use dedicated cooling system. Nevertheless, in summer, air conditioning is often needed as in warmer countries especially in building with large internal load. In addition, a solar heating system sized to operate in winter will be oversize in summer, and to avoid freezing and adequate winter operation, evacuated solar collector tubes are often used. This is why adding a cooling capability in such system might be an interesting option.

However, the field of application of such system is rather limited since the climatic conditions where they would be efficient are restricted. Indeed, according to one manufacturer of such systems (Solar Combi+ http://www.solarcombiplus.eu), they are likely to be useful in climate with heating degree day between 3000 and 5000 K. Outside this range, cooling or heating needs would not justify the added complexity.

This is why most dual use systems studied are conceived as a cooling system first with domestic hot water heating as an additional feature. Most of these designs were based on adsorption system (Aldhou et al. 2007). This makes sense since solar adsorption refrigeration system needs a relatively high desorption temperature (55-90°C) but low adsorption temperature. In such circumstances, recovering the heat of the sorption bed for heating domestic water increases the overall system efficiency.

Schwarz et al. (1997) describe a hybrid system for heating and cooling developed by Zeo-Tech of Munich. The system used zeolite as adsorbent and water as refrigerant. The sensible heat of the adsorber bed and the heat of adsorption were recovered to provide hot domestic water. Wang et al. (2000) developped a hybrid system of solar-powered water heater and icemaker. This system is intermittent, where the adsorber is placed in a water tank. Once the adsorber is regenerated, the hot water is flushed into the domestic system, while cold water gets inside the tank. Li et al. (2002) have also developed a similar system as Wang et al. (2002), who used a refrigeration process based on an activated carbon–methanol adsorption bed.

Zhang & Wang (2002) proposed continuous hybrid solid adsorption–ejector using zeolite–water working pair. The same group (Zhang &Wang 2002b) also designed a continuous system using two adsorption beds placed back to back. While one is regenerated by the solar heat, the second is cooled by a water flow. Once the first bed is regenerated, both beds exchange their position and the cycle restart.

Alghoul et al (2009) have designed a more complex arrangement. Their design incorporates two waters reservoirs where both adsorption bed (methanol and activated carbon pair) and condenser are immersed together. Adsorption bed and condenser are cross-coupled between reservoirs. This configuration allows an even better heat recovery. The efficiency can be improved further by recycling the heated water of the first reservoir into the second reservoir.

As a departure from adsorption system, a dual use absorption system has been conceived by (Helm et al 2009). The originality of their design lays not in the production of hot water, which is only a derivation of the hot water flow, by the application of dry air-cooling of the absorber. This approach is used to avoid the need of cooling water for absorption system. This alone is a serious hindrance for domestic system. To augment the air cooling, a latent heat storage system is use. This allows the storage of heat during the day for later release at night when outside temperature is lower and air cooling more effective.

6. CONCLUSION

Solar cooling is now a relatively mature technology. Many commercial systems are now available. The main obstacles for large-scale utilization are the lack of practical knowledge of these systems among architects, builders and planners. For domestic systems, there is no market available technology. Therefore, the development of low power cooling and air conditioning systems is of particular interest.

Most of these prototype relay on single stable absorption cooling. Nevertheless, recent researches have been mostly concentrated on adsorption system. This technology needed moderate driving temperature (55-90°C), which can be achieved by flat plate collector. The ability of using cheaper solar collector is fundamental since this aspect drive the overall cost of the system. Affordability will also come from integrated system, which can provide cooling and hot domestic water.

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