

# Performance Analysis and Parametric Variation of a Solar Adsorption Chiller

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## Abstract

Solar energy is the most promising among the available green energy sources and also the panacea to the increasing global warming potential and ozone depletion. In the last three decades, various technologies have been invented for extracting the latent potential of the solar energy. Among them, the one that is still unearthed and needs to be researched is the adsorption refrigeration cycle. In the present paper, we have designed a basic adsorption chiller driven by solar thermal energy which consists of a solar collector, an adsorbent bed, a condenser and an evaporator. The model provides a maximum COP of 0.452 with a refrigeration power of 6.78 kW. Moreover, we have provided the variation of COP system and COP cycle with time. Here, we have also inferred the response of COP with variation in mass and collector area and we came to the conclusion that the COP of the present system declines if the mass exceeds 15 Kg.

**Keywords: Solar Adsorption Chiller, Solar Refrigeration, Parametric Variation, Cop, Solar Collector**

## I. INTRODUCTION

Global warming, change in the seasonal cycle, limitation of primary energy compared to the need of the growing global population, are the prime concern of the twenty first century. Cooling and refrigeration are essentials for modern day's society to provide the human comfort. In tropical countries like India, which experience extreme in the mainland, demand for electricity shoots up due to the need for cooling. The high electricity demand not only overloads the grid but harms the environment as well due to the burning of fossil fuels, which are the primary source of power. Most of the technologies at present for providing cooling or refrigeration are vapor compressor technology. However, the vapor compressor refrigeration device is one of the technologies responsible for ozone layer destruction as most of these use HCFCs and HFCs. Solar energy for cooling applications provides an opportunity to overcome this problem. The amount of solar radiation intercepted by the Earth's surface is much higher than the annual global energy use. The energy available from the sun ( $82 \times 10^{15} \text{ W}_p$ ) is greater than about 5200 times the global world's need in 2006 [1]. In recent years, many promising technologies have been developed to harness the Sun's energy. These technologies help in environmental protection, economizing energy, and sustainable developments which are the major issues of the world in the 21<sup>st</sup> century. The fact that cooling demand in summer is proportional to the availability of solar energy has been spurring the researchers to further exploit solar energy.

In cooling applications, different types of sorption systems can be employed. Among them one is the adsorption cycles. Adsorption refrigeration is a thermal driven refrigeration system, which can be powered by solar energy as well as waste heat [2]. The use of thermal driven systems helps to reduce the carbon dioxide emission from combustion of fossil fuels in power plants. Another advantage for adsorption systems compared with conventional vapor compression systems is the working fluid used. Adsorption systems mainly use a natural working fluid such as water and ammonia, which have zero ozone depletion potential.

Adsorption is the process by which molecules of a fluid are fixed on the walls of a solid material via connections of the Van der Waals type [3]. The general principle of the basic adsorption refrigeration cycle is given in fig.1. The refrigeration circuit usually consists of three main components; a solid adsorbent bed, a condenser and an evaporator. Some system employ isolating valves between the various components and some utilize expansion valves between the condenser and the evaporator. The adsorption refrigeration cycle relies mainly on the natural affinity of the adsorbent bed (when at low temperature) to attract the refrigerant vapor from the evaporator thus creating a lower pressure in the evaporator. Once the adsorbent bed is close to the saturation point, the valve between the evaporator and the absorber is closed and heat is applied to adsorbent bed, thus releasing the refrigerant vapor which then gets collected and condensed in the condenser before returning to the evaporator. Once this cycle is completed the heat on the adsorbent bed is removed and in some cases forced cooling is introduced onto the adsorber

until the adsorption conditions are established then the valve between the evaporator and the adsorbed is reopened. In the present study, we have designed, fabricated and tested a single stage adsorption chiller.

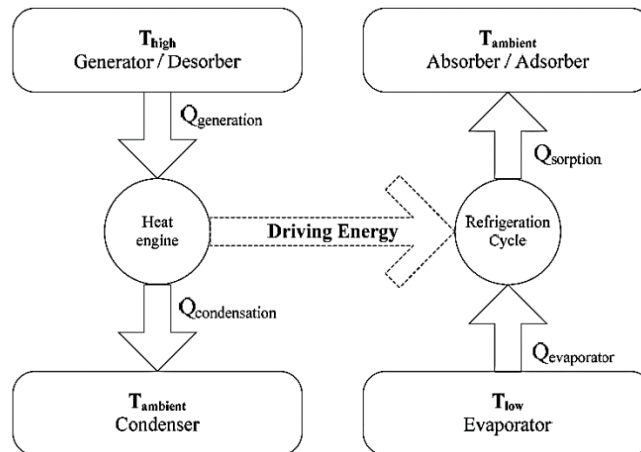


Fig. 1: Principle of basic adsorption cycle

## II. PREVIOUS WORKS

The sorption refrigeration driven by solar energy attracted broad attention because the heat supply and cool demand are very well matched with the season and the heat quantity. Compared with the absorption system, the adsorption system that are driven by the heat sources of lower temperatures makes the application of solar energy more feasible on the adsorption system.

The solid adsorption refrigeration technology driven by solar energy has been researched extensively since Tchernev [4] successfully developed the refrigeration system with zeolite–water as the working pair. Pons and Guillemot in France, studied activated carbon–methanol and zeolite–water adsorption systems driven by solar energy, in which the COP of the activated carbon–methanol ice maker [5] is 0.12–0.14 with a collector area of 6m<sup>2</sup> (four collectors) and adsorbent mass of 20–24 kg/m<sup>2</sup>, and the COP of a zeolite–water refrigerator [6] is about 0.10 with the collector area of 20m<sup>2</sup> (24 collectors) and the adsorbent mass of 360 kg. K. Sumathy *et al.* investigated an activated carbon–methanol ice maker powered by solar energy, and results showed that the daily ice production is 4–5 kg and the COP is 0.1–0.2 [7] when the area of flat plate collector is 0.92m<sup>2</sup>. Y.K. Tan [8–10] in South China University of Technology and Z.F. Li *et al.* in Guangzhou Institute of Energy Conversion [11] also developed the solid adsorption refrigeration system driven by solar energy, which had a similar performance to the system developed by K. Sumathy. Different from the refrigeration system with the integrated solar collector–adsorption generator, multi types of solar energy powered adsorption refrigeration systems were developed. Iloeje *et al.* [12, 13] utilized a tubular type of absorber, for which the adsorbent (such as calcium chloride, activated carbon) is filled inside the metal pipes. The concentric tube arranged at the center of the metal pipe served as the mass transfer channel of the refrigerant, and the metal tube is boned on the collector surface. Erhard [14] arranged the condensation part of the horizontal heat pipe inside the adsorbent bed to improve the heat flux density. Headley *et al.* [15] studied the activated carbon–methanol adsorption refrigerating system utilizing the compound parabolic concentrator (CPC) as the heat source. The system could realize refrigeration even if the solar radiation is very feeble, but the efficiency of the refrigeration system is very low. Bansal *et al.* [16] studied the SrCl<sub>2</sub>–NH<sub>3</sub> adsorption refrigerating system driven by the vacuum tube type collector. Vasiliev [17] developed a continuous adsorption heat pump with heat recovery process driven by solar energy and natural gas, using a parabolic concentrator for collecting the solar energy to heat the circulating water. The system employed solar energy as a main power supply, and the natural gas served as an auxiliary heat source when solar energy is not enough. The system can accomplish continuous refrigeration with the cycle time of 12 minutes. Z.Y. Liu [18, 19] put forward the refrigeration system which combined the unit adsorption tube with the collector for the solar energy. For such a design the adsorbent bed can be heated by solar energy directly.

On the topic of solar energy utilization, SJTU [20] developed a compound system of water heater and refrigerator driven by solar energy to improve energy efficiency. Meanwhile, SJTU also developed the silica gel–water adsorption chiller in 2004, which had been applied to the building and grain storage hall with solar energy as the driving power.

## III. BASIC ADSORPTION REFRIGERATION SYSTEM

Adsorption refrigeration system uses solid adsorbent beds to adsorb and desorb a refrigerant in order to obtain cooling effect. These adsorbent beds filled with solid material adsorb and desorb a refrigerant vapor in response to changes in the temperature of the adsorbent. The basic adsorption refrigeration system, commonly referred to as the adsorption heat pump loop, or an adsorption refrigeration circuit, mainly consists of four main components: a solid adsorbent bed, a condenser, an expansion valve and an evaporator. The adsorbent bed desorbs refrigerant when heated and adsorb refrigerant vapor when cooled. The adsorbent

is packed in a hermetically sealed container painted black for solar radiation absorption at a particular temperature in compliance with its condensing pressure.

A basic adsorption cycle consists of four thermodynamic steps.

**A. Heating and Pressurization**

The adsorber receives heat while being closed. The adsorbent temperature increases, which increases pressure from the evaporation pressure to the condensation pressure. This process is equivalent to the "compression" in compression cycles. Refer line AB in fig.2.

**B. Heating, Desorption and Condensation**

The adsorber continues receiving heat while being connected to the condenser. The adsorbent temperature continues increasing, which induces desorption of vapor. This desorbed vapor gets liquefied in the condenser. This is equivalent to the "condensation" in compression cycles. Refer line BC in fig. 2.

**C. Cooling and Depressurization**

During this period, low pressure vapor is entered to adsorber from evaporator. The adsorber releases heat while being closed. The adsorbent temperature decreases, which decrease pressure from the condensation pressure down to the evaporation pressure. This process is equivalent to the "expansion" in compression cycles. Refer line CD in fig. 2.

**D. Cooling, Adsorption and Evaporation**

The adsorber continues releasing heat while being connected to the evaporator. The adsorbent temperature continues decreasing, which induces adsorption of vapor. This adsorbed vapor 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 line DA in fig. 2.

The schematic of the adsorption chiller is shown in fig. 3. In the present case we have fabricated the adsorption chiller following the schematics shown. We have used activated carbon and methanol as the working pair.

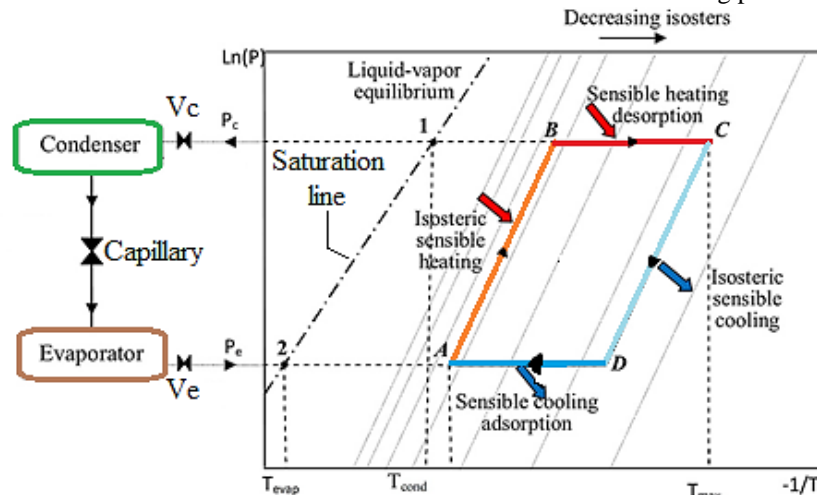


Fig. 2: Clayperon curve of basic adsorption refrigeration cycle.

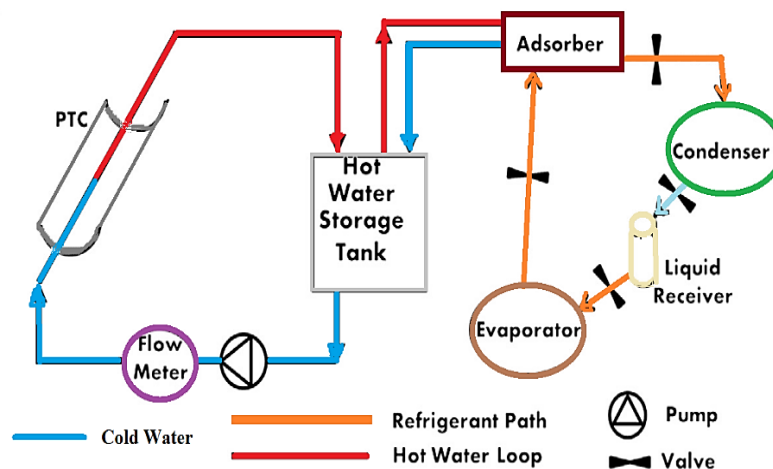


Fig. 3: Schematics of the adsorption chiller

#### IV. PERFORMANCE PARAMETERS

From the Clapeyron diagram, the total energy gained by the system during the heating period  $Q_T$  will be the sum of the energy  $Q_{AB}$  used to raise the temperature of the A.C+ methanol from point A to B and the energy  $Q_{BD}$  used for progressive heating of the A.C to point D and desorption of methanol.

$$Q_T = Q_{AB} + Q_B$$

$$Q_{AB} = (m_{A:C} C_{pA:C} + C_{pm} m_{mA})(T_B - T_A)$$

$$Q_{BD} = [m_{A:C} C_{pA:C} + C_{pm} \{ (m_{mA} + m_{mD}) / 2 \}](T_D - T_B) + (m_{mA} - m_{mD})H$$

The gross heat released during the cooling period  $Q_{e1}$  will be the energy of vaporization of methanol.

$$Q_e = (m_{mA} - m_{mD}) L$$

But the net energy actually used to produce ice  $Q_e$  will be

$$Q_e = Q_{e1} - Q_{e2},$$

where  $Q_{e2}$  is the energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates.

$$Q_{e2} = (m_{mA} - m_{mD}) C_{pm} (T_c - T_e)$$

$Q_{ice1}$  is the energy required to cool water from  $T_A$  to  $0^\circ\text{C}$  and to produce ice

$$Q_{ice1} = M^* (L^* C_{pwater} (T_A - 0)),$$

where  $M^*$  and  $L^*$  are the mass and latent heat of fusion of ice and net cooling produced will be

$$Q_{ice} = M^* L^*$$

1) The collector efficiency  $\eta_1 = Q_T / Q_I$ ,

where  $Q_I$  is the total solar energy input to the system during the day.

2) The cycle COP =  $Q_{e1} / Q_T$

3) The net solar COP<sub>net</sub> =  $Q_{ice} / Q_I$

Here,  $C_p$  is specific heat in kJ/kgK,  $H$  is heat of desorption in kJ/kg,  $L$  is latent heat of evaporation of the methanol in kJ/kg,  $M$  is mass in kg,  $Q$  is energy in kJ,  $T$  is temperature in  $^\circ\text{C}$ .

#### V. PERFORMANCE ANALYSIS

Fig. 4 shows the variation of the solar incident radiation and the ambient atmospheric temperature with the day hours. These data simulate a summer day in May 5, 2015, for Bhopal, India.

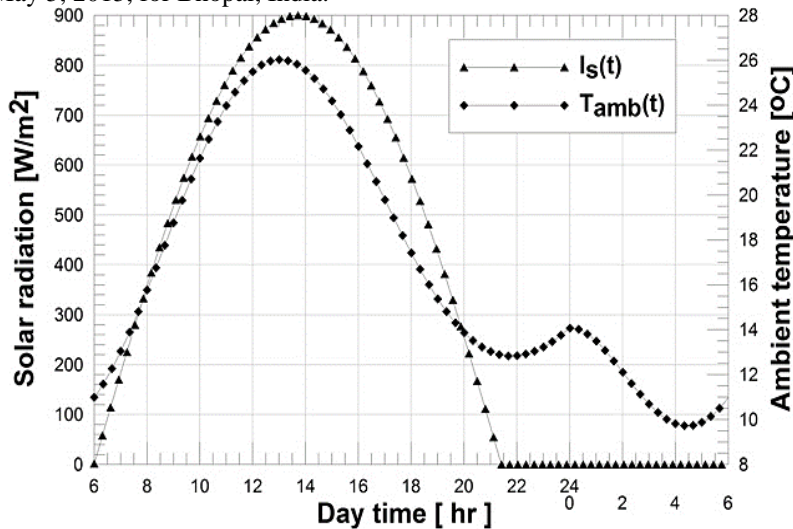


Fig. 4: Variation of Solar radiation and ambient temperature with time

Table 1 shows the experimental results obtained from the experiments performed on the basic adsorption system. It shows the per day solar intensity, average ambient temperature corresponding to the respective solar radiation intensity, condensation temperature, evaporator temperature and the coefficient of performance (COP). It shows that as the ambient temperature increases i.e. increase in solar radiation intensity, there is an increase in the condensation temperature along with a more reduction in evaporation temperature. From the results in table it is evident that there exists a relation among the COP,  $T_{con}$  and  $T_{evp}$ . The system possesses a monthly average COP of 0.4305 calculated for the month of May.

On the basis of the experiments performed, we went for calculating hourly performance of the refrigeration system i.e. calculating the variation of COP with time of the day. Fig. 5 shows the variation of the system COP with time of day. Also, it shows that in a day the maximum COP value that the system achieved is 0.35. On the same lines, we draw the variation of the COP<sub>cycle</sub> with time of the day, see fig. 6. It shows that the maximum COP value on a day can be of 0.465.

Table - 1  
Experimental performance of the adsorption chiller

Date	Solar Intensity (I) MJ/m <sup>2</sup> /day	Ambient temperature (T <sub>amb</sub> ) °C	Condensation temperature (T <sub>con</sub> ) °C	Evaporator temperature (T <sub>evp</sub> ) °C	COP
5/5/2015	22.6	25.4	32.3	19.6	0.412
10/5/2015	24.5	27.3	34.7	16.3	0.428
15/5/2015	27.2	30.7	37.8	12.2	0.447
20/5/2015	27.6	31.4	38.6	10.8	0.452
25/5/2015	25.3	28.8	35.4	14.7	0.435
30/5/2015	19.8	22.2	28.2	21.9	0.409

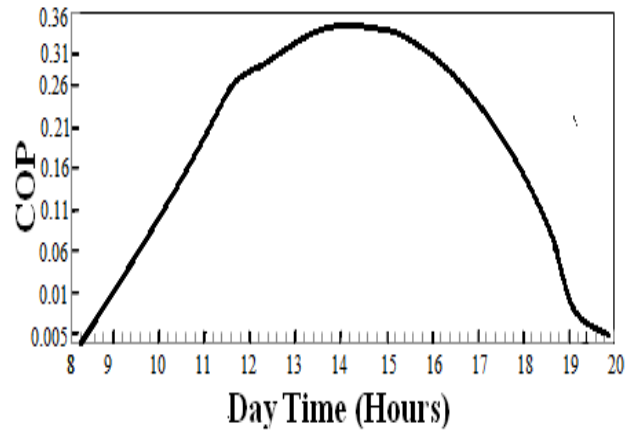


Fig. 5: Variation of COP with time of the day

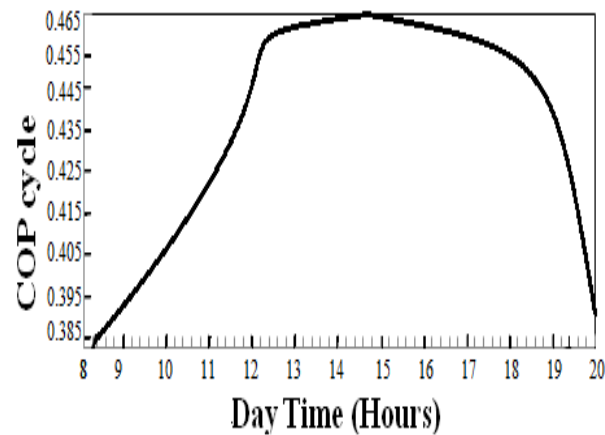


Fig. 6: Variation of COPcycle with time of the day

Fig. 7 shows the response surface of the COP of refrigerator as a function of mass and collector area using statistical software (Minitab), multiple regression method is used in this software. As shown in the figure, the optimum value of the COP lies in the region where the collector area is from 3 to 4.5 m<sup>2</sup>, and mass from 10 to 15 kg. The COP decreases beyond 5 m<sup>2</sup>. This is due to the fact that the cooling production does not increase much once the water temperature reaches above 100 °C which is attained if the collector area is beyond 5 m<sup>2</sup>. Hence, with further increase in the water temperature as a result of increasing collector area, the cooling production remains stable, but the COP decreases. The figure shows also that the COP and cooling production increases as long as the adsorbent mass is less than 15 kg. The increase in adsorbent mass indicates more methanol being adsorbed initially. Hence, during desorption phase, more methanol vapor can be desorbed, which produces more cooling and thereby results in high COP. On the other hand, if the mass of adsorbent is increased to more than 15 kg, the COP as well as the cooling production decreases. This is because with the given heat input, only the bed could be heated, and this is not sufficient to desorb the required amount of methanol.

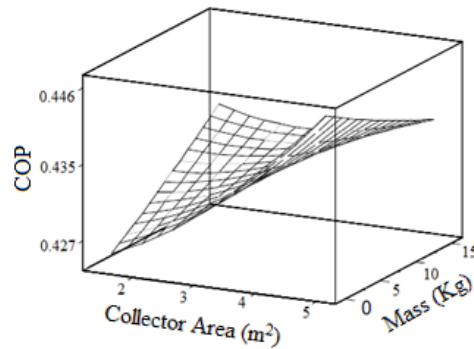


Fig. 7: Response surface of the COP of refrigerator as a function of mass and collector area

## VI. CONCLUSIONS

Adsorption cooling systems have received significant interest during the last few decades in order to satisfy the market demand of cooling systems and cope with the current environmental issues. In the present study we excavated, fabricated and tested a solar adsorption refrigerator which uses activated carbon and methanol as the working pair. This system was tested for the meteorological conditions of MANIT, Bhopal. Maximum COP and refrigeration power of the modelled chiller was calculated to be 0.452 that occurred on 20<sup>th</sup> of May and 6.78 kW respectively. From the experiments performed we can conclude that on a particular day COP follows a parabolic curve which attains its peak near 13:00 hrs. Also we can conclude that  $COP_{cycle}$  follows an approx. constant curve for a duration of 5 hours. The maximum value of  $COP_{cycle}$  is 0.465. Moreover, we can infer that if the collector area is increased then the COP would increase but simultaneously we have to maintain the generating temperature as if it crosses the optimum generating temperature the COP value will start declining. It is found that the present model is capable of operating only in night time with fairly good performance. Hence this system suffers from intermittency i.e. not capable of providing cooling for the 24 hours of the day. Hence, for this generally two stage adsorption systems are employed in order to overcome the intermittent nature.

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