REVIEW ON SOLAR ADSORPTION REFRIGERATION CYCLE

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ABSTRACT:

Solar adsorption refrigeration devices are of significance to meet the needs for cooling requirements such as air-conditioning, ice-making and medical or food preservation in remote areas. They are also noiseless, non-corrosive and environmentally friendly. Various solar powered cooling systems have been tested extensively, however, these systems are not yet ready to compete with the well-known vapor compression system. For these reasons, research activities in this sector are still increasing to solve the technical, economical and environmental problems. The objective of this paper is to provide fundamental knowledge on the adsorption systems and present a detailed review on the past efforts in the field of solar refrigeration systems. A number of attempts have been made by researchers to improve the performance of the solar powered adsorption subsystems. It is seen that, for successful operation of such systems, a careful selection of the adsorbent-adsorbate pair is essential apart from the collector choice, system design and arrangement of subsystems.

Keywords: Adsorbate; Adsorbent; Adsorption; Performance; Refrigeration; Solar energy

Despite a large potential market, existing solar refrigeration systems are not competitive with electricity-driven refrigeration systems because of their high capital...
costs. Improvements such as reduced collector area, improved system performance, and reduced collector cost will lower the cost of solar component. The energetic conversion efficiency is low, and solar cooling and refrigeration are not yet competitive economically with the conventional systems.

**INTRODUCTION**

The use of solar energy for environmental control is receiving much attention as a result of the limited storage and environmental issues of fossil fuels. Refrigeration is particularly attractive as a solar energy application because of the near coincidence of peak cooling loads with the available solar power. The traditional vapour compression refrigeration cycles are driven by electricity or heat, which strongly increases the consumption of electricity and fossil energy. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the world is employed for refrigeration and air-conditioning processes of various kinds, and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings. Moreover, peak electricity demand during summer is being reinforced by the propagation of air-conditioning appliances. So consume of electricity is a big problem for vapour compression refrigeration system. In developing countries, a large proportion of people live in rural areas where grid electricity is seldom available at present and is likely to be the case for the next few decades. Therefore conventional, electrically powered vapor compression refrigeration systems may not be of much use for them.

The conventional vapour compression system is run by commercial, non-natural working fluids, like the chlorofluorocarbons (CFCs), the hydrochlorofluorocarbons (HCFCs) and the hydrofluorocarbons (HFCs). These are directly responsible for in ozone depletion and/or global warming. Since the protocol of Montreal in 1987, international agreements have been signed to reduce the emissions of these refrigerants. European Commission Regulation 2037/2000, which has been implemented on 1\textsuperscript{st} October 2000, treats the whole spectrum of control and phase-out schedule of all the ozone depleting substances. It is indicated that till 2015 all HCFCs will be banned for servicing and maintaining existing systems. So echo-friendly refrigerant is required for refrigeration.
Many agricultural products like fruits, vegetables, milk, meat, fish etc., can be maintained in fresh conditions for significantly long periods of time if they are stored at low temperatures. Large quantities of these products are lost annually due to poor storage facilities. As a result, sharp differences in food supplies exist between the harvest and off harvest periods. Lot of medicine and vaccine are lost every year due to scarcity of electricity. Solar refrigeration can help change this trend.

Solar refrigeration is highly dependent upon environmental factors such as cooling water temperature, local weather, air velocity air temperature and solar radiation. Several solar refrigeration systems have been proposed and are under development such as sorption systems including liquid/vapor, solid/ vapor absorption, adsorption, vapor compression and photovoltaic-vapor/compression systems. Most of the above mentioned systems have not been economically justified.

The adsorption system is one of the promising solar thermal refrigeration methods, and it is environmentally friendly along with low cost and low maintenance requirements. Adsorptive processes have been applied extensively for gas separation and catalysis, but it is only recently that adsorptive processes have been widely studied for refrigeration and heat pumps.

This article details the various research aspects of adsorption refrigeration, which includes adsorption mechanism, the criteria to choose an appropriate working pair, the basic solar powered adsorption refrigeration cycle, problems of the basic cycles along with the published performance and limitations of the basic cycle and the scheme for various systems for improved performance.

**PRINCIPLE OF ADSORPTION**

Adsorption is a reversible process by which a fluid molecule is fixed onto a solid matrix, typically a surface or a porous material. Adsorption occurs at the surface interface of two phases, in which cohesive forces including electrostatic forces and hydrogen bonding, act between the molecules of all substances irrespective of their state of aggregation. Unbalanced surface forces at the phase boundary cause changes in the concentration of molecules at the solid/fluid interface. The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or
concentration at the surface of another. The adsorbing phase is the adsorbent, and the material concentrated or adsorbed at the surface of that phase is the adsorbate. Moreover, the thermodynamic equilibrium is bivariant, which can be described by the set of isosters i.e., processes during which concentration remain constant, in the Clapeyron diagram (LnP vs -1/T) (Figure 5).

Adsorption is an exothermic process accompanied by evolution of heat, the quantity of heat release depends upon the magnitude of the electrostatic forces involved, latent heat, electrostatic and chemical bond energies. Since in adsorbed phase, adsorbate molecules are in more ordered configuration, entropy decreases; and from \( \Delta G = \Delta H - T \Delta S \), exothermic character of the process is obvious. The three terms which are often used in adsorption process are: (i) Integral heat of adsorption—which is the total heat released from initial state to final state of adsorbate loading, at constant temperature; (ii) Differential heat of adsorption—is the change in integral heat of adsorption with change in loading; and (iii) Isosteric heat of adsorption is defined by using adsorption isosters and Clausius Clapryron relationship. In practice, the difference between differential heat of adsorption and isosteric heat of adsorption is so small that it can easily be neglected, as well as, these two can be considered as identical. Differential heat of adsorption for some adsorbent/adsorbate pairs are given in the Table - 1.

**SELECTION OF ADSORBENT AND ADSORBATE:**

There are several working pairs for solid adsorption. For the successful operation of a solid adsorption system, careful selection of the working medium is essential. For any refrigerating application, the adsorbent must have high adsorptive capacity at ambient temperatures and low pressures but less adsorptive capacity at high temperatures and high pressures. Adsorbents are characterized by surface properties such as surface area and polarity. A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume inevitably gives rise to large numbers of small sized pores between adsorption surfaces. The pore size distribution of micropores which determines the accessibility of adsorbate molecules to the internal adsorption surface, is important for characterizing adsorptivity of adsorbents. Materials such as zeolite and carbon molecular sieves can be engineered
specifically for precise pore size distributions and hence ‘tuned’ for a particular separation.

Based on the above discussion, the choice of the adsorbent will depend mainly on
the following factors:

- high adsorption and desorption capacity, to attain high cooling effect;
- good thermal conductivity, in order to shorten the cycle time;
- low specific heat capacity;
- chemically compatible with the chosen refrigerant;
- low cost and widely available.

On the other hand, the selected adsorbate, which is the refrigerant or working
fluid must have most of the following desirable thermodynamics and heat transfer
properties:

- Evaporation temperature below 0 °C.
- high latent heat per unit volume;
- molecular dimensions should be small enough to allow easy adsorption;
- high thermal conductivity;
- good thermal stability;
- low viscosity;
- low specific heat;
- non-toxic, non-inflammable, non-corrosive; and
- Chemically stable in the working temperature range.

Based on the above criteria, some of the appropriate working pairs are zeolite–
water, zeolite–organic refrigerants, silica gel–water, zeolite–water and activated carbon–
methanol in solid adsorption systems. Natural zeolites also have possibilities, but
significantly larger quantities would be required if water is the adsorbate since only a
modest amount of adsorbate is desorbed in going from room temperature to flat plate
solar collector temperature. However, zeolites have another unique property in that their
adsorption isotherms have extremely non-linear pressure dependence, which is of
importance in solar refrigeration applications. Activated carbon and silica gel have almost
linear pressure isotherms. Silica gel satisfies above criteria but it is expensive and may
not be available in most developing countries. The temperature lift capabilities of adsorbent/adsorbate pairs at adsorption–evaporation and generation–condensation temperatures have been used as the basis for selection. For AC-35/CH3OH, adsorption–evaporation temperature lift has to be limited to 40 °C and low generating temperatures (<150 °C). For NaX/H2O, the corresponding temperature lift may be up to 70 °C, or even more, with very high generating temperatures (250–300 °C). Activated carbon–methanol is limited to a maximum generating temperature of 150 °C due to methanol instability at higher temperatures. This feature of the pair makes it possible for low temperature heat sources to be used in the operation of its refrigeration cycle. The recent new development of activated carbon fiber (ACF) shows the possibility for applications in adsorption refrigeration. One good example is the development in Byelorussia of a refrigerator prototype using ACF–ethanol and ACF–acetone pairs has been reported [1]. New experiments have also been shown to use a heat pipe for heating/cooling ACF adsorbers for the ACF–NH3 pair [2].

Table – 1 Comparison between various solid adsorbent pairs:

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Adsorbate</th>
<th>Heat of Adsorption (kJ/kg)</th>
<th>Density of Adsorbate (kg/m3)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated alumina</td>
<td>H2O</td>
<td>3000</td>
<td>1000</td>
<td>Water is applicable except for very low operating pressure.</td>
</tr>
<tr>
<td>Zeolite</td>
<td>H2O</td>
<td>3300 – 4200</td>
<td>1000</td>
<td>Natural zeolite has lower values than synthetic zeolite.</td>
</tr>
<tr>
<td></td>
<td>NH3</td>
<td>4000 – 6000</td>
<td>681</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH3OH</td>
<td>2300 – 2600</td>
<td>791</td>
<td></td>
</tr>
<tr>
<td>Silica gel</td>
<td>CH3OH</td>
<td>1000 – 1500</td>
<td>791</td>
<td>Suitable for temperature less than 200°C.</td>
</tr>
<tr>
<td>Silica gel</td>
<td>H2O</td>
<td>2800</td>
<td>1000</td>
<td>Used mostly for descent cooling.</td>
</tr>
<tr>
<td>Charcoal</td>
<td>C2H4</td>
<td>1000 – 1200</td>
<td>789</td>
<td>Ammonia and methanol are not compatible with copper at high temperatures.</td>
</tr>
<tr>
<td></td>
<td>NH3</td>
<td>2000 – 2700</td>
<td>681</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2O</td>
<td>2300 – 2600</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH3OH</td>
<td>1800 – 2000</td>
<td>791</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2H5OH</td>
<td>1200 – 1400</td>
<td>798</td>
<td></td>
</tr>
<tr>
<td>Calcium Chloride</td>
<td>CH3OH</td>
<td>1800 – 2000</td>
<td>791</td>
<td>Used for cooling</td>
</tr>
<tr>
<td>Metal hydrides</td>
<td>Hydrogen</td>
<td>2300 – 2600</td>
<td>1000</td>
<td>For Air-conditioning</td>
</tr>
<tr>
<td>Complex compounds</td>
<td>Salts and ammonia or water</td>
<td>2000 – 2700</td>
<td>681</td>
<td>Refrigeration</td>
</tr>
</tbody>
</table>
BASIC ADSORPTION REFRIGERATION CYCLE

An adsorption cycle for refrigeration does not use any mechanical energy, but only heat energy. Adsorption cycles are intermittent in operation. Likely in a vapour compression system the adsorption refrigeration system also consists of a compressor, a condenser, a throttle valve, and an evaporator. However, in this system a thermal compressor that is operated by heat instead of a mechanical energy replaces the compressor. The vaporized refrigerant is adsorbed in the pores of the adsorbent in the reaction chamber. Thus the operation of the adsorption cooling system depends on adsorption/desorption characteristics of the particular adsorbent/refrigerant pair.

The main components of an adsorption unit are (refer Figure 1.):
1. Thermal Compressor for adsorption and desorption of refrigerant
2. Condenser
3. Expansion Valve
4. Evaporator.

The adsorbent is packed in a hermetically sealed container painted black for solar radiation absorption at a particular temperature corresponding to its condensing pressure, the refrigerant starts desorbing from the adsorbent. As the refrigerant vapour is condensed, heat is dissipated to the surroundings. The condensate flows by gravity into a liquid receiver or directly into the evaporator.

During the night cycle, the adsorbent is cooled to near ambient temperature, thus reducing the pressure of the entire system. When the adsorbent pressure equals the saturated vapour pressure of the refrigerant, the refrigerant boils in the evaporator and causes heat to be absorbed from the immediate environment. The resulting refrigerant vapour is re-adsorbed into the adsorbent, while cooling is produced.

The cycle consists of four processes.

- Heating and pressurization
- Heating and desorption & condensation
- Cooling and Depressurization
- Cooling and adsorption & evaporation
**Heating and pressurization:** - The adsorber receives heat while being closed. The adsorbent temperature increases, which induces a pressure increase, from the evaporation pressure up to the condensation pressure. This process is equivalent to the "compression" in compression cycles (refer fig1).

**Heating, Desorption and Condensation:** - The adsorber continues receiving heat while being connected to the condenser. The adsorbent temperature continues increasing, which induces desorption of vapour. This desorbed vapour is liquefied in the condenser. This is equivalent to the "condensation" in compression cycles refer Figure 2.

**Figure 1** Schematic diagram of heating and pressurization

**Figure 2** Schematic diagram of heating, desorption and condensation
Cooling and Depressurization: - During this period, low pressure vapour is entered to adsorber from evaporator. The adsorber releases heat while being closed. The adsorbent temperature decreases, which induces the pressure decrease from the condensation pressure down to the evaporation pressure. This process is equivalent to the "expansion" in compression cycles refer Figure 3.

Cooling, Adsorption and Evaporation: - The adsorber continues releasing heat while being connected to the evaporator. The adsorbent temperature continues decreasing, which induces adsorption of vapour. This adsorbed vapour is vaporized in the evaporator. The evaporation heat is supplied by the heat source at low temperature. This is equivalent to the "evaporation" in compression cycles refer to Figure 4.

Figure 3 Schematic diagram of cooling and depressurization

Figure 4 Schematic diagram of cooling, adsorption and Evaporation
A basic adsorption cycle consists of four thermodynamic steps, which can be well represented with the help of the Clapeyron [3] diagram, as shown in Fig. 5. Theoretically, the cycle consists of two isosters and two isobars. The process starts at point 1, where the adsorbent is at a low temperature $T_a$ (adsorption temperature) and at low pressure $P_e$ (evaporation pressure). While the adsorbent is heated by a solar energy, the temperature and the pressure increase along the isoster which the mass of the adsorbate in the adsorbent remains constant at $m_{\text{max}}$. The adsorber still isolated until the pressure reaches the condenser pressure, point 2 (The limit point of desorption $T_{c1}$). At this time, the adsorber is connected with the condenser and the progressive heating of the adsorbent from point 2 to 3 causes of adsorbate and its vapour is condensed in the condenser and collected in a receiver. When the adsorbent reached its maximum temperature value $T_g$ (regenerating temperature) and the adsorbed mass decreases to its minimum value $m_{\text{min}}$ (point 3), the adsorbent starts cooling along the isoster at a constant mass $m_{\text{min}}$ to point 4 (the limit point of adsorption $T_{c2}$). During this isosteric cooling phase, the adsorbent...
pressure decreases until it reaches the evaporator pressure $P_e$. After that, the adsorber is connected to the evaporator and both the adsorption and evaporation occur while the adsorbent is cooled from point 4 to 1. In this phase, the adsorbed mass increases up to maximum $m_{max}$ at point 1. The adsorbent is cooled until the adsorption temperature $T_a$ by rejecting the sensible heat and the heat of adsorption. During this phase cold is produce. Cooling systems are used to remove heat from a region which causes the temperature of the region to be lowered. This is done by circulating a fluid which is in turn compressed, condensed and evaporated. In adsorptive cooling systems the circulating fluid is adsorbed and desorbed from a material, an adsorbent, to achieve the desired compression of the fluid. This has the benefit that the energy needed to drive the adsorptive system can be in the form of heat which means that the cooling system may be gas or oil fired or even solar powered rather than powered by electricity. Of course electricity may still be required to operate control mechanisms and circuitry but the energy demand of such control circuitry is sufficiently low for it to be powered by a conventional battery. This means that adsorptive cooling systems may be operated in areas which are not connected to an electricity supply grid and can be inherently more efficient in their use of primary energy since they use heat directly rather than in a converted form such as electricity. To overcome the limitations of intermittent operation of the adsorptive refrigerator, a system for providing a continuous adsorptive cycle has been developed in which two adsorptive collectors or beds are arranged in tandem with suitable valving. In this way while one bed is being heated and is therefore desorbing refrigerant the other bed is cooling and is adsorbing refrigerant. The cycles of the two beds are ideally 180° out of phase and provide continuous compression of the refrigerant. In a refrigerator, the valves in the system route the adsorbed or desorbed refrigerant to the condenser and away from the evaporator accordingly. This enables the adsorptive beds to cycle through adsorbance and desorbance many times in one day, which reduces the amount of adsorbent needed to achieve the same cooling effect. The cycle time of the adsorbent beds is limited by the efficiency of conduction of heat through the beds which by their very nature are poor conductors of heat. Additionally, heat may be transferred from one of the adsorbent beds to the other of the beds and vice versa in order to improve efficiency.
HEAT OF ADSORPTION:

All adsorption processes are accompanied by heat release, i.e. they are, exothermic processes. Since in adsorbed phase, adsorbate molecules are in more ordered configuration, entropy decreases; and from $\Delta G = \Delta H - T \Delta S$, exothermic character of the process is obvious. The three terms which are often used in adsorption process are (i) Integral heat of adsorption—which is the total heat released from initial state to final state of adsorbate loading, at constant temperature; (ii) Differential heat of adsorption—is the change in integral heat of adsorption with change in loading; and (iii) Isosteric heat of adsorption is defined by using adsorption isosters and Clausius Clapryron relationship. In practice, the difference between differential heat of adsorption and isosteric heat of adsorption is so small that it can easily be neglected, as well as, these two can be considered as identical. At constant loading

$\left( dC_v=0 \right)$; using the Dubinn-Radushkevich Eq. $W=W_0 \exp \left[ \frac{A}{\beta E_0} \right]$ and the following

Clapeyron equation, \[ \frac{\Delta H}{RT^2} = -\left( \frac{\partial \ln P}{\partial T} \right)_{C_v} \]

So isosteric heat can be obtained by the equation

$-\Delta H = A + \Delta H_{vap} + \frac{(\beta E_0)^n}{nA^{n-1}} \partial T$

Thus, the isosteric heat is a summation of three terms. The first term is due to the adsorption potential, the second is the heat of vaporization and the third corresponds due to the change in maximum capacity with temperature.

The above expressions are often used in the study of adsorption refrigeration and the detail of adsorption equilibrium, working pair and heat of adsorption is summerized below.
<table>
<thead>
<tr>
<th>Research Group</th>
<th>Equilibrium equation</th>
<th>Adsorbent-adsorption pair</th>
<th>Adsorption Heat</th>
</tr>
</thead>
</table>
\ln(p) = a(w) + \frac{b(w)}{T} \\
a(w) = a_0 + a_1 w + a_2 w^2 + a_3 w^3 \\
b(w) = b_0 + b_1 w + b_2 w^2 + b_3 w^3 = \frac{\Delta H(w)}{R} 
\] | zeolite-water activated carbon-methanol | Enthalpy of adsorption \( b(w) = b_0 + b_1 w + b_2 w^2 + b_3 w^3 = \frac{\Delta H(w)}{R} \) |
| Crieof 1998 [7] | D-A equation | activated carbon methanol | Clausius-Clapeyron equation \( \Delta H = R \ln \left( \frac{P_2}{P_1} \right) \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \) |
| Gui2002 [8] | \[
q = q_0 \exp \left[ -K(T/T_{sat} - 1)^n \right] 
\] | activated carbon methanol | Constant |
| Guilleminot [9] | \[
q = W_0 \exp \left[ -D(T \ln P_{sat} (T)/P_{sat}(T_{cond}))^n \right] 
\] | activated carbon methanol | Clapeyron equation for ideal gas \( \Delta H = RT^2 \left( \frac{d \ln P}{dT} \right) \) |

Features of the adsorption cycle are as follows:

- The cycle is basically intermittent since cold production is not continuous. Cooling effect is obtained only during part of the cycle.
- When there are two adsorbers in the unit, they can be operated out of phase and the cold production is quasi-continuous.
- Typically, for domestic refrigeration conditions, the coefficient of performance (COP) of single effect adsorption cycles lies around 0.1 – 0.12.
- When all the energy required for heating the adsorber(s) is supplied by the heat source, the cycle is termed single effect cycle.
- In double effect cycles or in cycles with heat regeneration, some heat is internally recovered between the adsorbers, which enhance the cycle performance.
Performance of cycle is highly dependent upon environmental factors such as solar radiation, air temperature, cooling water temperature, etc.

There is a well-documented need for domestic refrigeration in areas that do not have access to grid electricity. Spoilage of many products, particularly fish, can be as high as 50%. This crisis has led to various international agreements including the Kyoto ‘Declaration and Plan of Action on the Sustainable Contribution of Fisheries to Food Security’ (NRI, 2000). Renewed interest in adsorption refrigeration is based on the advantages of (i) being CFC-free; (ii) cost effective (iii) simple construction; (iv) no need for solution pumps, and (v) they can be driven by low grade energy heat. Nineteen different possible technologies have been identified for adsorption refrigeration.

The reported performance of various solar adsorption refrigeration systems are shown in the Table - 2.

<table>
<thead>
<tr>
<th>Research group</th>
<th>Working pairs</th>
<th>Collector areas (m²)</th>
<th>Solar radiation Per day (MJ/m²) or Heat source Temperature</th>
<th>CO P</th>
<th>Ice mass per day (kg)</th>
<th>Year</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pons and Guillemiont[10]</td>
<td>Activated carbon–methanol</td>
<td>6</td>
<td>22</td>
<td>0.12</td>
<td>30–35</td>
<td>198 6</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Headley et al.[11]</td>
<td>Activated carbon–methanol</td>
<td>2</td>
<td>25</td>
<td>0.02</td>
<td>1.0</td>
<td>198 7</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Iloeje[12]</td>
<td>CaCl₂ and NH₃</td>
<td>1.41</td>
<td>12</td>
<td>0.1</td>
<td>1.4</td>
<td>198 8</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Boubakri.[13]</td>
<td>Icemaking</td>
<td>1.0</td>
<td>19.5</td>
<td>0.12</td>
<td>4</td>
<td>199 2</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Tan et al.[14]</td>
<td>Activated carbon–methanol</td>
<td>1.1</td>
<td>22</td>
<td>0.09</td>
<td>3</td>
<td>199 3</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Lin et al. [15]</td>
<td>CaCl₂ and NH₃</td>
<td>1.6</td>
<td>20</td>
<td>0.08</td>
<td>3.2</td>
<td>199 5</td>
<td>Icemaking</td>
</tr>
<tr>
<td>Y.X.Xu[16]</td>
<td>Activated carbon-NH₃</td>
<td>1</td>
<td>105°C</td>
<td>0.10</td>
<td>35</td>
<td>199 7</td>
<td>Icemaking</td>
</tr>
<tr>
<td>R.Z.wang[17]</td>
<td>Activated carbon–</td>
<td>1</td>
<td>19.2</td>
<td>0.14</td>
<td>6</td>
<td>200 2</td>
<td>Icemaking</td>
</tr>
</tbody>
</table>

Table 3 Some typical research results of solar adsorption:
<table>
<thead>
<tr>
<th>Methanol Type</th>
<th>Material</th>
<th>Temperature</th>
<th>Emissivity</th>
<th>Reflectivity</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.Z. Sun[18]</td>
<td>Activated Carbon-Methanol</td>
<td>1</td>
<td>20</td>
<td>0.14</td>
<td>6</td>
</tr>
<tr>
<td>C.Hilbrand[19]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>15.4</td>
<td>0.16</td>
<td>9.4</td>
</tr>
<tr>
<td>N.M. Khattab[20]</td>
<td>Activated Carbon-Methanol</td>
<td>1</td>
<td>&lt;120°C</td>
<td>0.18</td>
<td>27</td>
</tr>
<tr>
<td>S.G. Wang[21]</td>
<td>Activated Carbon-CaCl₂-NH₃</td>
<td>1</td>
<td>&lt;120°C</td>
<td>0.41</td>
<td>73</td>
</tr>
<tr>
<td>B.B. Saha[22]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>55°C</td>
<td>0.36</td>
<td>320</td>
</tr>
<tr>
<td>R.Z. Wang[23]</td>
<td>Activated Carbon-Methanol</td>
<td>1</td>
<td>100°C</td>
<td>0.4</td>
<td>73.1</td>
</tr>
<tr>
<td>Z.Z. Xia[24]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>65°C</td>
<td>0.28</td>
<td>120</td>
</tr>
<tr>
<td>T. Nunez[25]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>75-95°C</td>
<td>0.6</td>
<td>150</td>
</tr>
<tr>
<td>G. Restuccia[26]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>80°C</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Y.L. Liu[27]</td>
<td>Silicajel-Water</td>
<td>1</td>
<td>232°C</td>
<td>0.42</td>
<td>171.8</td>
</tr>
<tr>
<td>D.I. Tichernev[28]</td>
<td>Activated Carbon-NH₃</td>
<td>1</td>
<td>204°C</td>
<td>1.6</td>
<td>123</td>
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<tr>
<td>F. Poyelle[29]</td>
<td>Zeolite-Water</td>
<td>1</td>
<td>230°C</td>
<td>0.41</td>
<td>144</td>
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<tr>
<td>L.Z. Zhang[30]</td>
<td>Zeolite-Water</td>
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<td>310°C</td>
<td>0.38</td>
<td>97</td>
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<tr>
<td>Z. Taminot-Tello[31]</td>
<td>Activated Carbon-NH₃</td>
<td>1</td>
<td>100°C</td>
<td>0.2</td>
<td>25.7</td>
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<tr>
<td>Y.Z. Liu[32]</td>
<td>Zeolite-Water</td>
<td>1</td>
<td>230-300°C</td>
<td>0.21</td>
<td>600</td>
</tr>
</tbody>
</table>

**TECHNICAL PROBLEMS**
Although the solar adsorption refrigeration systems are promising, there are several problems which have limited the emergence of solar adsorption cooling technologies in the market to any significant extent. These can be classified as mainly two categories: technical and economic.

**Technical problems:**

The major technical problem associated with solar powered adsorption technology is its poor heat and mass transfer characteristics. The adsorbents, such as activated carbon, zeolite and silica–gel, in use have low thermal conductivity and poor porosity characteristics. The effect is the bulky collector/generator/adsorber component and, thus, its excessive heating capacity, leading to rather low system COP. The most significant work on testing and evaluating commercially produced solid adsorption solar refrigerators in the field has been undertaken by Boubakri et al. [33] in Agadir, Morocco. Spinner [33] reported a slight improvement of the system performance from adsorbent stabilization with graphite binders. Munyebvu [34] produced activated carbon from monolithic discs housed in a tube with internal fins to improve both its thermal conductivity and thermal contact with metal elements.

The solar heating efficiency is of course limited due to the heat dissipation to the environment. The thickness of adsorbent bed with plate-type heat collectors is too large causing large temperature difference between the surface layer and bottom in the bed leading to uneven adsorption or desorption. Evacuated tube type solar collectors can be used to improve heating efficiency for solar water heaters, but in these types of solar adsorber/collector, cooling of the adsorber will be difficult.

The cycle is intermittent with desorbing in the daytime and adsorbing at night. Possible solutions suggested are:

(I) Use of two cycles with different adsorbent/adsorbate combinations

(ii) Use of regenerative cycles, in which two adsorption cycles are operated out of phase such that when one is being heated, the other is being cooled. None of these possible solutions, however, is yet to be adopted in commercially tried solar adsorption refrigeration to permit evaluation of the effectiveness. Various solar refrigerators have been developed, mostly with plate type adsorber/collectors.
ECONOMIC PROBLEMS

The major economic problems militating against the widespread utilisation of solar cooling technologies are the costs of the units, which, in most cases, are several times those of comparable units using conventional cooling technology. For example, the price of one aqua-ammonia solar assisted refrigerator was 8-10 times more than that of a comparable conventional unit. For this reason, several companies which produced and marketed solar powered refrigerators have been forced to stop production because of purely economic reasons. A typical example is Sun-Ice of Denmark which produced CaCl\(_2\) refrigerators which were technically successful but expensive. The company has since ceased production. For the same reason, BLM of France produced a range of refrigerators using active carbon and methanol, but has now ceased production.

In order to evaluate the potential of the different adsorption cooling systems, a classification has been made by Best and Ortega. The relevant cooling technologies are:

- Intermittent Adsorption;
- Continuous Adsorption;
- Diffusion;

INTERMITTENT ADSORPTION SYSTEMS:

Because of the intermittent nature of solar energy, intermittent adsorption refrigeration cycles have long been considered as logical approaches to solar cooling systems. Adsorbent–refrigerant combinations which have been examined for solar application include silica gel–water, zeolite–water, activated carbon–methanol and activated carbon–ammonia. The theoretical principles of basic intermittent adsorption cycles have been described in detail in above.

CONTINUOUS ADSORPTION SYSTEMS:

Continuous solar adsorption refrigeration systems are being reported widely because of their higher system performance over intermittent alternatives and for their timely coincidence with the requirement of the cooling and refrigeration demand. Continuous adsorption can be realized through various cycles various continuous adsorption cycles depending on their technologies, can be grouped as:

- Heat recovery adsorption system
Mass recovery adsorption system
Multi-stage and cascading systems;
Thermal wave adsorption systems;
Convective thermal wave adsorption systems; and
Hybrid systems.

In general, thermal wave and convective thermal wave Adsorption systems are also called as ‘heat regenerative Systems’ owing to its heat recovery properties.

HEAT RECOVERY ADSORPTION REFRIGERATION CYCLE:

The semi-continuous heat recovery cycle is usually operated with two adsorption beds. The adsorber to be cooled will transfer its heat to the adsorber to be heated, which includes sensible heat as well as heat of adsorption. This heat recovery process will lead to a higher system COP. Multi-beds could be also adopted to get more heat recovery and thereby to attain higher COP, but the operation of

![Figure 6 Schematics of heat recovery two-beds adsorption refrigeration system.](image)

Figure 6 Schematics of heat recovery two-beds adsorption refrigeration system. a practical system will be complicated. A quasi-continuous adsorption refrigeration system with heat recovery was investigated by Wang et al. [35] and the flow path is shown in Figure 6. While adsorber 1 is cooled and connected to the evaporator to realize adsorption refrigeration in evaporator, the adsorber 2 connected to the condenser is heated to obtain heating-desorption-condensation. The condensed refrigerant liquid flows into evaporator via a flow control valve. The operation phase can be changed, and the go-between will be a short time heat recovery process. Two pumps are used to drive the thermal fluid in the circuit between two adsorbers (the connection to the heater and cooler
are blocked during this process). Miles [36] obtained an experimental COP of 0.8 for the activated carbon/ammonia system with an evaporation temperature and a condensation temperature of about 5 and 35 °C, respectively. At the same time, Istria et al. [37] achieved approximately the same theoretical value for these temperatures with the multi-salt system. Pons et al. [38] investigated the zeolite - water adsorption system under the fixed test temperature and offers the best possible theoretical maximum COP of 1.5. Jones [39] suggested an improvement to the process by installing more than two adsorbers into the system. The operating principle of the cycle remains the same, relying on heat transfer flowing between the adsorbers and the desorbers. As compared to the basic cycle, heat recovery in this process is only effective if the heat transfer fluid temperature leaving the adsorbers is sufficiently high. Simulation results have shown that the maximum value of the COP depends on the number of adsorbers and desorbers installed. The analysis was further extended to a system containing six adsorbers and six desorbers at the same test temperature conditions (evaporation at 5 °C and condensation at 35 °C) and it was possible to obtain COPs in the range of 1.16.

In order to simplify the management of the cycles and to achieve continuous operation avoiding any control during the cycle as well as to obtain good heat regeneration between adsorption and desorption, systems with several elementary adsorbers coupled with evaporators/condensers and rotated about a central axis, have been proposed [40]. Maier-Laxhuber [41] proposed a rotary system which, in principle, can be used for continuous production of cold based on a single effect adsorption cycle. Erickson [58] adapted the principle of the rotary system to a double effect chemical reaction cycle operating at three pressure levels. Although there is a problem for the practical management of the air flows, i.e. the heat transfer fluid used in rotary systems, these processes seem highly attractive as continuous cooling effect as well as high COP, in the range of 1, can be obtained. Based on above reasons, Ebbeson [42] proposed a rotary process which is designed for continuous operation with the concept of a heat regeneration developed for solid sorption cold production systems. The theoretical COP was about 0.9, which is comparatively low, due to the consideration of the thermal masses and thermal pinches necessary for heat exchange between the air and the elementary modules. In a recent work, Critoph [43] describes the operation of a
continuous multiple-bed regenerative adsorption system. The complete system, consisting of 32 modules was modeled in detail. The design has not yet been optimized but a parametric study has revealed the way in which key parameters affect COP and SCP. The effect of five major parameters such as thermal capacity ratio, number of modules, temperature of air leaving the heater, generator heat transfer coefficient and the evaporator air inlet temperature were reported.

MASS RECOVERY ADSORPTION REFRIGERATION CYCLE:

Apart from the above discussed heat recovery operation, it had been proved that mass recovery is also very effective for heat recovery adsorption heat pump operation. In this process, at the end of each half cycle, one adsorber is cold and the other one is hot. Meanwhile, the former one which is at low pressure $\Delta P + \delta P$ must be pressurized up to the condenser pressure, and similarly, the other one which is at high pressure must be depressurized down to the evaporator pressure. With just one tube between the adsorbers and a vapor valve, part of this pressurization–depressurization can be achieved by transferring vapor from the latter adsorber to the former one. This process can also be called as an ‘internal vapor recovery process’, and is reported to enhance the cooling power of the unit without reducing the COP by more than 10%. The above explained process involves only mass transfer and hence the process is rapid. To obtain a ‘double effect’, mass recovery could be initiated followed by heat recovery. An ideal heat and mass recovery cycle is shown in Figure 18, in which the heat recovery state for a two bed system is shown by the state points $e - e'$:

The mass recovery cycle $a_2 - a_3$, $g_1 - g_2 - g_3$, $a_1 - a_1$ - $a_2$ is an extended form of a
two bed basic cycle or two bed heat recovery cycle \((a_2 \ g_1 \ g_2 \ \ a_1 \ \ a_2\) shown in Figure 18), and the cycled mass is increased from \(\Delta x\) to \(\Delta x + \delta x\); which causes the refrigeration effect to increase. The principle of these cycles can be described using Figure 7. The very first part of each half cycle is the mass recovery process (path \(g_2 - g_3\) and \(a_2 - a_3\)). Then the heat recovery process proceeds: heat is transferred from the hot adsorber to the cold one (path \(g_3 - e\)). As a consequence, the hot adsorber is first depressurized (path \(g_3 - a_1\)), it then adsorbs vapor from the evaporator (path). Meanwhile, the cold adsorber is first pressurized (path \(a_3 - g_1\)), and then vapor that is desorbed passes into the condenser (path \(g_1 - e\)). Theoretically, the heat recovery process develops until the adsorbers reach the same temperature. Actually, there still remains a temperature difference between the adsorbers at the end of this period. Then, for closing each half cycle, the adsorbers are, respectively, connected to the heat source and heat sink (path \(e - g_2\) and \(e' - a_2\)). The second half-cycle is performed the same way except that the adsorbers now exchange their roles. Due to this process, about 35% of the total energy transmitted to each adsorber can be internally recovered, including part of the latent heat of sorption.

**THERMAL WAVE CYCLE:**

To further improve the heat regenerative ratio, Shelton [44] had proposed an attractive cycle called ‘thermal wave cycle’. In this process, it is assumed that a large temperature gradient exists along an adsorption bed. Heating and cooling of the adsorbent beds is achieved via a heat transfer fluid such as high temperature oil. The system consists of two adsorber beds and two heat
exchangers connected in series (Figure 8) to effect semi-continuous process. The function of the bed and heat exchanger is to combine a large area of heat transfer surface with a low oil flow rate. A typical thermal wave cycle is shown in Figure 8. The cycle consists of two phases: In the first phase, the oil recovers heat from bed 2 (hot), has a further heat addition from the heat exchanger and then proceeds to heat bed 1 (cold). As the heating of the bed proceeds, bed 1 desorbs refrigerant which passes to the condenser (giving a useful heat output in the case of a heat pump) and bed 2 adsorbs gas from the evaporator which provides cooling. In the following phase (second phase) of the cycle the pump is reversed, and hence, bed 1 is cooled (adsorbing) and bed 2 is heated (desorbing) in a similar fashion until the original conditions are reached and the pump can again be reversed. Though the procedure is simple, significant heat recovery can be achieved. Further, the system would achieve much better performance due to the combination of the special nature of the internal bed heat exchangers and the low flow rate. Although many researchers have studied the cycle, up to now, there is no report of a successful prototype adopting thermal wave cycle. Also, some experimental reports had shown that
the performance of the thermal wave cycle is not very good. The efficiency of the thermal wave regenerative system depends on a relatively large number of parameters: for example, rates of various heat transfer processes, the flow rate of the circulating fluid, the cycle time, the adsorber configuration, etc. A numerical analysis of adsorptive heat pumps with thermal wave heat regeneration had been presented by Sun et al. [45]. They had derived two time constants which can be used directly to quantify the relative importance of the two heat transfer processes. This allows ready determination of which of the two processes is rate limiting and needs to be improved. The work has also confirmed that the performance of an adsorptive heat pump system using a traditional packed-bed would be too low, even with a heat regeneration, and therefore a significant enhancement of heat transfer properties inside the adsorber is necessary. Similar to the above numerical study, the effect of various operating parameters on the performance of an adsorptive thermal wave regenerative heat pump had been studied by Ben Amar et al. [46], theoretically. They had developed a two-dimensional model which simultaneously considers heat and mass transfer in the bed. The results have shown that under ideal conditions, the performance of a thermal wave regenerative heat pump is considerably better than that of a basic ‘uniform temperature’ heat pump. The study showed that a COP greater than 1 and a power of cold production of near 200 W per kg of adsorbent could be obtained. For air-conditioning applications, these figures are slightly higher than those obtained with other single-stage solid-gas systems as chemical heat pumps [47].

CONVECTIVE THERMAL WAVE CYCLE:

Thermal wave cycles normally suffer from low power density because of poor heat transfer through the adsorbent bed. Rather than attempting to heat the bed directly, it is possible to heat the refrigerant gas outside the bed and to circulate it through the bed in order to heat the sorbent. The high surface area of the grains leads to very effective heat transfer with only low levels of parasitic power needed for pumping. Hence, Critoph [48] has presented a modified version of a thermal wave cycle, known as ‘convective thermal wave cycle’. The concept is the same as thermal wave cycle, however, the thermal fluid for heating and cooling to the beds is initiated by the refrigerant itself, thus the heat transfer between thermal fluid and adsorption bed is a direct contact heat transfer, which
is incorporated with mass transfer in the system. A practical schematic of the proposed system is shown in Figure 9. The two ‘active’ beds are packed with activated carbon and the two ‘inert’ beds are packed

![Figure 9 Adsorption refrigeration system with convective thermal wave cycle.](image)

with non-reactive particles such as steel balls. The diagram shows the first half of the cycle, during which Active bed 1 is heated and desorbs ammonia while Active bed 2 is cooled, adsorbing ammonia.

In the fluid circulation loop shown on the left, a low power pump circulates ammonia steam through inert bed 1 which is initially hot. The gas stream is heated by the bed and a ‘cold’ wave passes through the bed from right to left. Having been preheated by the inert bed, the ammonia stream is heated to the maximum cycle temperature (150–200 °C) in a heat exchanger. The ammonia gas then passes to active bed 1 where it heats the carbon. A ‘hot’ thermal wave passes from left to right through the active bed. As the temperature of the active bed rises it desorbs ammonia which first increases the pressure in the left hand loop and then condenses in the condenser, rejecting heat to the environment.

The mass flow rate of circulating ammonia is typically ten times that of the condensing stream of ammonia and it may take about ten minutes for the two thermal waves to travel the length of their respective beds. In similar fashion to the left hand loop the circulating flow might be ten times the adsorption flow from the evaporator. The advantages of this system are the four packed beds are in effect heat exchangers of very high surface areas but at minimal cost. They are not only cheap but very compact. † There are only four conventional heat exchangers and this is the minimum number
allowed by thermodynamics. These are the evaporator and condenser, a gas heater whereby high-grade heat is input and a gas cooler whereby the low grade heat of adsorption is rejected to the environment. The cycle is highly regenerative since the packed beds act like large counter-flow heat exchangers. This results in good energy efficiency (i.e. high COP).

MULTI-STAGE AND CASCADING SYSTEMS:

The adsorption cycles discussed in previous sections are applicable only to a single stage cycle. The single stage cycle systems have certain limitations, that is, they cannot effectively utilize high temperature heat source, as well as do not perform well at very low temperatures. Hence, to improve the system performance under such situations, adsorptive processes may be adapted for advanced cycles, such as, multi-stage and cascading cycle. The basic idea of a multi-stage cycle is to perform the desorption–condensation processes and evaporation–adsorption processes at different temperature/pressure levels by using the ‘same working pair’. The internal re-use of heat of condensation or adsorption can increase the system performance significantly. Another practical cycle that can make good use of high temperature heat source is the ‘cascading cycle’, which operates with ‘different working pairs’ (either liquid/liquid or solid/liquid), such as zeolite–water/activated carbon–methanol, or zeolite–water/silica gel–water, etc. These cascading cycles are applied to situations especially, when there exists a large temperature difference between the heat source/ambient and the temperature in the evaporator/refrigeration space. For such situations, it may not be practical to use single stage cycle. Hence, one way of dealing with such situations is to perform the evaporation/refrigeration process in stages, that is, to have two or more cycles that operate in series at different temperature levels (cascading). A high temperature heat source (e.g. boiler) is used to drive the high temperature stage adsorption refrigeration cycle.
The low temperature stage adsorption refrigeration is driven by sensible heat and heat of adsorption obtained from high temperature stage. To minimize the contribution of sensible heat, special care has been attached to the heat management of the adsorbers; n-adsorber cycles operating with a single evaporator and a single condenser have been proposed with sequences of heat recovery between adsorbers. Such cycles offer some advantages: for example, a single condenser is used and pressure in the n-adsorber unit is not higher than that in the unit operating an intermittent cycle; moreover, adsorption heat at high temperature is used as desorption heat at low temperature. Counteracting heat transfer fluid circuits between adsorbers reduces entropy generation in comparison with what happens in intermittent cycles. The driving heat supplied to the cycle is at high temperature level (Fig10) so that the entropy generation—due to the inadaptation between the temperature levels of the source and of the adsorber is much less in an n-adsorber cycle than in an intermittent cycle. The same thing happens for the rejected heat: the rejection temperature is much closer from the utility temperature with an n-adsorber cycle than with an intermittent cycle.

Very similar conclusions to that drawn by Scharfe et al. [49] have been presented by Meunier [50] in the case of heat recovery between adsorbers. In a particular case, Meunierb has shown that using an infinite number of adsorbers with ideal heat recovery between adsorbers, the maximum achievable with given conditions of operating temperatures would be a cooling COP equal to 1.85 corresponding to 68% of ideal Carnot COP. An other cascading cycle which includes a triple effect machine operating a cascade between a water zeolite heat pump and a single stage LiBr–H₂O refrigerator has been tested in Munich [51].
Douss and Meunier [52] had reported the experiments on a cascading adsorptive heat pump. The cycle comprised of a two-adsorber zeolite–water system at high temperature stage and an intermittent active carbon–methanol system at low temperature stage. Driving heat was supplied by a boiler to zeolite adsorbers while active carbon adsorber was heated by heat recovered from zeolite adsorber under adsorption. Evaporators from both basic cycles operated at the same temperature and contributed to the evaporating load. Experimental cooling COP was found to be 1.06, which is much higher than the COP of an intermittent cycle (<0.5) and that of a two-adsorber zeolite water cycle (<0.75). An analysis of the results showed that the components which limit the power of the unit were the evaporators and basically it was the water evaporator. The COP of the cascading cycle was very sensitive to the evaporating temperature lift. Also, it was reported that the cycle had adapted well to air conditioning as long as the evaporation temperature lift was less than 45 °C.

A similar study on combined cycle comprising of an adsorption–absorption cascading multi-effect refrigeration cycle was carried out by Shu et al. [53]. The system consists of a high temperature stage of solid adsorption unit working with zeolite water and a low temperature stage of double effect.

![Figure 11 Adsorption–absorption cascading multi-effect refrigeration cycle: (1) adsorption cycle; (2) high pressure absorption cycle and (3) low pressure absorption cycle.](image-url)
absorption unit working with LiBr–water. The working principle of this multi-effect cascading cycle can be explained using Clapeyron diagram shown in Figure 11. The single stage cycle with heat source $Q_h$ represents the adsorption cycle using zeolite–water as working medium. The double stage cycle obtains the absorption heat of the single stage cycle as its driving heat $Q_{ads}$ for its high temperature stage. The heat obtained from the condenser of the single stage cycle is used as the heat source for its low temperature stage. The study has shown that the COP of the cycle can be greatly improved by efficient utilization and recovery of energy within the system. Also, they had reported that there exists no corrosive problem though the temperature of the working pair is higher than 200 °C in the adsorption unit.

Saha et al. [54] has proposed a two-stage non-regenerative adsorption chiller design and experimental prototype using silica gel–water as the adsorbent refrigerant pair. The main advantage of the two-stage adsorption chiller is its ability to utilize low temperature solar/waste heat (40-75 °C) as the driving heat source in combination with a coolant at 30°C. With a 55°C driving source in combination with a heat sink at 30°C, the COP of the two-stage chiller is 0.36.

Wang [55] carried a study on a four-bed adsorption refrigeration system and the multi-stage system.

![Diagram of four-bed cascading adsorption refrigeration cycle](image)

Figure 12 The system configuration of four-bed cascading adsorption refrigeration cycle. The system consists of four adsorbers (A1; A2; B1; B2) one condenser (C), and one evaporator (E). The working principle can be explained as follows according to the Clapeyron diagram as shown in Figure 24. To begin with, A1
and A2 are in the high temperature stage, for which generation (temperature about 200 \(^{\circ}\)C) is initiated by heat input. The desorbed water vapor will go through the adsorber B1 or B2 at the low temperature stage to release heat for desorption. The adsorption pressure of the two stages are the same because only one evaporator is used in the system. During phase 1, the desorption process in desorber B1 is furnished by the heat from desorber A1 and adsorber A2 in the high temperature stage. The coordination of adsorption and desorption of the two stages is very important to operate the system properly. By the way, the desorption pressure in desorber A1 must be higher than the desorption pressure of desorber B1 in order to facilitate the vapor desorbed from A1 to pass through desorber B1 effectively. In this multi-stage system, water is the refrigerant and the desorbed vapor flows through the adsorbent bed in desorber B1 to get a triple-effect installation. Here, a double effect is accomplished with sensible and adsorption heat recovery to generate low temperature stage in addition to the heat input to the high temperature stage, a triple effect is accomplished with the heat recovery of the desorbed vapor in the high temperature stage in addition to the heat used in a double effect arrangement to generate low temperature stage. The maximum energy recovery from high temperature stage can be arranged by a triple effect system, in which the sensible heat of adsorbent bed, heat of adsorption and the latent heat of refrigerant vapor are fully used to drive the low temperature stage system. The simulation work has shown that, the performance of a cascading cycle in term of COP can be triple (COP = 1.56), compared to two independent
stage system (COP = 0.6). This concept could be used for multi-effect adsorption systems, as well as extended to adsorption–absorption cascading systems [56].

**DESIGN AND PRINCIPLE OF THE HYBRID SYSTEM**

The basic solid adsorption bed is normally designed according to the fabrication of plate-type heat collector. Such design has two disadvantages as following: (1) The encapsulation thickness of adsorbent is so large that the temperature difference of adsorbent between surface layer and bottom in the bed is too big for adsorbent to adsorb or desorb evenly; (2) Only be used in intermittent cycle with desorbing in the daytime and adsorbing at night.

To overcome the two disadvantages of traditional adsorption bed, the hybrid adsorption bed is combined by two adsorption beds which are covered by glass layer similar with solar collector shown in Fig.13. To avoid the mutual thermal effect, an adiabatic layer is placed between the two beds. Such hybrid bed is devised like a slat and is made of alloy, which will make for keeping vacuity and increasing heat-transfer areas. Black lacquer is coated on the surface of the bed. A U-type flume is devised as the bed wall through which the cold water flows to cool adsorbent that is adsorbing. When the two beds are in a state of saturated adsorption/desorption respectively, the two beds exchange their positions through a rotation of 180° by an axis, still with the upper bed desorbing and the lower bed adsorbing for refrigerating continuously.

![Figure 14 The design of hybrid adsorption bed.](image)

The schematic design of solar continuous solid adsorption refrigeration and heating hybrid system is shown in Figure 14. The system consists of a hybrid adsorption bed array, water tank, condenser, evaporator, liquid receiver, throttle valve, valves and so on.
In an ideal process, the working principle is shown in Figure 5. In the morning, the upper bed absorbs solar energy as a heat collector. As time going, the temperature of adsorbent in upper bed rises. When the temperature of adsorbent rises up to a temperature \((T_{a2} \rightarrow T_{g1})\) which causes the vapor pressure of the desorbed refrigerant up to the condensing pressure \((p_{ev} \rightarrow p^{co})\), desorption at constant pressure is initiated, the desorbed vapor is condensed in the condenser and collected in the receiver. The liquid flows into the evaporator via a throttle valve. The temperature of adsorbent in upper bed continues rising due to solar heating. After 2 h, when the temperature of adsorbent reaches the expected desorption temperature 80–90°C \((T_{g1} \rightarrow T_{g2})\), the first heating of upper bed ends, and the hybrid bed is rotated by 180°. The upper bed is substituted for the lower bed, which is heated by solar energy now, and the upper bed, which is now lower bed, is cooled by water. Cold water from water tank circulates from tank to cool the lower bed by its natural convection and the water is heated.

The temperature of adsorbent in lower bed is reduced rapidly \((T_{g2} \rightarrow T_{a1})\), and the vapor pressure of refrigerant drops too \((p^{co} \rightarrow p_{ev})\). Evaporation, i.e. refrigeration could happen if the connecting valve is open. The cooling by cold water and air natural convection causes the temperature of adsorbent in lower bed to drop \((T_{a1} \rightarrow T_{a2})\). In the evening, by several cycles the water will reaches high temperature, and can be used by the family.

![Figure 15 Solar Continuous solid adsorption refrigeration and heating hybrid system](image.png)
Figure 16 The Clapeyron diagram of ideal adsorption cycle.

The thermodynamic cycle for adsorption refrigeration can be demonstrated in a $p-T-x$ diagram shown as Figure 5. But in such hybrid cycle, because the temperature of cooling water in water tank is rising after every cycle, $T_{a2}$, $T_{g1}$, $T_{g2}$, and $T_{a1}$ will have increasing values. So the cycle will not be repeated exactly due to the dynamic change of the several parameters.

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.

**THEORETICAL ANALYSIS OF THE HYBRID SYSTEM**

Zhang and Wang [57] carried out a theoretical analysis on the system of a single hybrid adsorption bed. Their results obtained with daily solar radiation of 21.6 MJ, the mean ambient temperature of 29.9°C, the evaporating temperature of 5°C, are summarized in the Table 4. The system with 2 kg adsorbent is also capable of supplying 30 kg hot water at 47.8°C.

Table 4 Simulation results when the water mass in water tank is 30 kg

<table>
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<th>Names of performance parameter</th>
<th>Value</th>
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<tbody>
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<td>Final water temperature increment in water tank in the daytime (°C)</td>
<td>22.8</td>
</tr>
<tr>
<td>Mean cooling COP in the daytime</td>
<td>0.18</td>
</tr>
<tr>
<td>Mean heating COP in the daytime</td>
<td>0.34</td>
</tr>
<tr>
<td>Continuous mean specific cooling power of adsorbent in the daytime SCPa (W/kg)</td>
<td>17.6</td>
</tr>
<tr>
<td>Continuous mean sp. cooling power of heat-collecting area in the daytime SCPc (W/m²)</td>
<td>87.8</td>
</tr>
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</table>
CONCLUSIONS

The development of adsorption system for refrigeration is promising. An overall thermodynamics-based comparison of sorption systems shows that the performance of adsorption systems depend highly on both the adsorption pairs and processes. The technology continues to develop, and the cost of producing power with solar thermal adsorption refrigeration is falling. If the costs of fossil fuels, transportation, energy conversion, electricity transmission and system maintenance are taken into account, the cost of energy produced by solar thermal adsorption systems would be much lower than that for conventional refrigeration systems. This paper presents an overall review on the fundamental understanding on the various adsorption refrigeration cycles and the applicability of solar adsorption both in air conditioning and refrigeration, with the improvement of the COP.

Of the several kinds of adsorption systems analyzed in this paper, the intermittent system has been extensively studied both theoretically and experimentally, owing to its simplicity and cost effectiveness. However, the main disadvantages such as long adsorption/desorption time have become obstacles for commercial production of the system. Hence, to compete with conventional absorption and vapor-compression technologies, more efforts should be made in enhancing the COP and SCP (A summarization on the different systems along with their respective COPcooling and SCPs is listed in Table 3). Heat recovery, mass recovery, multi-bed and multi-stage technologies are promising technologies in improving the COP and SCP. Also, recent developments of activated carbon series—activated carbon fibre (ACF)—has called attention to the possibility for application in adsorption refrigeration. For instance, with a specially treated ACF, the measured adsorption capacity on methanol is 2–3 times that of normal activated carbon, and the estimated adsorption time of ACF on methanol is about 1/5 to 1/10 of that of normal activated carbon. Besides, activated carbon can be made with properties to suit particular applications by varying the activation time and temperature. Hence, with such technologies the specific refrigeration capacity as well as

| Continuous mean sp. heating power of heat-collecting area in the daytime SHPc (W/m²) | 165.9 |
| Cooling capacity of per kg adsorbent at night (MJ/kg) | 0.26 |
| Cooling capacity of per m² heat-collecting area at night (MJ/m²) | 1.3 |
the COP of the adsorption refrigeration cycle can be improved.

Adsorption technology combined with other technologies for multi-purpose application seems to be a new trend in the research. This will widen the area of applications of adsorption technologies and make the adsorption refrigeration more cost effective. Any method that improves the efficiency even marginally would improve the economic viability of operating such devices. Thus, further studies need to be carried out to validate the potential for possible application in household refrigerators.

REFERENCES


[34] Wen Wang *, Ruzhu Wang, Zaizhong Xia.Impact of refrigerant flowing resistance on active carbon–ammonia adsorption refrigeration cycle School of Power and Energy Engineering, Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Huashan Road 1954, Shanghai 200030, PR China

225


