# SOLAR ADSORPTION COOLING SYSTEM: SOME MATERIALS AND COLLECTORS ASPECTS

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ABSTRACT

Conventional cooling technologies are generally based on the electrically driven refrigeration system. These systems have several disadvantages: they require high levels of primary energy consumption, causing electricity peak loads and employ refrigerants with negative environmental impacts. Solar adsorption refrigeration is an option to overtake the drawbacks of the conventional cooling system. However, the COP of the prevailing solar adsorption refrigeration system is quite low. Therefore, it is necessary to increase the systems performance with higher COP. To develop such a system with low cost and higher COP, the design of solar collector and selection of adsorbent-adsorbate materials suitable for these systems is a significant aspect for solar cooling applications. Simple adsorption refrigeration nominally requires heat of 70-90°C. High temperature flat plate, concentrating or evacuated tube solar collectors are needed for improved COP. Consequently, selection and optimization of solar collector is a vital role in the adsorption refrigeration system. Several studies have also been carried out, both experimentally and theoretically for selection of adsorbent-adsorbate material; although the cost of adsorbent–adsorbate materials still makes them non-competitive for commercialization. Therefore, some research investigations are also focused on cost effective materials and on increasing the efficiency of these systems. The present paper elaborates the state of art of adsorbent materials, solar collection aspects of technically and economically viable solar adsorption cooling systems for Indian conditions. Some of these studies will be presented in this communication.

## 1. INTRODUCTION

Harvesting solar energy as an alternate energy resource is good proposition. Solar energy conversion to provide cold storage of farm produce is an important & relevant application for the rural areas in a giant tropical country like India. A solar-based adsorptive refrigeration system is having main components as 'solar collector' and "sorbent material". The solar collectors of different kinds have been studied around the world with the aim of collecting maximum amount of energy at minimum cost. Several studies on glazed solar collectors using one or more covers have been recognized [1] and their costs are still comparatively less. It is important to select the appropriate type of solar collector to meet the temperature needs of the solar cooling systems. Although, solar adsorption refrigeration systems can provide relatively high coefficients of performance (COP) with high temperature heat sources. Nevertheless, flat-plate collectors can provide a temperature of 60°C to 90°C and the evacuated tube solar collectors can provide 80°C to 120°C (higher temperatures are possible but at a lower flow rates). The parabolic trough collector can easily operate at temperatures between 110°C and 195°C.

A wide range of sorbent materials are available for sorption cooling systems. However, most operating pairs used water as refrigerant (sorbate) because of highest latent heat of vaporization compared to other operating fluids. Furthermore, water is non-toxic and easy to handle. The disadvantage of water is limited application above 0°C. For ice making or refrigeration below 0°C, therefore, methanol or ammonia can be used as a refrigerant with a variety of solid adsorbents. The following sections give an overview of classical and new adsorption materials as well as the solar collector developments. The objective of this paper is (1) to review better solar collector technology and (2) to analyze suitable adsorbent-adsorbate materials for solar adsorption refrigeration systems.

1.1 Basic principle of adsorption refrigeration cycle

The ideal adsorption refrigeration cycle can be explained by four thermodynamic processes with help of Clapeyron diagram, as shown in Fig. 1. The cycle begins at a point A, where the adsorbent is at low temperature $T_A$ and at low evaporation pressure $P_E$. The process A–B represents the heating of adsorbent-adsorbate material. The adsorbent collector is connected to the condenser and the progressive heating of the adsorbent from B to D causes adsorbate to be desorbed and its vapor to be condensed (at point C). The desorption process ceases when the adsorbent reaches its maximum temperature $T_{D.}$ Then the liquid adsorbate is allowed into the evaporator from C to E and the collector is closed and cooled down. The decrease in temperature from D to F induces the decrease in pressure from $P_C$ to $P_E$: Then the adsorption bed is connected to the evaporator and evaporation occurs while the adsorbent is cooled down from F to A. In this cooling period, heat is withdrawn to decrease the temperature of the adsorbent.

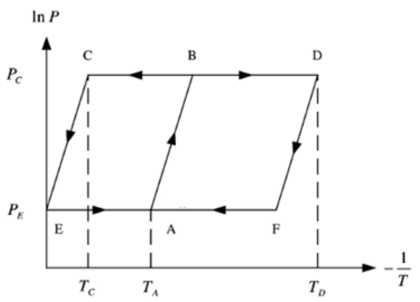


Fig.1:Clapeyron diagram of ideal adsorption cycle

2.0 SOLAR COLLECTOR CHOICE FOR ADSORPTION COOLING SYSTEM

The design of solar collectors is a significant aspect for solar cooling applications. Table-1 depicts the taxonomy of different types of solar collector for adsorption refrigeration system. It depends on the level of temperature required by the process. For example, an efficient water-ammonia solar adsorption refrigerator requires collector temperature of around 150°C. This can be performed generally by collectors which are either parabolic or with evacuated tubes [2]. Table-2 demonstrates the selected performance of different solar collectors based adsorption refrigeration systems.

TABLE 1: CLASSIFICATION OF SOLAR COLLECTOR

| Category | Temperature range (°C) | Collector type |
|---|---|---|
| No concentration | 60-90 | Flat plate |
| | Up to 200 | Evacuated tube |
| Medium concentration | 250-500 | Parabolic cylinder |
| High concentration | 1500 and more | Parabodial |

2.1 Flat plate collector

Many parameters affect the performance of solar adsorption refrigerator, such as solar radiation, wind speed, ambient temperature, number of glass covers, coating material etc [3]. Among these parameters, two parameters are most important viz. the number of glazings and the selective coating material. In this study, the authors found out that when single glass cover and double glass covers are used the COP values are respectively 0.116 and 0.113. In addition, when black coating and selective coating for single glass cover are used, the COP values are 0.116 and 0.145, respectively. Further single glass cover with black coating and double glass cover with selective coating material are used, the COP values are 0.116 and 0.193, respectively. The authors concluded that in the practical design of solar refrigerator, double glass covers with selective material should be used to improve the performance of solar refrigerator.

In an effort to utilize solar heat with flat plate collector [4] it is desirable to increase the heat transfer in the collector having heat transfer fins. This kind of arrangement can reach the maximum bed temperature of 80°C. To further enhance the heat transfer inside the adsorbent bed Li.*et al.* [10] arranged a number of fins in the flat plate collectors. The top surface of the adsorbent bed is coated with selective paint to enhance absorption of solar radiation. The experimental results showed that the COP is found to be 0.12-0.14.

TABLE. 2 SOLAR ADSORPTION COOLING SYSTEM WITH TYPICAL SIZE.

| Type of Collector | Area | COP | Ref. |
|---|---|---|---|
| Flat plate | 0.4 $m^2$ | 0.40 | [3] |
| Flat plate | 6$m^2$ | 0.1-0.12 | [5] |

| | | | |
|---|---|---|---|
| Flat plate | 20 $m^2$ | 0.10 | [6] |
| Flat plate | 2 $m^2$ | 0.36 | [7] |
| Vacuum tube | 170$m^2$ | 0.2-0.3 | [8] |
| Evacuated tube | 150 $m^2$ | 0.35 | [9] |

Boubakari *et al.* [11] developed a collector – condenser assembly by using flat plate collector. The units are mainly composed of a single glazed collector-condenser connected by a flexible tube with an evaporator. In this experiment, the collector reached the maximum temperature of 110°C. Instead of two valves necessary to fulfil the adsorption and desorption processes of a basic refrigeration system, a no valve, flat plate collector based solar ice maker was developed by Li *et al.* [12] and the performance was tested for the real solar radiation condition. In this system, there are no reservoirs, connecting valve and throttling valve. The adsorbent bed was made of flat plate stainless steel box having a surface area of 1.0 $m^2$. The results showed that 6.0-7.0 kg of ice was produced under the condition of about 17-20 MJ/$m^2$ daily solar radiation. Liu *et al*. [13] also designed a simplified no valve adsorption refrigeration system. This feature reduced the cost of the chiller and also made it more reliable as there were less moving parts that could lead to air infiltration.

Fig. 1:Solar-powered icemaker without valves [ 12].

Louajari *et al*. [14] presented the performance of the adsorption machine with and without fins in the solar flat plate collector. The COP increases from 0.075 corresponding to a tube without fins to 0.11, which corresponds to a tube with fins. The cycled mass of the refrigerant is also higher than the one having tubes without fins. It shows that fins in the solar collector increases the COP of the system. Anyanwu and Ezakwe [15] also designed a combined flat-plate type collector/generator/adsorber system whose effective exposed area was 1.5$m^2$ with overall COP of 0.11-0.16. The maximum temperature attained in the collector was 109 $^0$C with an area of 1.2$m^2$.

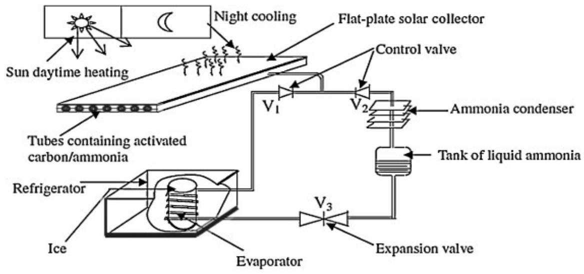


Fig. 2. Schematic of solar finned tube system. [14]

2.2 <u>Compound Parabolic Collector (CPC)</u>

Solar adsorption cooling systems are usually based on the flat plate collector, whereas little attention has been paid on concentrating solar collectors [16]. Manuel *et al*. [17] presented a CPC collector (which is separated by four tubular receivers) contains the sorption bed where only a portion of the receiver is exposed to sunlight. The total collection area was 0.55 $m^2$. The maximum and minimum bed temperatures were 116°C and 38°C, respectively and solar COP ranges from 0.078 to 0.096.

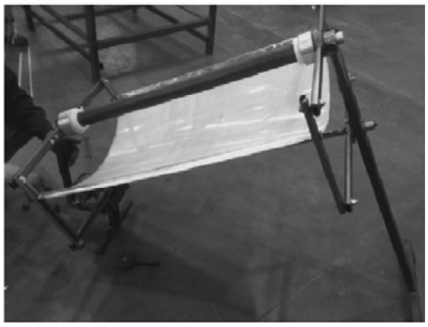

Fig. 3:Experimental setup of the model used in the adsorption system. [18]

Thermal design of solar powered adsorption refrigeration system was presented by Tashtoush et al., in 2010, which consists of an [18] evacuated glass tube equipped with a parabolic solar concentrator sorption bed. The adsorber is heated to 125°C by solar energy collected by a parabolic solar concentrator. Headley *et al.* [19] constructed CPC with an aperture area of 2.0 $m^2$ in order to increase desorption temperature in excess of 150°C. It is found to cause conversion of methanol to dimethyl ether, a non-condensable gas which inhibits both condensation and adsorption. The author also reported that system is not economically viable.

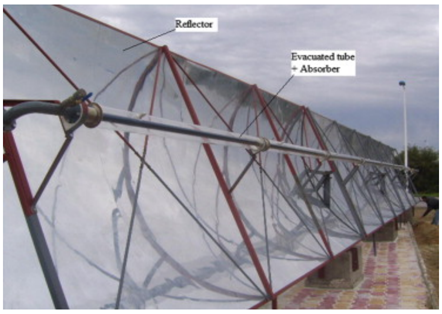


Fig. 4:Parabolic trough solar collector. [20]

Balghouthi et al., [20] designed an innovative approach to heat the adsorption bed via 39 $m^2$ of linear parabolic trough solar collectors.  The testing of the module was focused on the sorption bed. Therefore, four types of bed and four reflector arrangements to heat the sorption bed were proposed and tested under climatic conditions of Tunisia (36° latitude and 10° longitude). Testing module as a refrigerator could provide net solar COP of 0.136 and 0.159 in cold and hot climates respectively.

2.3 <u>Evacuated Tube Collector (ETC)</u>

Different approaches to increase the overall efficiency of the adsorption refrigerator have been studied by various researchers for the past few years.  In this way, Niemann *et al.* [21] designed and constructed an ETC collector coupled with an external parabolic concentrator to operate a large adsorption refrigeration system.The envisaged collector field consists of evacuated tube collectors with 1.6 $m^2$ area and achieved the collector fluid temperature of 170°C. Mahesh [22] presented a solar powered adsorption refrigerator performance with an ETC solar collector area of 2$m^2$ which can produce the COP of about 0.15-0.23. The specialty of the proposed system was adsorption bed immersed into a water bath and powered by vacuum tube solar collector.  In this arrangement adsorption bed reaches temperature of 90-110°C. In a large air conditioning system developed by Zhai and Wang [23] using evacuated tube collectors (ETC) with heat sources temperatures above 100°C, the area of ETC significantly influenced the COP of the system. The adsorption system with an ETC area of 80 $m^2$ lead to a COP of 0.32 while operating with an ETC area of 240 $m^2$ lead to a COP of 0.37. To further improve the performance of the system, the authors also used a tube and plate heat exchanger between the plates and with this new design, the improved COP obtained was 0.40.

3.0 <u>SELECTION OF ADSORBENT-ADSORBATE MATERIALS</u>

A number of studies have been carried out both experimentally and theoretically, for the selection of adsorbent-adsorbate materials. An adsorbent–refrigerant working pair for a solar refrigerator requires the following characteristics:

1. A refrigerant with a large latent heat of evaporation.
2. A working pair with high thermodynamic efficiency.
3. A small heat of desorption under the envisaged operating pressure and temperature conditions.
4. A low thermal capacity of the adsorbent material.

However, the high cost for these adsorbent – adsorbate materials still makes them non-competitive for commercialization. Therefore, some investigations have been focused on cost reduction and on increasing the efficiency of the machines.  The most widely used working pairs are such as zeolite – water, activated carbon – methanol, silica gel – water and activated carbon – ammonia. The performance of adsorbent-adsorbate pair is reviewed here based on heat source temperature.

3.1 <u>Zeolite –water</u>

The development of sorption refrigeration systems powered by zeolite –water emerged in 1978 following the pioneering work of Tchernev [24].  At the end of the 1980s, Grenier *et al.* [6] designed a solar adsorption air conditioning system using zeolite-water working pair with adsorbent mass of 22 to 15 kg/$m^2$.  In an innovative approach, Dong Wu [25] presented a truck air-conditioning driven by engine waste heat.  The working pair of 13X Zeolite – water was used with per module mass of 45 g and 10.50 g respectively. Under the typical, condition of the evaporator temperature of 10°C, the value of COP and Specific Cooling Power (SCP) of 0.40 and 180 W/kg, respectively. A thermally powered prototype adsorption cooling system using natural zeolite–water was investigated by Ismail Solmus in 2011[26]. The mean COP and SCP values of the experimental prototype were 0.25 and 6.4 W/kg, respectively for the heat source temperature of 150°C.

Table-3 shows some of the achieved performance of solar adsorption refrigeration systems.  Form the above studies, the authors found that large quantities of zeolite and high adsorption temperature would be required if water is the adsorbate since only a modest amount of adsorbate is desorbed in going from room temperature to solar collector temperature. As a result, the zeolite – water pair is not suitable for flat plate solar collector adsorption refrigeration system.  However, zeolites have another unique property in that their adsorption isotherms have extremely nonlinear pressure dependence, as reported by Tchernev [24], which is an important criteria in solar refrigeration applications.

<u>TABLE. 3 ZEOLITE-WATER SOLAR ADSORPTION REFRIGERATION SYSTEM</u>

| Heat source | Mass of adsorbent | COP | Ref. |
|---|---|---|---|
| 110°C | 50 kg/m$^2$ | 0.15 | [24] |
| 93°C - 103°C | 15-22 kg/m$^2$ | 0.10 | [6] |
| 220°C - 250°C | 140 kg/m$^2$ | 0.21 | [27] |
| 150°C | 1.87 kg/m$^2$ | 0.25 | [26] |
| 325°C | 45 -10.5 g per module | 0.40 | [25] |

3.2 Activated carbon – Methanol

Activated carbon – methanol is one of the most widely used working pair in adsorption systems because of their large cyclic adsorption capacity, low desorption temperature, low adsorption temperature and high latent heat of methanol. Table-4 shows some performance results of activated carbon-methanol refrigeration system. Buchter et al. [28] tested an adsorption ice-marker using 40 kg of activated carbon and 5.6 kg of methanol at Burkina Faso for the heat source temperature from 60 -100°C. The outcome of this prototype was compared with similar systems of Pons & Grenier in Orsay [29] and Boubakri *et al*. [30, 31] in Morocco. The machine (Burkina Faso) presented a cooling performance of about 28% and 35 % higher than that of the machine tested in Orsay and Morocco, respectively. The limitation of the system was mainly due to the ambient temperature, an increase in the ambient temperature beyond 23°C reduced the system performance significantly.

TABLE. 4 ADSORBENT –ADSORBATE PAIRS USED IN THE SOLAR ADSORPTION REFRIGERATION SYSTEM.

| Adsorbent-Adsorbate pair | System COP | Ref. |
|---|---|---|
| Silica gel- Water | 0.16 | [32] |
| Silica gel- Water | 0.10-0.13 | [33] |
| Silica gel- Water | 0.2-0.3 | [8] |
| Activated carbon-Methanol | 0.15-0. 23 | [22] |
| Activated carbon-Methanol | 0.1-0.12 | [30] |
| Activated carbon-Methanol | 0.1-0.12 | [34] |
| Activated carbon-Methanol | 0.16 | [35] |
| Domestic charcoal- Methanol | 0.14-0.16 | [36] |
| Activated carbon-Ammonia | 0.2-0.7 | [37] |

Wang *et al*. [38] tested two different types of adorbers in which two types of bed one filled with solidified activated carbon and another filled with granular activated carbon. The authors reported that the performance of solidified activated carbon adsorber is better than that of granular activated carbon adsorber since the heat transfer coefficient is higher. Accordingly, COP and SCP of the solidified activated carbon were 0.125 and 16 W/kg while the granular activated carbon pair gave COP and SCP of 0.104 and 13.1 W/kg respectively for the same heat source temperature of 110°C. It is due to the design of gas flow channels in adsorbers which is very important in the heat and mass transfer performance of the whole system. In this concern, Mahesh [22] presented a prototype solar powered adsorption refrigeration system using an activated carbon / methanol pair. The solar collector area of 12 m$^2$ using activated carbon pair produced net COP was 0.23 for the heat source temperature of 110°C. Ferreira Leite presented [39] characterization and pre-dimensioning of an adsorption chiller in which each adsorber consist of 25 kg of activated carbon and 72 kg of methanol, respectively. The effective COP obtained was 0.5, which is still low as compared to that of conventional vapor compression systems.

3.3 Silica gel – Water

The silica-gel-water is an alternative working pair allowing cycles to be driven by relatively lower driving heat-source temperatures. Table- 4 also illustrates the performance results of siligca gel – water adsorption refrigeration system as reported by previous researchers. Novel silica gel–water adsorption chillers [40] with two single bed systems were built and tested in Shanghai Jiao Tong University (SJTU). Each adsorber contains 52 kg of silica gel. The refrigerating capacity and the COP of the chiller are, respectively, 83.6 W/kg and 0.388 for the heat source temperature of 82.5°C. In an innovative approach a compact adsorption chiller integrated with a closed wet cooling tower was designed by Chen *et al.* [41]. The system performance was investigated against the heat source temperature of 85°C with 65 kg of silica gel and 169 kg of water. The achieved COP and SCP were 0.51 and 165W/kg respectively.

3.4 Activated Carbon- Ammonia

Explorations in the use of charcoal–ammonia were apparently more during the 1990s. A small solar adsorption refrigerator was built and tested under preliminary level by Critoph [42]. The collector area 1.4m$^2$ contains 17 kg of active carbon and 1.60 kg of ammonia was tested for 150 $^0$C heat source temperature. It produced up to 4 kg of ice per day in a diurnal cycle. Fadar *et al.* [43] proposed a novel solar adsorptive cooling system with 5-30 kg of activated carbon and its performance was tested for the heat source temperatures of 70-170°C. From the investigation, the authors reported that, COP increases first with increase in adsorbent mass and then the COP decreases. The reason is that the increase in adsorbent mass induces high adsorption of ammonia initially in adsorption phase and then desorption of large amounts of ammonia in subsequent desorption process. This produces more cooling and consequently, results in high COPs. Nevertheless, beyond this optimal value, the adsorbent though heated, but not sufficient to desorb the required amount of ammonia for cooling purpose.

The working system of activated carbon – ammonia pair was developed by Miles and Shelton [44]. The COP obtained varied between 0.19 and 0.42, for ambient temperatures from 20°C to 35°C. However, the practical difficulties and disadvantages of activated carbon–ammonia systems are the high-pressure requirement (resulting in the bulkiness of the refrigerator) and the corrosive nature of the refrigerant (ammonia). The problem of the bulky large systems can be avoided by the development of rapid cycling units.

## 4.0 CONCLUSIONS

In this paper, state of art review of the adsorption technologies related to the better utilization of solar energy for the production of cooling energy is presented. Among the various types of systems, emphasis is made on choice of the solar collector designs and the adsorbent-adsorbate pairs. The literature reveals that the performance of various adsorption systems varies over a wide range. Most of the works is experimental in nature under different operating conditions. Some of them use separate solar collectors with some concentration while others used the adsorbent bed itself (contained in a transparent tube) as the solar energy absorbing material, but the most common configuration seems to be consisting of metallic flat-plate solar collectors with single- or double-glazed covers and/or with a selective coated surface ( filled with the adsorbent bed) with evacuated tube solar collector. Another concern in the performance of the adsorption cooling system is mainly choice of the working adsorbent – adsorbate pairs.

A well-designed system should have the characteristics of large adsorption capacity, temperature variation, and more flat desorption isotherm and refrigerant fluid whose choice depends on the evaporator temperature. It must possess high latent heat of vaporization and small molecular dimensions to achieve an easy adsorption. Since, the refrigeration system will operate at a cooling temperature below 0°C, thus methanol seems to be a good adsorbate because it can evaporate at a temperature even below 0°C, its enthalpy of vaporization is high and its molecule is small enough to be easily adsorbed into micropores. Its working pressure is always lower than the atmospheric one, which means a safety factor in case of leakage. As a result activated –carbon methanol is the most widely used adsorbent reported in the literature due to its extremely high surface area and micro pore volume. The operating temperature is one of the limitations that constraints the operation of an activated carbon – methanol pair cooling system. At temperature more than 150°C, the methanol decomposes into dimethyl. A very low cooling performance is found due to the decomposition products and this may be one of the main reasons for the low performance of the cooling system.

Silica gel –water systems require the operation under vacuum condition, which poses a hurdle. In addition, the practical difficulties in water are for not using it at an ice -making temperature. Therefore, it is more desirable choice for air conditioning purposes only. Zeolite –water pair requires a regeneration temperature of about 100°C, activated carbon – ammonia pair also requires more than 150°C for its regeneration. These temperatures are not obtainable by simple flat plate collectors. So evacuated tube solar collector or solar concentrating collectors can achieve these temperatures. It is known that such solar collectors increase the initial cost of the system. Although activated – carbon methanol pair also works at a low regeneration temperature and it is suitable for ice production and freezing application. Comparing with activated carbon –ammonia system, activated carbon methanol system is a high vacuum system and that is safer than high – pressure system though not so reliable. Activated carbon-ammonia adsorption system operates in the high – pressure state, and ammonia is a corrosive and flammable refrigerant.

Finally, it can be concluded that activated carbon-methanol is suitable working pair of solar energy because of its high COP and relatively low regeneration temperature and low freezing point & no corrosion problem. In addition maximum adsorption capacity of the activated carbon methanol pair is very good as compared to the other adsorbent – adsorbate materials. As a result flat plate collector-reflector is also good enough to achieve nominal cooling but with expensive solar collectors systems like concentrating and evacuated tube collector, the cooling performance can be enhanced if desired.

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