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Evaluation of thermal parameters and simulation of a solar-powered, solid-sorption chiller with a CPC collector

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ABSTRACT

A model is presented to simulate the operation of a solid-sorption chiller using the methanol-activated carbon pair and a CPC (compound parabolic concentrator) solar collection system. The model is based on assigning constant thermal exchange parameters to all the main elements (generator/reactor, condenser, evaporator and cold box) of a previously tested unit. In particular, the generator is assigned a collector heat-removal factor and an overall heat-loss coefficient. The way in which experimental records have been used to obtain these and the other parameters is explained in detail, and can be adapted to many other configurations of solar cooling units. A validation of the model is carried out for various cycles of operation, showing good agreement between calculated and experimental records. Finally, the model has been used to estimate the chiller performance under conditions that differ from those encountered experimentally.

1. Introduction

Adsorption cycles for cold production are one of the most promising applications of solar energy, as they require only thermal energy to operate and because the more abundant the solar radiation, the higher the demand for cooling power.

In the past few decades a great deal of work has been carried out in developing countries to implement such cycles in cold storage and ice making applications [1–6]. More recently, interest has grown in developed areas as well, especially in the context of air conditioning [7,8]. The more common adsorbents in solar cooling literature are silica gel, zeolites and activated carbon; the preferred adsorbates/refrigerants are ammonia, water and methanol.

The well-known ideal, intermittent adsorption cycle is usually represented in a ($\ln P$, $-1/T$) diagram such as the one shown in Fig. 1. The stages are isosteric heating (AB); isobaric desorption/condensation (BC); isosteric cooling (CD); and isobaric adsorption/evaporation/cold production (DA). In the case of solar-powered cycles the first two stages are usually referred to as the daily phase, while the last two are the nightly phase.

Most of the reported solar prototypes are based on the flat-plate solar collector, whereas much less attention has been paid to the use of concentrating collectors [9,10]. In this context we have developed a new class of compound parabolic concentrator (CPC) which we think is well adapted to solar cooling. Its main feature is that only a portion of the cylindrical receiver is exposed to solar radiation. The non-exposed portion is covered during the daily phase by an insulating bottom (Fig. 2) which is removed during the night to improve the natural cooling of the adsorptive bed.

Although Section 2 gives a short description of the prototype, most of this paper is devoted to providing a simple but accurate model to describe its operation (Section 3), and to explain how the experimental data can provide us with the parameters of the model. In Section 5 a comparison between the predictions of the model and the experiments is made. Finally, the model is used in Section 6 to forecast the operation of the prototype in conditions different to those encountered in the campaign of measurements.

2. The prototype

Fig. 2 displays a schematic view of the prototype, which has been described in detail in Ref. [11]. The generator consists of four parallel receiver tubes, filled with an activated carbon bed. Each receiver has its own non-truncated CPC collector. The receiver radius is $R = 38$ mm, the concentration factor is $CF = 1.41$ (which means an acceptance half-angle of 45°) and the exposed and non-exposed areas of the receiver are equal. The adsorbate/refrigerant is methanol.

The condenser consists of a cylindrical chamber crossed by an array of parallel pipes. The cooling fluid is water, which is stored in a tank annex to the unit. The water flows inside the tubes, whereas the condensation occurs outside. The condensate falls directly into the evaporator.

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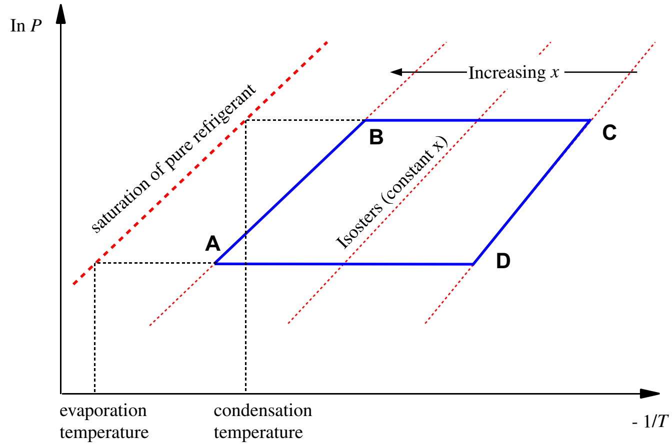

Fig. 1. The ideal adsorption cycle. The dashed line represents the saturation conditions of pure adsorbate; the other diagonal lines are the isosters, joining the points with constant concentration *x*.

The evaporator is a grid of vertical copper tubes. Each of these is surrounded by a small cylindrical reservoir, containing the water to be chilled. The cold box–evaporator set is thermally isolated by means of 8 cm thick polystyrene walls.

The main quantities recorded are ambient temperature, irradiance on the CPC aperture plane, tank temperature, cold box temperature (several probes) and pressure. No attempt was made to measure the temperature inside the porous bed in order to preserve the air tightness of the generator. Three pressure probes were installed at the generator, at the top and at the bottom of the evaporator. The latter two allow for hydrostatic measurement of the liquid methanol column height, from which the methanol concentration at the generator can easily be inferred at any time in the cycle. This information is one of the key points in the model described in the following sections, since adsorption/desorption heat, which is the dominant thermal contribution in stages BC and DA, can easily be computed in terms of the concentration change rate.

Table 1 shows some design and operational parameters of the unit not previously given in the text.

The prototype was tested in Burgos (Spain) in July 2005. Experimental solar COP ranged from 0.078 to 0.096. Daily

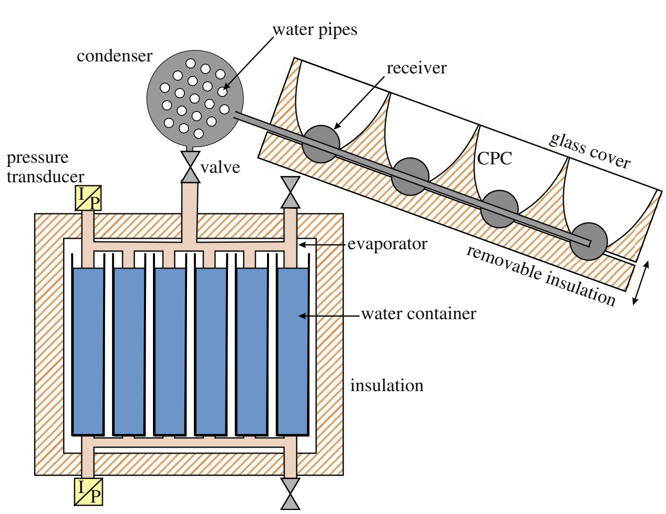

Fig. 2. Schematic view of the prototype. The water tank is not shown.

Table 1
Design and operational parameters of the prototype

Name	Symbol	Value
Generator, aperture area (m^2)	$A^{(g)}$	0.55
Receiver, exposed area (m^2)		0.39
Receiver, non-exposed area (m^2)		0.39
Generator, activated carbon mass (kg)	$m_{ac}^{(g)}$	7.2
Generator, metallic mass (copper) (kg)	$m_{cu}^{(g)}$	15
Condenser, exchange area (m^2)	$A^{(c)}$	0.32
Tank, water mass (kg)	$m_w^{(t)}$	90
Evaporator, metallic mass (copper) (kg)	$m_{cu}^{(e)}$	10
Evaporator, exchange area (m^2)	$A^{(e)}$	0.35
Cold box, water mass (kg)	$m_w^{(b)}$	5
Total mass of methanol (kg)	$m_{me}^{(g)} + m_{me}^{(e)}$	2.2

evaporated refrigerant masses ranged from 1.62 to 2.25 kg m^{-2} aperture area. The average gross cold production was 2.2 MJ m^{-2} per day, while the average net heat extraction to $m_w^{(b)}$ was 0.8 MJ m^{-2}.

3. The model

Fig. 3 schematically displays the main thermal exchanges occurring in the prototype as well as the parameters used to describe them. Solar radiation input to the generator is described by means of the well-known collector heat-removal factor F_R (see below) whereas thermal losses to ambient depend on the collector overall heat-loss coefficient U_L. Thermal exchange between the condenser and the tank water is described by a transmission coefficient $h^{(c)}$. Two other tank heat loads are also considered: convective heat transfer to the ambient through the tank walls ($h^{(t)}$) and direct gain caused by exposure to sunlight ($\Sigma^{(t)}$).

During the nightly phase the heat flux through the cold box walls is quantified by means of the conductance $K^{(b)}$, whereas the transmission coefficient $h^{(e)}$ describes the transfer between the evaporating methanol and the cold box. The exact way in which all of these quantities are defined will be given below.

3.1. Assumptions of the model

A list with the basic assumptions and hypotheses of the model follows:

- All the parameters shown in Fig. 3 are considered to be constant in value. The only exceptions to this rule are F_R and U_L, whose daily and nightly values may be different as a consequence of the removal of the insulating bottom.
- The whole porous bed and its absorbed refrigerant are assumed to be, at a given moment, at a uniform generator temperature $T^{(g)}$. This is a *computed* temperature. Its relation to the experimental methanol concentration *x* and pressure *P* is given by the Dubinin–Astakhov equation:

$$x(P, T^{(g)}) = W_0 \rho \exp\left\{ -D\left[T^{(g)} \ln \frac{\Pi}{P}\right]^n \right\}. \quad (1)$$

The parameters W_0, *D* and *n* were found experimentally in Ref. [12]. Their values are $W_0 = 1.17$ L kg^{-1}, $D = 1.3 \cdot 10^{-4}$ and $n = 1.40$. ρ is the density of liquid methanol and Π is its saturation pressure at the temperature $T^{(g)}$.

- The heat of adsorption/desorption implied in stages AB and CD (see Fig. 1) is computed, as reported by Leite [13], by applying the well-known Clapeyron equation to D–A equation (1):

$$\Delta H = L + RT^{(g)} \ln \frac{\Pi}{P} + \frac{RT^{(g)}\beta}{nD}\left[T^{(g)} \ln \frac{\Pi}{P}\right]^{1-n}, \quad (2)$$