

A REVIEW ON ADSORPTION DUAL-PURPOSE HYBRID SYSTEMS – COOLING AND HEATING APPLICATIONS

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Abstract*. Adsorption cooling is widely known as a simple thermal driven system that uses natural refrigerants in a sustainable way without contributing to the greenhouse effect. Nevertheless, the coefficient of performance and specific cooling power of the cycle are too low to be economically viable. Due to the rising energy demand and need for sustainable emissions, improvements in various aspects are being researched to make adsorption a competitive alternative by increasing the performance of the system. One major revolution in adsorption is the development of hybrid cycles. This work presents a review of the principal hybrid adsorption systems for domestic purposes and an application analysis was made. The systems involved in the research were all experimental prototype recent units that have been developed and tested, and they were chosen in order to cover the most used types of working-pairs including: Silica-gel-water, Zeolite-water, Activated carbon-methanol and Activated carbon-ammonia. A table was elaborated to summarize the review data and to enable clear comparison. Silica-gel-water and Activated carbon-methanol pairs presented the best results among the analysis made and seem to be the most promising for the applied use of adsorption technology.*

Keywords*: adsorption, hybrid cycle, COP, domestic water heating*

1. INTRODUCTION

Adsorption refrigeration technology is attracting more and more attention in recent years because it can save energy and is environmentally friendly. Adsorption cycles can be driven by low-grade waste heat or solar energy under 80 °C and they do not have to use ozone-depleting chlorofluorocarbons (CFCs) and electricity or fossil fuels as driving sources (Wang, R.Z. et al, 2000).

Solar water heating technologies for residential use have been studied over the past several decades, and solar water heater has been got enormous application in the world. For example, in China, the total collector areas of solar water heater used in domestic using has reached 26 millions square meter by the end of year 2000, and it will keep a strong increment in recent years. By the other hand, there is a the lack of accessibility for cooling systems, especially for a large proportion of people in developing countries that live in rural or remote locations where electricity is presently unavailable or far from sufficient. Since the electrically powered vapor compression refrigeration systems may not be of much use in such areas, for essential applications such as food and drugs preservation, alternative refrigeration systems are required (Li et al., 2002).

The alternative that has emerged as a sustainable substitute to those pollution processes is the development of adsorption systems, aiming to counter the aforementioned effects, without reducing the desired level of comfort (Florides et al., 2002). They use heat as primary energy source, sustainable refrigerants such as methanol and water and have no movable parts, which makes the machines noiseless and with minimal maintenance needs. Adsorption is also attractive since it does not have crystallization problems and can operate at temperature as low as 50°C, while absorption systems require at least 70°C (Askalany et al., 2012).

Actually, the major problem involving this new technology is that while vapor compression and absorption are intrinsically continuous processes, adsorption is an intermittent one, and at least two adsorbent beds out of phase must be used to work in a quasi-continuous way, what corresponds to the hybrid systems. Because of this, the efficiency of the system is greatly reduced, providing the worst coefficient of performance (COP) among the three systems.

From this motivation, and due to the importance of this point, this paper features the description of a selection of seven different hybrid cycles experimental prototypes aiming to reveal the most promising technology that could rise the very low COP of the adsorption system in order to make it worth the investment. An application analysis was made to clarify the relationship between the working-pairs commonly used by adsorption researches.

2. METHODOLOGY

2.1. Working Pairs description and applications

Firstly, it is important to clarify that only physical sorption working pairs will be treated in this study because the thermochemical sorption working pairs involve deep analysis on chemical reactions with oxides, metal hydrides and many other metals, what can explain the shorter number of studies and experimental analysis in the literature. The attention will be focused on experimental prototype analysis.

Among the experimental cases, four types of working pairs compose the systems: Silica-gel/water, Zeolite/water, Activated-carbon/methanol and Activated-carbon/ammonia.

Silica-gel/water: The heat source temperature is about 60-85°C, it has high latent heat of water vaporization, is suitable for solar-powered and desiccant cooling systems, and are able to reutilize low-temperature waste heat. Despite that, it is still unsuitable for many refrigeration applications and vacuum system and it is very sensitive to the leakage risk.

Zeolite/water: (The common kinds of zeolite includes zeolite 13X and zeolite 4A) The heat source temperature is over 150-200°C, it is applied for solid-gas sorption air-conditioning, has high latent heat of vaporization of water and yet it is suitable for the reutilization of high-temperature exhaust gas and desiccant cooling systems. On the other hand it can only be used for refrigeration temperatures higher than 0°C, and it has a high desorption temperature.

Activated-carbon/methanol: The heat source temperature is about 80-110°C and it is applied for air-conditioning, refrigeration and also ice-making. Commonly, it has a large sorption capacity, low adsorption heat and it is suitable for solar-powered refrigeration systems. The disadvantage is due to the low latent heat of vaporization of methanol and it is unsuitable for heat source temperatures higher than 120°C.

Activated-carbon/ammonia: The heat source temperature is over 130-150°C and it is applied for air-conditioning, refrigeration and ice-making as well. The advantages are the good mass transfer, relative high latent heat of ammonia vaporization and the wide range of heat source temperatures it can achieve. Nevertheless, it shows high toxicity and pungent smells of ammonia, low sorption capacity and it is incompatible with the copper used in heat exchangers (Li et al., 2014).

2.2. Working principle of the hybrid system

In an ideal process of solar continuous solid adsorption refrigeration and heating hybrid system, the working principle can be described exactly as what is shown in Fig. 1.

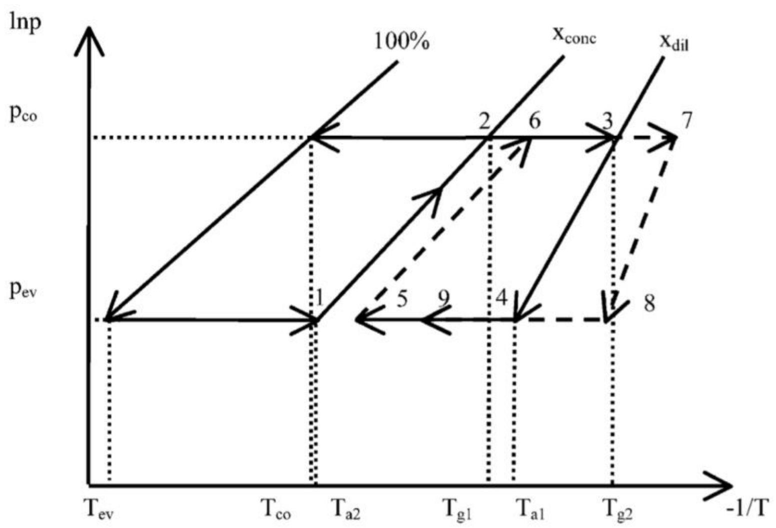

Figure. 1. The Clapeyron diagram of ideal adsorption cycle (Zhang and Wang, R.Z., 2001).

In the morning, the upper bed absorbs solar energy as a heat collector. As time goes, the temperature of the adsorbent in upper bed rises, reaching T_{a2}→T_{g1}, temperatures that indicates the end of adsorption (T_{a2}) to the beginning temperature of desorption (T_{g1}), respectively. This leads to the elevation of desorbed refrigerant evaporating pressure (p_{ev}) up to the condensing pressure (p_{co}) - p_{ev}→p_{co}, initiating the desorption process at constant pressure. The desorbed vapor is then condensed and collected in the receiver, form where the liquid flows into the evaporator via a throttle valve. The temperature of adsorbent in upper bed continues rising due to solar heating and after an insolation period of about 2 hours, when it reaches the required desorption temperature 80–90°C (T_{g1}→T_{g2}), the first heating of upper bed ends and the hybrid bed is rotated by 180 degrees (Zhang and Wang, R.Z., 2001).

This promotes the substitution of the upper bed by the lower one, which starts to be heated by solar energy from now, while the upper bed is cooled by cold water which circulates from the tank to bed by natural convection. The temperature of adsorbent in lower bed is reduced rapidly (T_{g2}→T_{a1}), and the vapor pressure of refrigerant drops as well (p_{co}→p_{ev}). The cooling generated by cold water and air natural convection causes the temperature of adsorbent in lower bed to reduce (T_{a1}→T_{a2}). In the evening, after several cycles the water acquires an adequate high temperature, being available for domestic tasks that would perfectly suit a family house needs, for example. In general, when the upper bed desorbs, the lower bed adsorbs, and the hybrid system refrigerates and heats simultaneously and continuously. At night, because the ambient temperature is low, all the two beds will adsorb refrigerants and have refrigeration effects (Zhang and Wang, R.Z., 2001).

3. HYBRID SYSTEMS

The adsorption cycle, by itself, is not very efficient at all. The first major improvement to promote its utilization is to overcome the intermittence of the process making it quasi–continuous. That could be made using at least two adsorbent beds out of phase (one would be heating while the other would be cooling), what would raise the COP and specific cooling power (SCP) (Askalany et al., 2012).

In the case of solar driven adsorption, alternatives had to be made, since the insolation is only present during the day, and even so, it is not constant. One of the primary ways to make a continuous solar adsorption refrigeration system consists mainly of a cooling tower (normally a water tank) and at least two adsorbents. The quasi–continuous operation can be obtained by making both beds work out of phase. While one bed is heating, the other is chilling. The thermal tank is charged by the solar collector, and is used by night (Zhang and Wang, R.Z., 2002).

The most promising point to increase the system efficiency is related to changing solar adsorption operation form through the use of hybrid cycles. In total, eight hybrid adsorption hybrid systems designed mainly for domestic heating and cooling will be investigated in order to acknowledge a promising trend to enable the day-to-day use of this new technology.

3.1. Solar flat plate hybrid system

Li et al. (2002) presented a solar flat plate hybrid system for water heating and cooling. The system consists of a combined adsorbent bed, an evaporator, a condenser, two water tanks, a reservoir, and valves, being performed as a prototype solar flat plate hybrid system with heating and cooling. Figures 2 display a basic hybrid cycle. The first part of the system is a conventional solar water heater and the second one represents the adsorption refrigeration system.

This hybrid system proved to be suitable for household applications such as: vacuum collector used for water heating, thereby heating the adsorber at same time, and during the night time, by draining the hot water from the tank, cold water was refilled to the tank, thus the adsorber was cooled and refrigeration was able to take place. The results showed to be very promising for the utilization of solar energy in this type of application. It is able to produce 5–6 kg of ice per m² each day under the condition of 18–22 MJ/m² solar radiation, while 60 kg of hot water at 45–50°C could be provided for residential use. The COP result was 0.11 (Li et al., 2002).

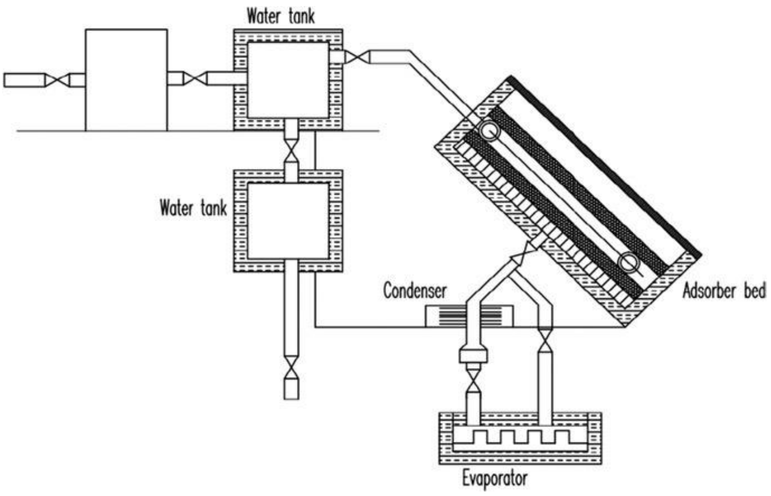

Figure 2. Sketch of the flat plate solar hybrid system (Li et al., 2002)

3.2. Solar-powered heater and ice-maker

Wang, R.Z. (2000) developed a system that consists of a solar collector, water tank adsorber/generator, condenser, evaporator, receiver, ice-box, etc. It uses a combination of solar water heater and adsorption refrigeration. Heating of the water tank is started in the morning through vacuum tube type solar collector and the temperature in the adsorbent bed rises. When it achieves a temperature which causes the vapor pressure of the desorbed refrigerant up to the condensing pressure, desorption at constant pressure is initiated, the desorbed vapor is condensed in the condenser and collected in the receiver. This liquid flows to the evaporator via a flow-rate regulating valve. In an ideal process, the adsorbent temperature could be very close to the water temperature in the tank.

The adsorber of the ice-maker is put into a water bath which is powered directly by vacuum solar collector. No thermal insulation or enhanced convection are needed for the adsorber, it is just immersed into the water bath of a solar powered water heater, which guarantees, both heating or cooling of the adsorber. It was verified that the hybrid system is capable of heating 60 kg water to about 90.8°C as well as producing ice at 10 kg per day with a 2m² solar-collector. The COP for cooling purposes stated between 0.144 – 0.143 (Wang, R.Z., 2000). Figure 3 shows the schematic of the hybrid ice-maker.

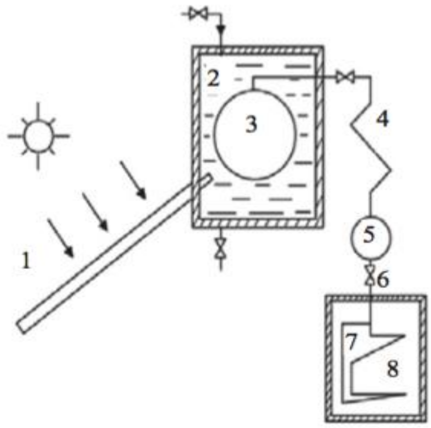

Figure 3. Schematic of the hybrid system - 1- Solar collector, 2- Water tank, 3- Adsorber, 4- Condenser, 5- Receiver, 6- Valve, 7- Evaporator, 8- Refrigerator (Wang, R.Z. et al., 2000)

3.3. Combined adsorption heating and cooling system prototype

Zhang and Wang, R.Z. (2002) developed a new combined heating and cooling hybrid adsorption system. It was constructed with a heater, a water bath, an activated carbon-methanol adsorption bed and an ice box, composing a combination of solar water heater and solar adsorption ice maker. The experiment consisted of applying 55 MJ heating to 120kg of water at 21°C. Controlling the condensing temperature at about 30°C, the result was the production of 4 kg of ice at -2°C. When testing the cooling capacity of the ice and the refrigerant in the evaporator, authors found that it was able to keep the temperature below 5°C of a 100L cold box for about three days. That revealed that the hybrid solar water heating and ice making is consistent and a successful application of the new cooling adsorption technology. Figure 4 presents the schematic of the prototype.

The system was able to refrigerate with a COP of 0.1 in the daytime and with a COP of 0.23 in the night at normal working conditions. It could be concluded that the new combined cycle can raise the COP totally and can refrigerate in the daytime. However, due to the introduction of the steam ejector into the combined system, the thermodynamic performance properties of the combined system are greatly affected by the ejector, by which the desorption is restrained. In order to improve the COP of this combined system, it is necessary to raise the flow entrainment ratio of the ejector at a lower desorbing-saturation temperature (Zhang and Wang, R.Z., 2002).

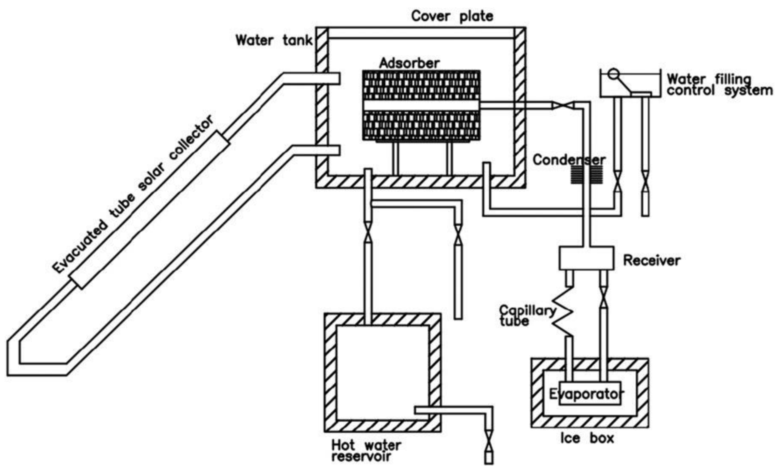

Figure 4. Schematics of a solar water heater and adsorption refrigerator (Zhang and Wang, R.Z., 2002)

3.4. Two bed silica gel/water adsorption chiller

Li and Wu (2009) developed a theoretical micro combined cooling, heating and power adsorption hybrid system. The system comprised one gas engine generator set with 16 kW generating capacities, two beds silica gel-water adsorption chiller with 10 kW cooling capacity, one exhaust heat exchanger, 500L water tank, and three pumps. Average value and variation rate of the electric load, as well as the average value of the cooling load affected significantly cooling capacity and the COP of the chiller.

The achieved COP varied between 0.06-0.18, depending on how severe disturbs occurred and the state of open or close cycle. It also showed that COP in open cycle was always a little greater than that in closed cycle, and thus the open cycle should be adopted for further researches using this hybrid system. Figures 5 shows the schematic of the silica gel/water chiller.

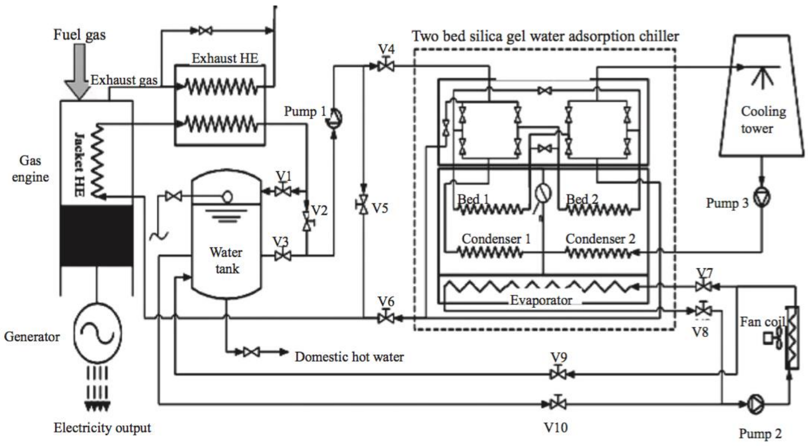

Figure 5. Schematic diagram of the micro combined cooling heating and power system (Li and Wu, 2009)

3.5. Compound system for heating and cooling

Chang et al. (2009) developed a compound system for cooling and heating. It consists of an integrated, two-bed, closed-type adsorption chiller that uses a plate fin as an adsorber and tube heat exchangers as evaporator/condenser. A typical daily operation showed that the efficiency of the solar heating system, the adsorption cooling and the entirely solar cooling system was 28.4%, 45.2%, and 12.8%, respectively. Figure 6 displays a schematic of the compound system.

Field tests have been performed for providing air-conditioning and hot water. The efficiency of the collector field lies between 18.5–32.4%, with an average value of 27.3%. The 9-month average for the system as a cooling purpose unit points to a COP of 0.128 (Chang et al., 2009).

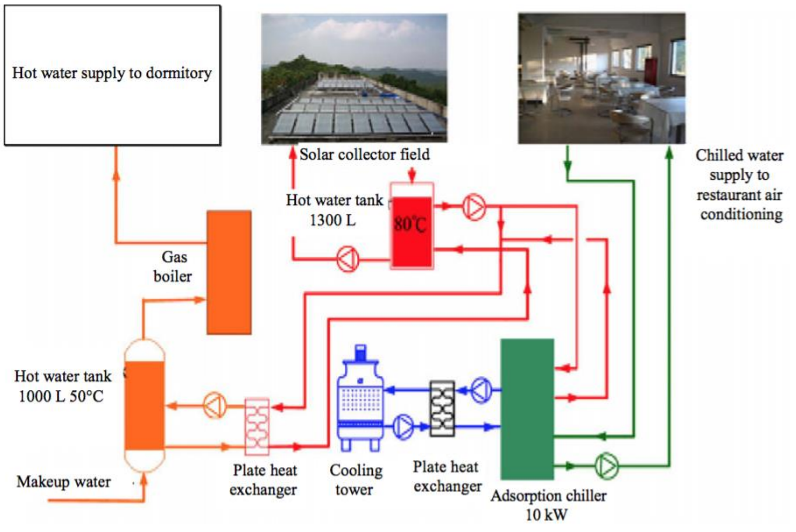

Figure 6. Schematic diagram of the solar-powered system for heating and cooling (Chang et al., 2009)

3.6. Residential air conditioning and heating system

Clausse et al. (2008) used an enhanced compound parabolic solar collector as a heat source of an adsorption system (activated carbon/methanol) and during the winter; direct coupling with the building was performed. The project included the solar system, the adsorption machine and the floor heating/ cooling system. All sub-systems were directly connected to each other without storage or control system to regulate the temperature.

The air-conditioning application showed promising results as it was able to provide thermal comfort keeping indoor temperature below 25°C during five consecutive hot days. However, for the use of the heating application, indoor temperature remained below the comfort temperature value, 21°C. The COP of the cycle was about 0.2-0.23 and the cooling capacity reached was 4.6 kW. Figure 7 illustrates the complete system layout.

The use of Circular Plastic Connectors (CPCs) explained the good results obtained, because they have increased efficiency compared to other solar collector. They consist of lightweight, all-plastic and metal-shell connectors and are made of stabilized, heat resistant, self-extinguishing thermoplastic material, while they are polarized for proper mating of connector halves (Clausse et al., 2008).

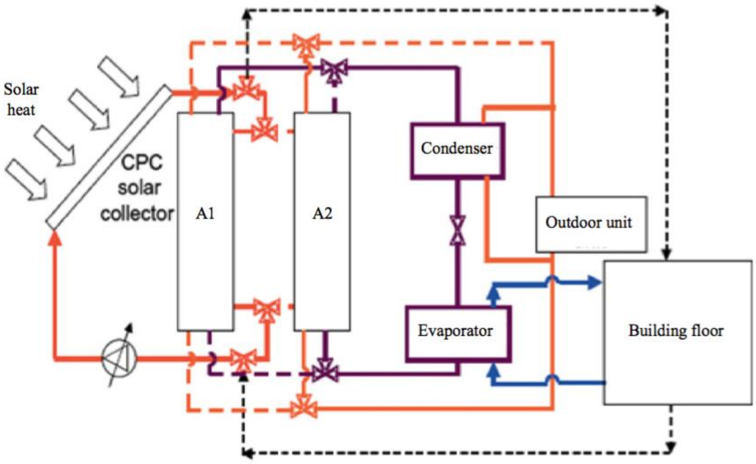

Figure 7. Solar cooling adsorption installation sketch (Clausse et al., 2008)

3.7. Micro-combined system driven by a gas engine

Kong et al. (2005) developed a natural gas and LPG-fired micro-combined cooling, heating and power system using a small-scale generator set driven by a gas engine and a new small scale adsorption chiller. Silica gel-water was used as the working pair in the adsorption cooling system. The COP of the chiller was over 0.3 for 13°C evaporation temperature. Tests proved refrigeration power variations with heat-source water temperature, resulting on a COP that sits around 0.3-0.34, making it even more interesting. The overall thermal and electrical efficiency is over 70%. Figure 8 shows a picture for the adsorption cooling system.

Figure 8. Silica gel/water adsorption chiller (Kong et al., 2005)

3.8. Solar continuous system using methanol/activated carbon

Alghoul et al. (2009) tested the performance of a dual-purpose solar continuous adsorption system for domestic refrigeration and water heating. Malaysian activated carbon and methanol were used as the adsorbent–adsorbate pair.

The heat rejected is recovered and used to heat water for the purpose of domestic consumption. It is able to produce 44.7 MJ/day for water heating and 5.3 MJ/day for ice making, what corresponds to 12 kg/day. This project achieved a COP for the refrigeration system of 0.44.

Because the heat produced by the adsorber beds and condensers are recovered, the coefficients of performance of this system are maximized. In a continuous 24-h cycle, 16.9 MJ/day of heat can be recovered for heating water in the storage tanks. Typically, in the previous hybrid cycles systems described in this paper – common solar adsorption refrigerator - this heat was wasted. Figure 9 presents the dual-purpose system.

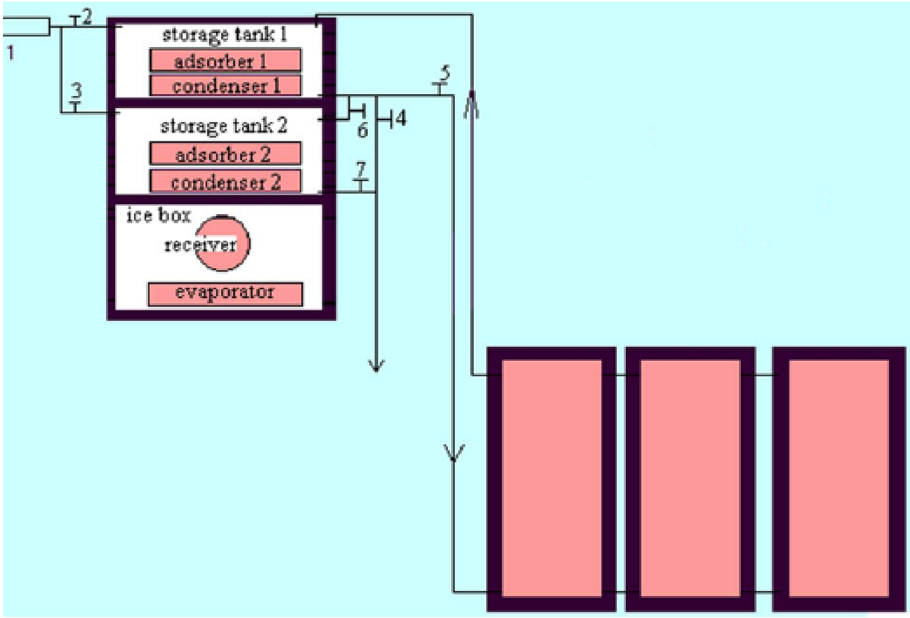

Figure 9. Schematic of the dual-purpose system (Alghoul et al., 2009)

3.9. Summary table

Table 1 presents all systems reviewed in this article, with its working pair, cooling COP and application.

Table 1. Systems associated working pairs, cooling COP and applications

System	Adsorbent/Refrigerant Pair	Cooling COP	Application
Solar flat plate hybrid (Li et al., 2002)	Activated Carbon-Methanol	0.11	Household cooling, ice maker
Solar-powered heater and ice-maker (Wang, R.Z. et al., 2000)	Activated Carbon-Ammonia	0.143 - 0.144	Household cooling, ice maker
Combined adsorption heating and cooling system prototype (Zhang and Wang, R.Z., 2002)	Zeolite-Water	0.1 – 0.23	House cooling low efficiency system and ice maker
A two bed silica gel/water adsorption chiller (Li and Wu, 2009)	Silica gel-Water	0.06 – 0.18	Micro combined cooling
Compound system for heating and cooling (Chang et al., 2009)	Silica gel-Water	0.128	Air conditioning
Residential air conditioning/heating system (Clausse et al., 2008)	Activated Carbon-Methanol	0.2 – 0.23	Residential air conditioning
Micro-combined system driven by gas engine (Kong et al., 2005)	Silica gel-Water	0.3 – 0.34	Micro combined cooling
Solar continuous system for domestic applications (Alghoul et al., 2009)	Activated Carbon-Methanol	0.44	Domestic refrigeration and Water heating

4. CONCLUSION

The hybrid cycles are suitable for domestic applications such as: residential water heating, air-conditioning, ice making and indoor heating.

Silica gel-water showed to be an interesting working-pair because it can be driven by low temperature heat source, what is great for solar energy purposes, and it was found that, despite its low mass and heat transfer capacity, it was able to achieve one of the best cooling COP on hybrid systems of quasi continuous operation that aims to raise the system efficiency.

However, further research is required to enable silica gel/water use. Since the adsorbate is water, it cannot operate under 0°C and it also needs high vacuum. The solution seems to be the development of new material to reduce the problems with the silica gel.

Good experimental results also have been obtained with activated carbon-methanol working pair, the highest COP among the water driven systems investigated. Heat recovery appears as a crucial part to enhance this working-pair efficiency. Solar ice making is attractive, even though it needs good heat collecting and releasing for the adsorber, which seems to be a contradiction.

Although many devices were designed just for solar energy utilization, it can be applied to many energy saving fields such as waste heat recovery in industry and air conditioning energy, driven by exhaust gas of automobiles. This novel concept of energy utilization provides an efficient way for sustainable development, and hybrid cycles tend to be the technology to achieve the desired efficiency to make it suitable for day-to-day household applications and lower the technology costs, bringing adsorption to the reality of daily domestic tasks in the future.

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