Adsorption 11: 543–548, 2005

Experimental Evaluation of a Multi-Tubular Adsorber Operating with Activated Carbon-Methanol

ANTONIO PRALON F. LEITE* AND MARCELO BEZERRA GRILO
Mechanical Engineering Department, Federal University of Campina Grande, 58109-970 Campina Grande-PB, Brazil
antpralon@yahoo.com.br

RODRIGO RONELLI D. ANDRADE AND FRANCISCO A. BELO
Solar Energy Laboratory, Federal University of Paraíba, 58059-900 João Pessoa-PB, Brazil

FRANCIS MEUNIER
Laboratoire du Froid, CNAM, 292, Rue Saint Martin - 75141 Paris Cedex 03, France

Abstract. It is the purpose of this work to present an experimental analysis of the thermodynamic cycles in a multi-tubular adsorber of a solar-powered icemaker that uses activated carbon-methanol pair. The experimental cycles were obtained from tests made under different meteorological conditions—mainly the conditions pertaining to cloud cover degree. The system was tested in a Brazilian region close to the Equator (7°8′S, 34°50′WG) during the period October-December 2003. On a typical clear sky day, the regenerating temperature reached 94°C, the condensed methanol mass amounted to 3 kg, and the machine produced 6 kg of ice/m^2 day at −3.3°C, with a net solar coefficient of performance (COP_s) of 0.085. These results were compared to those obtained from a similar prototype that utilizes the same adsorptive pair and an usual flat adsorber, tested in Tunisia (35°45′N, 10°45′WG).

Keywords: activated carbon, methanol, solar refrigeration

1. Introduction

Solar refrigeration is one of the most inviting applications of solar energy because, for the stronger the solar incidence, the greater the demand for cooling. In most developing countries—especially in non-electrified areas—solar energy can be very important for the storage and preservation of foods and medicines. Many different solar energy technologies have been proposed and tested in recent years for their economic viabilities as the main component of autonomous sorption cooling systems. These systems are usually based upon one of the following technological alternatives: liquid absorption, solid absorption (chemical reaction) or adsorption. Adsorption—when compared to the other above mentioned techniques—exhibits the following advantages: the adsorbent does not require a rectifying column as it does in the case of liquid absorption, and it is not subjected to any change of volume as it happens to solid absorption. The main disadvantages, however, are the low coefficients of performance and the long time taken for the adsorption to complete. Solar ice making by means of adsorption is acceptable, despite the fact that it demands enough heat gains and suitable heat release from the adsorber.

The development of adsorptive systems is still curtailed by the cost of the solar adsorption collector

*To whom correspondence should be addressed.

component and by solar radiation intermittence, which renders them incapable of competing with conventional compression systems. Different technologies for solar adsorptive cooling devices have been tested in order to increase ice production and reduce its manufacturing costs as shown in a recent study (Boubakri et al., 2003). The present paper describes a multi-tubular adsorber—suitable for intermittent daily cycles—as a component of a solar- powered refrigerator for ice production that utilizes soft technology for thermal solar conversion. The adsorber-solar collector is static and bi-facially irradiated with a highly effective transparent insulation cover. In order to improve thermal performance, the adsorber is either covered with two transparent plates stuffed with a polycarbonate honeycomb material, known as *transparent insulation material* (Rommel and Wagner, 1992; Buchberg and Edwards, 1976), the so-called TIM cover. Reflectors were installed down below the tubes to allow solar incidence to reach the lower face of the adsorber. Activated carbon is used as an adsorbent, and it is placed inside the tubes whose surfaces make up the solar radiation adsorber plate. Methanol is used as adsorbate, or working fluid.

2. Icemaker Operation and the Adsorption Refrigeration Cycle

The operation of an ordinary refrigerator is based on a vapor compression cycle, in which a gaseous working fluid is mechanically compressed, making it to expand from a liquid phase into a saturated state. From this state, the fluid evaporates at low temperature and low pressure producing in this way the desired cooling effect. In the adsorption refrigeration cycle, the cooling effect is produced by the reversible interaction between a fluid and an adsorbent material. Our icemaker operates in an intermittent way, and there is no heat recovery; during the night the working fluid evaporates, and during the day there occurs the adsorbent regeneration by solar energy. The machine's evaporator is placed inside a thermo-insulated cold chamber as shown in Fig. 1. The fluid evaporation—adsorption process—occurs during the night, and the ice is formed on around the tubes that make up the evaporator, which is previously submerged in a water basin.

The adsorption refrigeration cycle consists of two well-defined stages: one is described as the adsorber cooling with a consequent adsorption process, when the evaporation of the working fluid (the adsorbate) takes place (Fig. 1(a)); and the other consists of the solid medium (the adsorbent) regeneration by solar energy, when the adsorbate is condensed (Fig. 1(b)). During the refrigeration stage, the TIM covers are removed so as to improve heat dissipation from the adsorber, as shown in Fig. 1(a). The ideal thermodynamic cycle can be represented by two isosters (iso-lines with constant adsorbed phase concentration, a) and two intercalated isobars, as shown in Fig. 2(b). The adsorber cooling is represented by an isosteric process 1-2, according to ambient conditions. This process continues until the adsorber pressure reaches its minimum value (point 2), i.e., equals to the evaporator pressure. At this point, the adsorption process starts, and prolongs until its

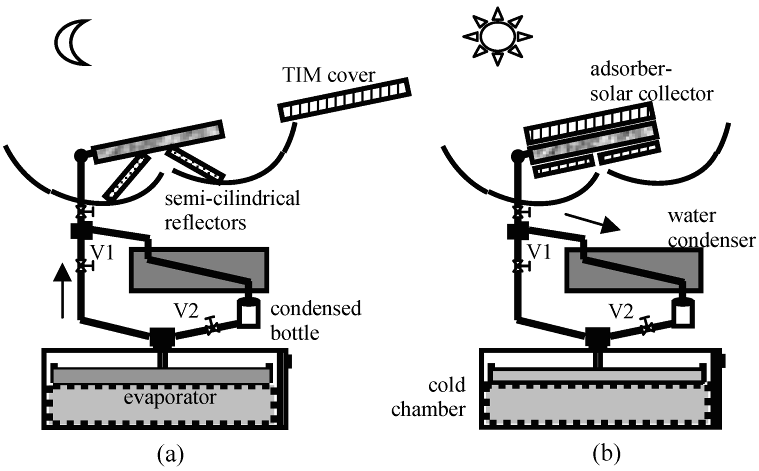
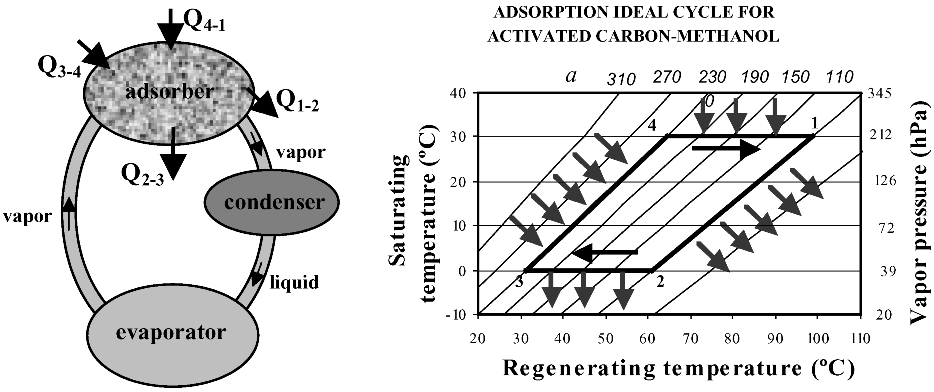


Figure 1. Adsorptive icemaker operation: (a) refrigeration and (b) regeneration.



(a) (b)

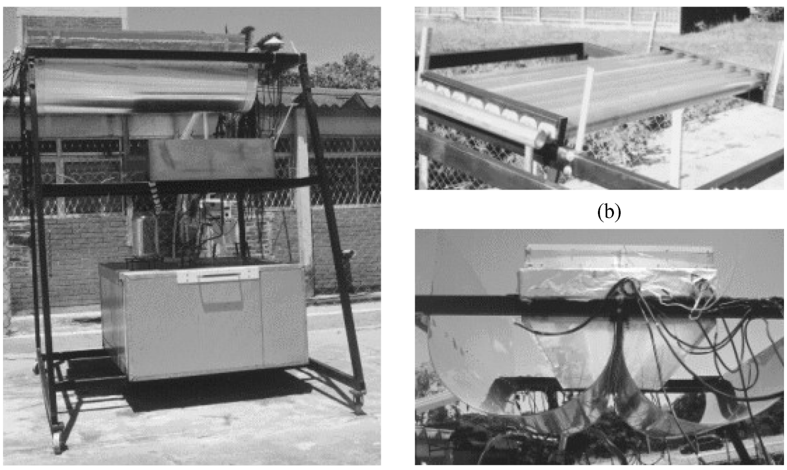
Figure 2. Principle of functioning (a); network of isosters and theoretical adsorption refrigeration cycle (b).

temperature reaches the minimum value (point 3). During this stage, the valves V1 and V2 are open. When the sunlight acts on the adsorber, the regeneration process takes place, and it is represented by the way 3-4-1, with valves V1 and V2 closed. The adsorber is heated following another isosteric process (3-4), until its pressure reaches a maximum value (point 4). Desorption starts at this point, and goes on until the adsorber temperature reaches its maximum value (point 1), completing the cycle, in this way.

The heat dissipated from the adsorber during cooling and adsorption (exothermal process), and the heat supplied to it during the heating and the desorption (endothermal process) are shown in Figs. 2(a) and (b).

3. Description of the Solar-Powered Adsorptive Icemaker

The solar-powered refrigerator is basically composed of an integrated adsorber-solar collector linked to a water condenser and an evaporator (Figs. 1 and 3(a)). All components are multi-tubular and are made of stainless steel. The direction of the gaseous flow changes according to the stage of the cycle; it flows from the evaporator into the adsorber during the adsorption process (Fig. 1(a)), when valves V1 and V2 are open, and from the adsorber into the condenser during the desorption process (Fig. 1(b)), when valves V1 and V2 are closed.



(a) (b) (c)

Figure 3. General view of the prototype (a) and components of the adsorber-solar collector (b, c).

Numerical simulations, utilizing meteorological data valid for Joao Pessoa (7°8′S, 34°50′WG) that lies northeast of Brazil in hot and humid climate (Leite and Daguenet, 2000), served as the basis for the design and construction of the present prototype. Figure 3(a) gives a general view of the actual prototype and its various components. These components are: a multi-tubular adsorber (Fig. 3(b)) integrated to a bi-facially irradiated solar collector (Fig. 3(c)), a water condenser, and an evaporator inside of an insulated cold chamber.

The adsorber covers a 0.60 × 1.65 m^2 area, from which the adsorbent occupies an annular space between the tube wall and an axial tube made of a metal net, through which the refrigerant fluid circulates. The amount of activated carbon and methanol used in the system corresponds to 21 kg and 6 kg, respectively. The tube surface acts as a solar absorbing surface, and it is painted in matt black. Semi-cylindrical reflectors are installed below the adsorber (Fig. 3(c)) to allow the incidence of solar radiation on both faces, as proposed by Goetzberger et al. (1992).

4. Experimental Procedure

Temperatures were taken from all parts of the component at every hour for the whole day by means of Pt-100 thermo-resistive sensors. To evaluate the longitudinal temperature distribution over the absorbing surface, eight sensors were positioned in the central tubes. As for the transversal distribution, four sensors were installed at mid-plan. To obtain an average value for the upper face of the adsorber, temperatures were taken from four points at each extremity above and below the tubes. The pressure was measured by means of a piezometric sensor installed between the adsorber and the condenser. The adsorber phase concentration was determined by direct measurement of the condensed methanol volume in a transparent graduated reservoir placed between the condenser and the evaporator (Figs. 1 and 3(a)).

Temperatures were also taken in other parts of the system—in the condenser water and on the condenser tubes, in the water to be frozen, on the evaporator tubes, on the chamber roof, on the external faces of both upper and lower TIM covers, and, finally, on the reflectors. The following meteorological parameters were also measured: total solar radiation, ambient air temperature, relative humidity and wind velocity. Some empirical observations were also conducted, mainly at night, so as to evaluate the cloud cover degree. Sky was classified here, according to some predominant conditions, into three categories: cloudless (clear sky), partially cloudy and mostly cloudy.

5. Results and Discussion

A number of tests were conducted in the period October-December 2003. Three typical cycles were obtained thereby in relation to cloud cover degree: cycle 1 (10.5-6)—clear sky; cycle 2 (11.29-30)—partially cloudy; and cycle 3 (12.8-9)—mostly cloudy. The corresponding thermodynamic cycles, which were experimentally obtained, are presented in a pressure-temperature diagram, as illustrated in Figs. 4–6. In all cycles, the hours that refer to each limit point are also given.

An analysis of the cycles allows us to obtain the extreme temperatures during the adsorption and the desorption processes. Moreover, another practical aspect of the adsorption cycles consists in obtaining, straight away, the saturated methanol minimum temperature inside the evaporator. For cycles 1, 2 and 3, these values were roughly: −6.5°C, −5.5°C and −5.0°C, respectively.

5.1. *Durations of the Desorption and the Adsorption Processes*

As indicated by the cycle limit point hours, the longest desorption period (4 h 32′) took place in cycle 1. Consequently, a larger concentration variation was verified in this cycle, which could be verified experimentally by direct measurement of the condensed methanol in a

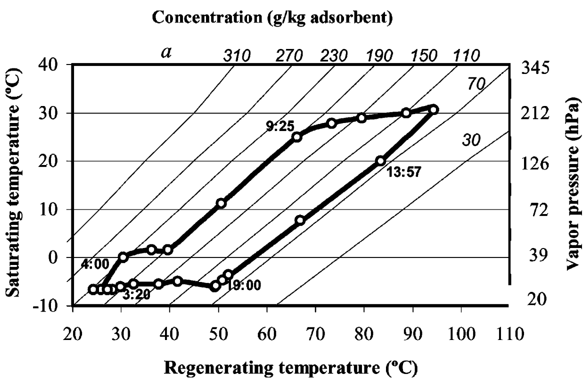


Figure 4. Experimental adsorption refrigeration cycle for 10.5-6 (cloudless).

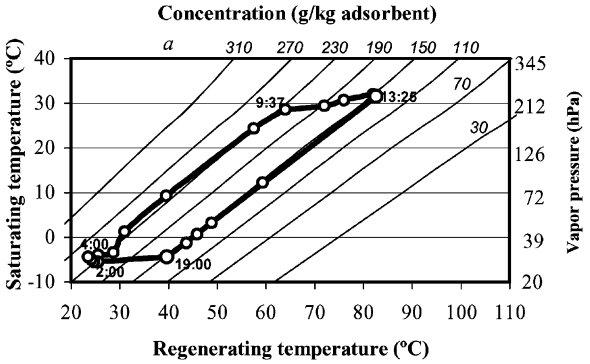


Figure 5. Experimental adsorption refrigeration cycle for 11.29–30 (partly cloudy).

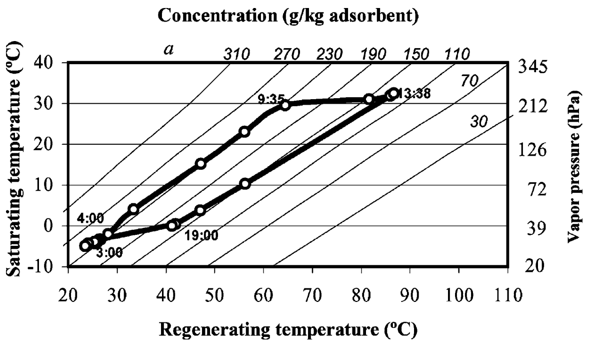


Figure 6. Experimental adsorption refrigeration cycle for 12.8-9 (cloudy).

transparent bottle. The solar energy incidence verified on October 5th, for cycle 1, accounts for such a long regeneration. This was noticed to be more intense than in the other cycles because of a very low cloud cover degree verified in cycle 1 that caused a significant beam radiation predominance to happen, mainly during the period 10:00 a.m. to 1:00 p.m. As for the other cycles, although daily solar radiation was observed to be quite the same for both cycles 2 and 3—when radiation data were compared—one could see that the beam component for December 8th was larger than that for November 29th, mainly from 10:00 a.m. till noon. As a result, regeneration temperatures were much higher than those observed in cycle 2.

A comparative analysis of the adsorption process for these three cycles has demonstrated that the concentration increases far more slowly in cycle 1 than it does in the other cycles. This can be easily noticed by the agglomeration of points close to the larger isoster in cycles 2 and 3, whereas in cycle 1 these points are somewhat scattered during adsorption. Taking into account the recorded times at the limit points, the longer adsorption period was seen to happen in cycle 1, which amounted to 8 h and 20′. This was due to three important factors: a larger amount of previously condensed methanol, delay in opening TIM covers, and predominant night sky conditions. In cycle 1, the sky remained basically clear throughout the adsorption process.

5.2. *Deviation of the Actual Cycle from the Ideal Cycle*

The resulting thermodynamic cycles differ from the theoretical cycles mainly at the desorption and adsorption processes because they are not isobaric—as in the ideal cycle shown in Fig. 2(b). In the desorption process, this was seen to happen because, during the methanol transfer to the condenser, the adsorber suffered enormous temperature variations due to solar radiation incidence and an efficient energy heat conversion. At this stage, the adsorbent temperature is much more influenced by atmospheric conditions than by the adsorption itself.

As to the isosteric processes, small deviations were detectable in the adsorber heating and cooling systems in all cycles. In cycles 1 and 2, the concentration remained practically constant in both processes. In cycle 3, however, some re-adsorption was seen to occur before the opening of the valve V1 (Fig. 1).

6. Conclusions

The system's performance has responded very well to night clear sky conditions, even when it had been submitted to good solar irradiation in previous regenerating stage. Under cloudy night sky conditions, the water temperature inside the cold chamber can drop to below 0°C, though not cold enough to freeze water. Only under clear sky conditions—especially around the zenith—the temperature in the evaporator attained the appropriate level to freeze water. In cycles 2 and 3, the condensed methanol masses weighed 2.0 kg and 2.3 kg, and the evaporated masses were equivalent to 2.0 kg and 1.3 kg, respectively. The ice produced weighed 2.1 kg for cycle 2, and, as for cycle 3, no ice was produced. Such discrepancy was due to the difference between the quantities of condensed and evaporated methanol that happened in cycle 3.

On a clear sky day (cycle 1), with the regeneration temperature reaching 94°C, the condensed and evaporated methanol masses were of 3 kg, and the machine produced 6.05 kg of ice/m^2 at a temperature of −3.3°C. The net solar coefficient of performance (COP_s)—defined as the ratio of the effective cooling load to the incident total solar radiation (E_i) that runs across the projected plan of the adsorber—was of 0.085 ($E_i = 23.7$ MJ/m^2). These values were compared to the ones obtained from a prototype tested in Monastir (35°45′N, 10°45′WG), Tunisia, under clear sky condition, using the same adsorptive pair, a water condenser, and a flat adsorber-solar collector with selective surface covered by a single glass plate (Medini et al., 1991). The ice quantity produced by our machine was 21% higher, and its COP_s was about 27% higher than that produced by the Tunisian prototype ($COP_s = 0.067$). This discrepancy can be explained by the expressive difference in the ambient temperatures; at Monastir this temperature was considerably lower, which facilitated both the adsorption process and the cooling effect.

References

Boubakri, A., "A New Conception of an Adsorptive Solar-Powered Ice Maker," *Renewable Energy*, **28**, 249–263 (2003).

Buchberg, H. and D.K. Edwards, "Design Considerations for Solar Collectors with Cylindrical Glass Honeycombs," *Solar Energy*, **18**, 193–203 (1976).

Goetzberger, A. et al., "A New Transparently Insulated, Bifacially Irradiated Solar Flat Plate Collector," *Solar Energy*, **49**(5), 403–411 (1992).

Leite, A.P.F. and M. Daguenet, "Performance of a New Solid Adsorption Ice Maker with Solar Energy Regeneration," *Energy Conversion & Management*, **41**, 1625–1647 (2000).

Medini, N. et al., "Etude d'une machine solaire à fabriquer de la glace," *Int. J. Refrigeration*, **14**, 363–367 (1991).

Rommel, M. and A. Wagner, "Application of Transparent Insulation Materials in Improved Flat-Plate Collectors and Integrated Collector Storages," *Solar Energy*, **49**(5), 371–380 (1992).