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Applications of Adsorption Refrigeration Cycle –Review

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Abstract: -

Energy conservation is ad infinitum growing around the world and this situation yields research to find sustainable energy solutions. The increasing fossils fuel price and the consciousness of environmental problems recommend many potential applications to thermal powered adsorption cooling. Many of the conventional refrigeration systems use Chlorofluorocarbons (CFCs) as refrigerants, particularly in developing and under developed countries. The ozone layer, which protects life on earth from the sun's ultra-violet radiation, is getting depleted due to use of chlorine containing chemicals in conventional refrigeration systems. The aim of study the design and fabrication of the experimental chamber, the experimental procedure and its feasibility towards development of an alternative eco friendly refrigeration cycle for replacement of chlorofluorocarbons. As solar power is freely accessible, solar adsorption refrigeration devices are of significance to meet the needs for cooling requirements such as air-conditioning, ice-making and food preservation in isolated areas. Various solar powered cooling system have been tested comprehensively; however these system are not yet ready to compete with the well-known vapor compression system. The objective of the work is to provide deep-seated knowledge on the adsorption systems and present a proposed model which will give refrigeration effect.

Keywords - Solar Refrigeration, Adsorption, Heat pipe, COP

I. INTRODUCTION

The make use of solar energy for environmental be in command of is receiving much awareness as a result of the predictable world energy shortage. Refrigeration is particularly attractive as a solar energy application because of the near concurrence of peak cooling loads with the available solar power. Solar refrigeration has the potential to improve the quality of life of people who live in areas with electricity in-sufficient. It is usually used for storage of agricultural products, food and medicines (e.g. vaccines) in isolated areas. Solar cooling to produce ice accumulates latent heat, thus leading to smaller volume of ice-makers. 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.

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 components. 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.

Solar refrigeration is highly dependent upon environmental factors such as cooling water temperature, air temperature and solar radiation. The energetic conversion efficiency is low, and solar cooling and refrigeration are not yet competitive economically with the conventional systems. This article particulars the various research aspects of adsorption refrigeration, which includes adsorption mechanism, the criteria to choose an appropriate working pair, thermodynamic analysis of several refrigeration cycles, adsorbent properties and various solar powered adsorption refrigeration systems based on various cooling technologies.The interest in adsorption systems first started to increase due to the oil crisis in the 1970s, and then later, in the 1990s, because of ecological problems related to the use of CFCs and HCFCs as refrigerants. Such refrigerants, when released into the atmosphere, deplete the ozone layer and contribute to the greenhouse effect. Furthermore, with the increase in energy consumption worldwide, it is becoming even more urgent to find ways to use the energy resources as efficiently as possible. Thus, machines that can recover waste heat at low temperature levels—such as adsorption machines—can be an interesting alternative for wiser energy management [2].

The conventional adsorption cycle has been presented extensively and it mainly includes two phases: (1) Adsorbent cooling with adsorption process, which results in refrigerant evaporation inside the evaporator and, thus, in the desired refrigeration effect. At this phase, the sensible heat and the adsorption heat are consumed by a cooling medium, which is usually water or air. (2) Adsorbent heating with desorption process (also called generation), which results in refrigerant condensation at the condenser and heat release into the environment. The heat necessary for the generation process can be supplied by a low-grade heat source, such as solar energy, waste heat, etc. In comparison with mechanical vapour compression systems, adsorption systems have the benefit of saving energy, if powered by waste heat or solar energy, simpler control, no vibration and lower operation costs. In comparison with liquid absorption systems, adsorption systems can be powered by a large range of heat source temperatures, starting at 50 1C and going up to 6001C or even

higher. Moreover, the latter system does not need a liquid pump or rectifier for the refrigerant, does not present corrosion problems due to the working pairs normally used, and it is less sensitive to shocks and to the installation position[1].
These last two features make it suitable for applications in locomotives, busses, boats and spacecrafts. Although adsorption systems offer all the benefits listed above, they usually also have the drawbacks of low coefficient of performance (COP) and low specific cooling power (SCP). However, these inconveniences can be overcome by enhancing of the heat and mass transfer properties in the adsorber, by increasing the adsorption properties of the working pairs and by better heat management during the adsorption cycle. Thus, most research on this system is related to evaluation of adsorption and physical-chemical properties of the working pairs, development of predictive models of their behavior in different working conditions and the study of the different kinds of Cycles[4-5].

II. PRINCIPLE OF ADSORPTION

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. Adsorption processes can be classified as either physical or chemical, depending on the forces causing the adsorption process. Physical adsorption (physisorption) occurs when Van der Waals forces bind the adsorbing molecule to the solid phase, these intermolecular forces are as same as ones that bond molecules to the surface of a liquid. Molecules that are physically adsorbed to a solid can be released by applying heat; therefore, the process is reversible. Chemical adsorption (chemisorption) occurs when covalent or ionic bonds are formed between the adsorbing molecules and the solid substance. The bonding forces of chemical adsorption are much greater than that of physical adsorption. Thus, more heat is liberated. This bonding leads to change in the chemical form of the adsorbed compounds and hence, it is irreversible. For this particular reason, most of the adsorption processes applicable to the thermal system or cooling machine mainly involve physical adsorption[1-3].
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. The heat of adsorption is usually 30 – 100% higher than the heat of condensation of the adsorbate. In general adsorption is stronger than condensation to liquid phase. Hence, if a fresh adsorbent and adsorbate in liquid form coexist separately in a closed vessel, transport of adsorbate from the liquid phase to the adsorbent occurs in the form of vapor. The liquid temperature becomes lower while the adsorbent temperature rises. Air-conditioning and refrigeration utilize this phenomenon to obtain a cooling effect[6].

A. Refrigerants and adsorbents:-

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. It is because the performance of the system varies over a wide range using different working pairs at different temperatures. The advantages and disadvantages of different working media and their properties are listed and discussed. The adsorbents are first characterized by surface properties such as surface area and polarity. A large specific surface area is preferable for providing large adsorption capacity, and hence an increase in internal surface area in a limited volume inevitably gives rise to large number of small sized pores between adsorption surfaces. The size of the micropores determines the effectiveness of adsorptivity and therefore distribution of micropores is yet another important property for characterizing adsorptivity of adsorbents.
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.

The selected adsorbate (working fluid) must have most of the following thermodynamics and heat transfer properties

- 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

III. THERMODYNAMICS OF ADSORPTION CYCLES

Adsorption refrigeration with different cycles have been studied extensively, and the typical adsorption refrigeration cycles are: basic cycle, continuous heat recovery cycle, mass recovery cycle, thermal wave cycle, convective thermal wave cycle, cascade multi effect cycle, hybrid heating and cooling cycle etc.

A. Basic adsorption cycle

A basic adsorption cycle consists of four thermodynamic steps, which can be well represented with the aid of the Clapeyron diagram, as shown in Fig. 3.1. The idealized cycle begins at a point (point A in Fig. 1) where the adsorbent is at low temperature T_A and at low-pressure P_E (evaporating pressure). A – B represents the heating of adsorbent, along with adsorbate. The collector is connected with the condenser and the progressive heating of the adsorbent from B to D causes some adsorbate to be desorbed and its vapor to be condensed (point C). When the adsorbent reaches its maximum temperature T_D; desorption ceases. Then the liquid adsorbate is transferred into the evaporator from C to E and the collector is closed and cooled. The decrease in temperature D to F induces the decrease in pressure from P_C to P_E :Then the collector is connected to the evaporator and adsorption and evaporation occur while the adsorbent is cooled from F to A. During this cooling period heat is withdrawn to decrease the temperature of the adsorbent [3,5].

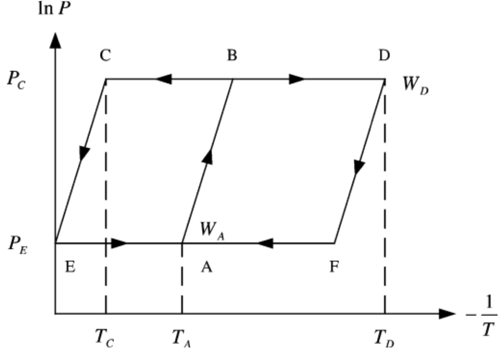

Fig.1 Clapeyron diagram (ln P vs.21=T) of ideal adsorption cycle.

B. 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 a practical system will be complicated. A quasi-continuous adsorption refrigeration system with heat recovery was investigated by Wang et al. and the flow path is shown in Fig. 2. 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[1-2].

Miles 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 8C, respectively. At the same time, Istria et al. [2] achieved approximately the same theoretical value for these temperatures with the multi-salt system. Pons investigated the zeolite water adsorption system under the fixed test temperature and offers the best possible theoretical maximum COP of 1.5. Jones 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 8C and condensation at 35 8C) 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 .

Maier-Laxhuber proposed a rotary system which, in principle, can be used for continuous production of cold based on a single effect adsorption cycle. Erickson 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 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 due to the consideration of the thermal masses and pinches necessary for heat exchange between air and the elementary module.

C. Mass recovery adsorption refrigeration cycle

Apart from the 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 ðP_C Þ 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%[2-3].

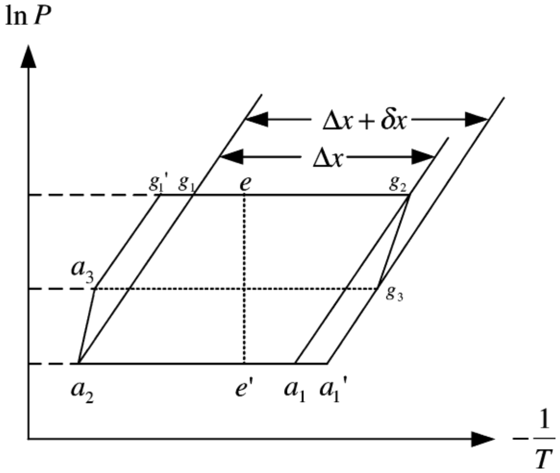

Fig. 2 Fig 2. Diagram of mass versus heat recovery cycle[1].

D. Thermal wave cycle:-

To further improve the heat regenerative ratio, Shelton 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 (Fig. 2) 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 Fig.3. 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.

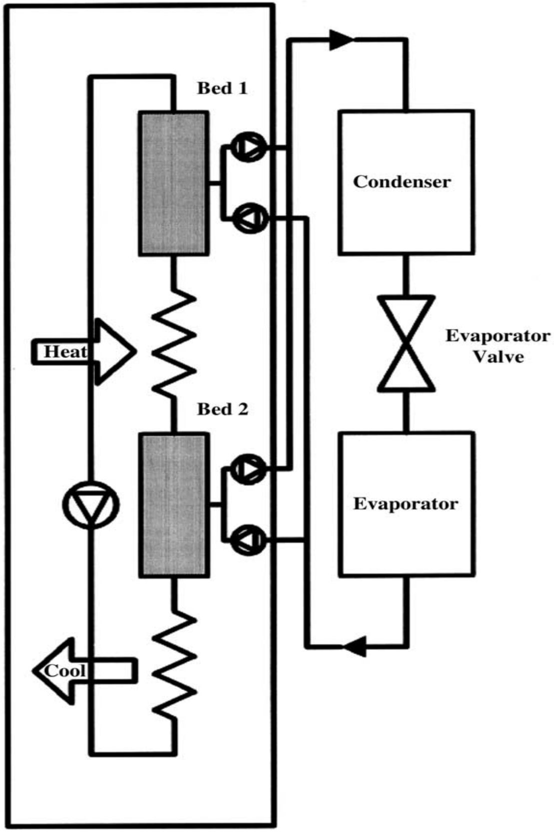

Fig.3 Adsorption -Thermal wave cycle.

E. 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 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 Fig.4 . The two 'active' beds are packed with activated carbon and the two 'inert' beds are packed 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.

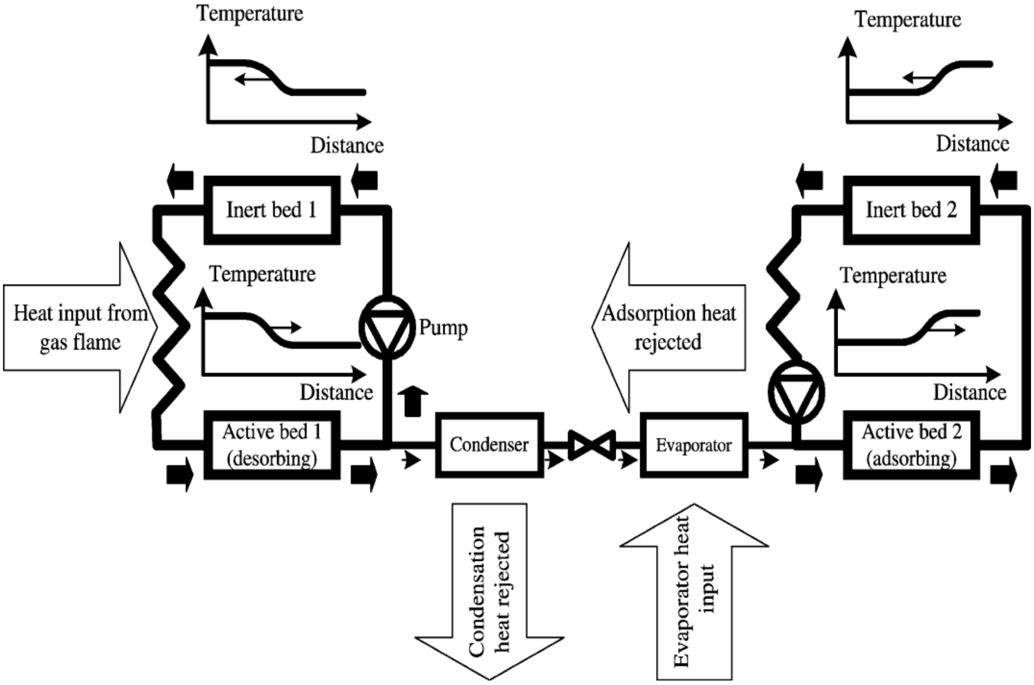

Fig..4 Convective thermal wave cycle in adsorption system

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 8C) 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 environ- ment. 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).

IV. SSOLAR COOLING TECHNOLOGIES

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

- intermittent adsorption;
- continuous adsorption;
- diffusion; and
- absorption systems;

A. 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[1,8].

A.a. Silica-gel/water and silica-gel methanol systems

Since early 1980s, the work on silica-gel/water systems have been popular and lot of work was carried out mainly in Japan. In an effort to utilize solar heat, Sakoda and Suzuki [1] achieved a solar COP of about 0.2 with a solar collector 500 x 500 x 50 mm^3 depth, packed with 1 kg of silica-gel particles and with 1.5 kg of distilled water in the evaporator. On a clear day with total solar insulation of 19.3 MJ m^{22}day ^{21}, it was estimated that a COP of about 0.4 can be possible just with 0.4 m^2 solar collector.
Utilizing the benefits of cogeneration, manufactured a 34.5 kW (10 TR or tonne of refrigeration) adsorption chiller and ice thermal storage system, comprising two adsorption units, an evaporator and a condenser, as shown in Fig. 5. Both adsorbers were installed in an evacuated hermetic enclosure, and each adsorber was alternatively heated and cooled in a cycle time of 7 min. The COP of the system was found to be 0.4. They had reported that a 100 TR system can obtain a COP of about 0.6.

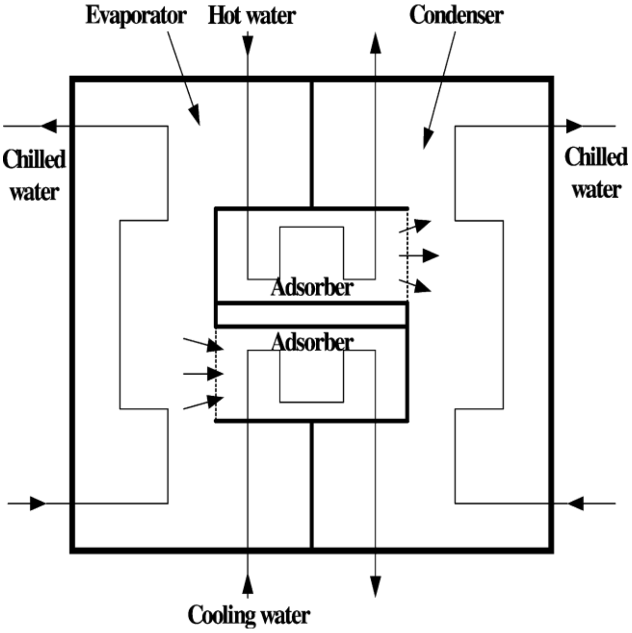

Fig 5. Chiller methodology.

B. 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 which are detailed. Hence, various continuous adsorption cycles depending on their technologies, can be grouped as:

- Multi-stage and cascading systems;
- Thermal wave adsorption systems;
- Convective thermal wave adsorption
- 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.

B a. Hybrid system

Although solid adsorption refrigeration has received much attention from most of the refrigeration companies and laboratories around the world, some of the main disadvantages such as long adsorption/desorption time and small refrigeration capacity per unit mass of adsorbent, have become obstacles for the real mass production of the system.
Better design of the adsorbers and improvements in the thermal conductivity of the adsorption bed are the main tools to reduce cycle time, while treatment of adsorbent to increase its adsorption capacity on a refrigerant could increase the refrigeration capacity of adsorbent per unit mass and also the COP of the cycle. Besides, several investigations had attempted to further improve (hybrid) the performance of the existing solar refrigerators, (i) by combining the basic adsorption cycle with other refrigeration cycles, as well as, (ii) in designing a dual system[6,10].

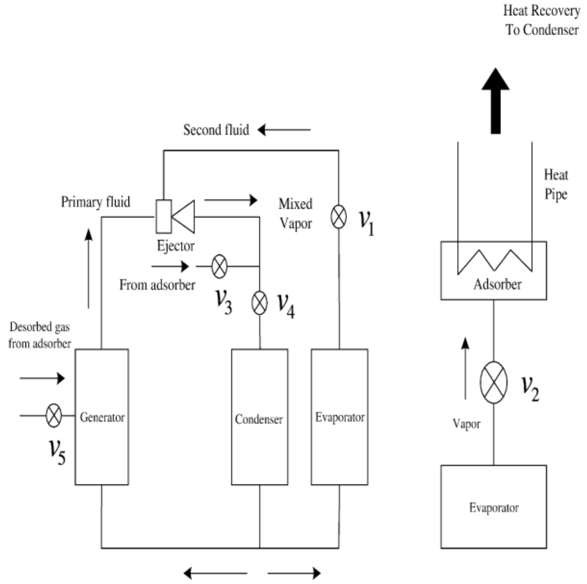

Fig 6. Ejection refrigeration and adsorption refrigeration systems.

In an attempt to overcome the intermittence of adsorption refrigeration, and realize the continuity, a novel combined cycle of a solar-powered adsorption– ejection refrigeration system has been studied by Li et al.. As shown in Fig.6, it includes two subsystems: the adsorption sub-system, which refrigerates at night time and the ejection subsystem, which refrigerates during the day.

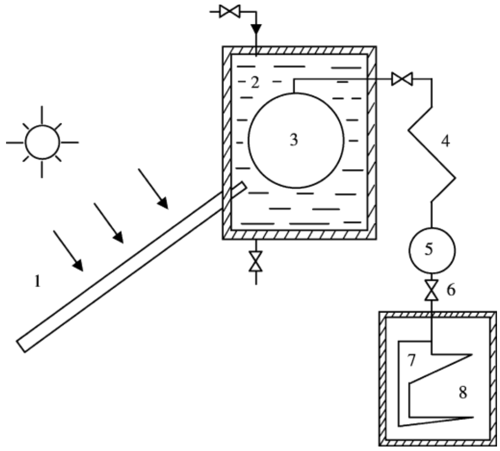

Fig.7 Schematic of the hybrid system: (1) solar collector; (2) water tank; (3) adsorber; (4) condenser; (5) receiver; (6) valve; (7)evaporator; (8) refrigerator.

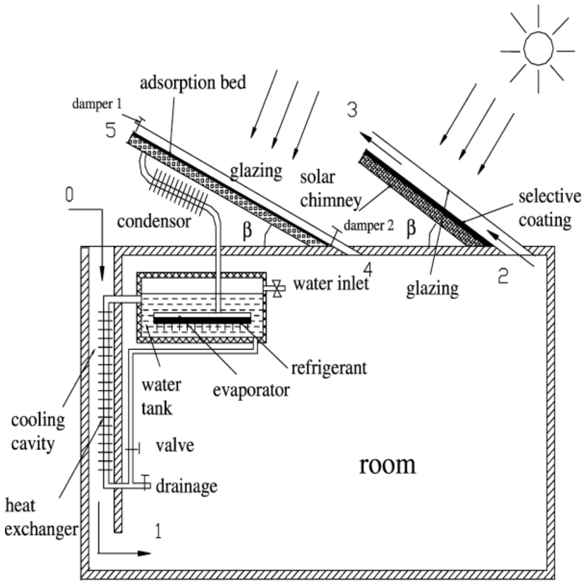

Fig.8. Schematic of the solar house with enhanced natural ventilation driven by solar chimney and adsorption cooling cavity

V. KEY ISSUES FOR THE DEVELOPMENT OF ADSORPTION SYSTEMS

The adsorption systems must comprise their size and cost reduced to become more commercially attractive. The most promising alternatives to achieve these goals include the enhancement of the internal and external heat transfer of the adsorber to increase the SCP, and the improvement of the heat management to increase the COP. The main technologies to enhance the external heat transfer in the adsorber are related to the increase of the heat exchange area, the use of coated adsorbers and the utilization of heat pipe technology, which was described in the previous section. To improve the internal heat transfer, the most suitable option is the employment of consolidated adsorbents[1-3].

A. Extended surfaces:

Several types of extended surfaces can be considered, such as finned tubes, plate heat ex- changers and plate–fin heat exchangers. This solution is suitable if the wall heat transfer coefficient is not low and if there is no swelling or shrinking effect of the sorbent which could produce a considerable alteration in this coefficient. The drawback of this technology is that it increases the thermal capacity of the adsorber; therefore, extended surfaces heat exchangers require efficient heat management to produce reasonable COPs. Furthermore this solutions should be avoided if the operation pressure is very low and the Knudsen effect can occur.

B. Coated adsorbers:

The utilization of coated adsorbers is particularly suited for applications where high COP is not as important as high SCP. This technology consists in the increase of the wall heat transfer coefficient by the effective decrease of the contact thermal resistance between the heat exchange surface and the adsorbent. Dunne developed coated tubes where zeolite crystals monolayers grew on the tube metal surfaces. The heating rate of this adsorber is higher than 1500 W kg^{-1} of sorbent. Bou et al. developed a coated heat exchanger where the adsorbent bed was inserted in an expanded graphite plate. With this technique, the contact between the heat transfer fluid and the adsorbent is not as close as in the previous coated tube, but the ratio between the mass of adsorbent and the mass of inert material is much higher, since the thickness of the adsorbent bed can reach a few millimeters.

VI. CONCLUSIONS

The development of adsorption system for refrigeration is promising. An overall 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, 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 vapour compression technologies, more efforts should be made in enhancing the COP and SCP.

Abbreviations

A	adsorption potential (J mol ^{21})
Cm	adsorbed concentration (mol kg ^{21})
Cms	saturation adsorbed concentration (mol kg^{21})
E	interaction energy between solid and adsorbing molecule (J mol ^{21})
E_0	characteristic energy used in Dubinin equation (J mol ^{21})
H	enthalpy (J mol^{21})
n	adsorption parameter of adsorption pair
P	pressure (Pa)
P_C	condensing pressure (Pa)
P_E	evaporation pressure (Pa)
P_S	saturated vapor pressure (Pa)
T	temperature (^{0}C, K)
T_A	ambient temperature (^{0} C)
T_C	condensing temperature (^{0} C)
T_E	evaporation temperature (^{0} C)
T_R	regeneration temperature (^{0} C)
Ts	saturated refrigerant liquid temperature (^{0} C)

REFERENCES

[1] K. Sumathy, K.H. Yeung, Li Yong, "Technology development in the solar adsorption refrigeration system", Progress in Energy and Combustion Science 29 (2003) 301–32.

[2] R.Z. Wang, R.G. Oliveira, "Adsorption refrigeration An efficient way to make good use of waste heat and solar energy", Progress in Energy and Combustion Science 32 (2006) 424–458.

[3] Ning Mei, Yingchun Xie, Zhen Xu, Jian Su, "Experimental investigation and mathematical modeling of a solid adsorption refrigeration system", International Communications in Heat and Mass Transfer 32 (2005) 349-359.

[4] X.J. Zhang, R.Z. Wang, "Design and performance simulation of a new solar continuous solid adsorption refrigeration and heating hybrid system ", Renewable Energy 27 (2002) 401–415.

[5] X.J. Zhang, R.Z. Wang], "A new combined adsorption–ejector refrigeration and heating hybrid system powered by solar energy", Applied Thermal Engineering 22 (2002) 1245–1258.

[6] ASHRAE. Absorption air-conditioning and refrigeration equipment. ASHRAE guide and data book, equipment. New York: ASHRAE; 1972. Chapter 14.

[7] B.J. Huang et al., A 1-D analysis of ejector performance, Refrigeration 22 (1999) 354–364.

[8] D.-W. Sun, Solar powered combined ejector–vapor compression cycle for air conditioning and refrigeration, Energy Convers. Mgmt. 38 (5) (1997) 479–491.

[9] D.-W. Sun, Performance characteristics of HCFC-123 ejector refrigeration cycles, Energy Res. 20 (1996) 871–885.

[10] V.M. Nguyen et al., Development of a solar-powered passive ejector cooling system, Appl. Thermal Eng. 21(2001) 157–168.

[11] J.H. Keenan et al., An investigation of ejector design by analysis and experiment, J. Appl. Mech. Trans. ASME 17(3) (1950) 299–309.