1. Introduction

Solar energy technologies attract worldwide attention owing to their non-polluting nature. Indeed, the technology is matured in some countries and for more than 30 years exploitation has proceeded. Among various applications, refrigeration is one of the attractive applications of solar energy, because, the amount of sunshine and the need for refrigeration reach maximum levels in the same season. Solar cooling could be a useful technology in areas of the world where there is a demand for cooling, high insolation levels, and no firm electricity supply to power conventional systems. One of the very effective forms of solar refrigeration is the production of ice.

Solar thermal systems for refrigeration have been studied for some years, and many refrigerators build and tested. Earlier work concentrated on intermittent absorption cycles such as the ammonia-water machines built by Exell. In 1981, Pons and Grenier [1,2] (1986-1987) worked on a solid adsorption pair of zeolite and water, to produce a refrigerating effect and the coefficient of performance was about 0.1. In 1986, they successfully experimented with the adsorption pair of activated carbon and methanol. Similar work was carried out by Exell [3] in 1987 employing a flat-plate collector, which consists of an array of 15 copper tubes. Sakoda and Suzuki [4] (1986), utilizing solar heat, presented the advantages and limitations of the simultaneous transport of heat and adsorbate in a closed-type adsorption cooling system. Headley [5] (1994) constructed a charcoal-methanol adsorption refrigerator powered by CPC concentrating solar collectors, but the solar COP was very low (about 0.02).

In 1980's, Tchernev [6] experimented an adsorption refrigeration system with the pair of zeolite and water. K Sumathy [7] constructed a solar powered adsorption ice maker with solid adsorption pair of activated carbon and methanol. In his work a simple flat plate collector with expo-
A sed area of 0.92 m² is employed to produce ice of about 4-5 kg per day. He has proposed a new technique of hybrid system of solar icemaker which would increase the overall efficiency of the system. Information gathered from the literature reveals that the performance of various solar refrigeration systems varies over a wide range and the reported COP is only about 0.1.

From the above analysis it is evident that so far no study has been made on a hybrid system of solar powered refrigerator that is suggested in this paper. The adsorber of the adsorption refrigeration system is simply placed inside the water bath that is directly powered by a solar collector and produce cooling when it goes through some thermodynamic processes. So the objective of this study is to simulate the proposed system with a small prototype and performance study with different adsorbent-adsorbate pair.

2. Solar adsorption system

The ideal cycle of adsorption refrigeration system is shown in figure 1. The design configuration of a solar powered refrigerator is shown in figure 1. In an ideal process the adsorbent temperature could be very close to the water temperature of the tank. When the temperature in the adsorbent rises up to a temperature \( T_{g1} \) which causes the vapor pressure of the desorbed refrigerant up to the condensing pressure \( P_c \), desorption at constant pressure is initiated, the desorbed vapor is condensed and collected in a receiver. Then it is allowed to flow to the evaporator via a regulating valve.

The temperature of the water and the adsorbent bed continues rising due to solar heating to a maximum temperature \( T_{g2} \) of 80 - 100 °C at the end of the process. In the evening the hot water is drained out from the tank and refilled with the supply water that reduce the temperature of the bed rapidly and the system pressure drops to a value below evaporation pressure. At such condition the evaporation will start if the valve is opened. Figure 2 shows the design configuration of a solar powered refrigerator. This system consists of a solar collector, water storage tank, adsorber with enhanced surface area, condenser with fins, evaporator consist of four trapezoidal cells, receiver and refrigeration chamber.

The whole system is just a combination of solar water heater and adsorption refrigeration. Solar collector absorbs the incident solar radiation, convey the heat to the circulated water and store it in the water tank. With the increase of water temperature, the temperature of the adsorbent bed rises. During the adsorption-evaporation process the cold water temperature is increased by several degrees which is the heat recovery from the system.

3. Development of solar refrigerator

In the proposed design a flat-plate collector with an exposed area of 0.4 m² and a storage tank of cylindrical shape with 900 mm length and 600 mm diameter having a capacity of 150 liters has been employed. The storage tank is placed at a height of 1880 mm above the ground level. As shown in figure 3 condenser fins are made of aluminium with good thermal conductivity having total heat transfer area 3.62 m² consisting 100 fins (150 mm outside diameter and 10 mm apart). The evaporator part is designed in such a way that makes good surface contact with the water and distribution of the refrigerant in each of the trapezoidal cell. The dimensions of the evaporator are : 0.38 x 0.28 x 0.095 m³ and the exchange area is 0.206 m² with four trapezoidal cells inside of which there is a refrigerant flow channel as shown in figure 4 for uniform distribution of the refrigerant in each of the cell.
The length of the receiver is 150mm and outside diameter is 81 mm. Adsorber is 300 mm outside diameter and 90 mm height with 0.33 m² surface areas which contain 2 kg of activated charcoal mixed with 500 ml methanol as the refrigerant. Refrigeration chamber is made of wood with good thermal insulation having the dimension 0.510 x 0.410 x 0.255 m³.

Selection of the materials is important for the system. Materials for the adsorber and the evaporator must be selected on the basis of thermal conductivity of the material which enhance the heat transfer process and hence improve the system performance. In our case the following materials have been selected:

1. Brass sheet metal for adsorber and evaporator.
2. Copper sheet metal for adsorber fins.
3. Aluminium sheet metal for condenser fins.
4. Copper tube (1/4” dia.) for refrigerant piping.

4. Experimental analysis

Solar adsorption refrigeration as shown in figure 1 did not prove successful due to unavoidable leakage in the system that causes change of working pressure as well as the poor heat transfer through the bed. To make the system simpler a modified small prototype hybrid system for water heating and refrigeration has been developed. The adsorber is made of brass material consisted of 150 mm length having 80 mm diameter, in which 500 gm activated charcoal was filled. An electric heater is used to simulate the solar collector.

A typical experiment is conducted with the initial water temperature in the water tank is 18°C. Then the water is heated to a maximum temperature of 90°C during entire heating process for the pair activated charcoal and refrigerant R-11. Desorption process starts as soon as the pressure reaches condensing pressure. After that the hot water was taken away from the tank and refilled with cold water. The adsorbent temperature is then rapidly reduced to a minimum temperature of 38°C and system pressure drops to a minimum working. For the case of activated charcoal and methanol the evaporating temperature attained 16°C that indicates a good sign of cooling effect. Two separate observations have been made for both the pair and revealed almost the similar situation as discussed.

Figure 4 and 5 shows the thermodynamic processes as obtained from the experimental analysis of adsorption refrigeration with a pair of activated charcoal and methanol. Here it is observed that as the temperature increases pressure also increases to a maximum of 300 mm of Hg and minimum pressure attained 119 mm of Hg.

Figure 6 and 7 shows the thermodynamic processes as obtained from the experimental analysis of adsorption refrigeration with a pair of activated charcoal and refrigerant R-11. Here it is observed that as the temperature increases pressure also increases to a maximum of 300 mm of Hg and minimum pressure attained 119 mm of Hg.
Figure 6 and 7 shows the experimental cycle for activated charcoal and refrigerant R-11. It is found that the maximum system pressure reaches 4.2 bar and minimum pressure attains 1.7 bar which keeps the desire condition for the cycle. Activated charcoal and refrigerant R-11 follows more close process as compared to ideal process than that of activated charcoal and methanol.

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5. Conclusions
The prototype system has proven the suggested idea of combined heating and cooling cycle. The system discussed above is an intermittent system which can also be set in continuous cycle by employing two adsorber together. Such type of technology can be used commercially for the places where the grid electricity is not available to run the conventional vapour compression refrigeration system but still there is need for preserving the vaccine at a certain temperature. As the hybrid system has been proposed here, the hot water due to heat recovered during the adsorption period can also be used for so many household purposes. Although such a technology is very expensive for its high installation cost, but still it will get more importance to meet the future need for cooling as well as heating.

References