SIMULATION OF AN ADSORPTIVE SOLAR REFRIGERATOR OPERATING IN MOROCCO

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SUMMARY: Adsorptive solar cooling units have been successfully tested in the last years. In this paper, a numerical simulation of one year operation in Rabat is presented. The main result is according to the model, every day the heat extraction is positive. The highest efficiencies are obtained in winter: this is due to the significant influence of nocturnal cooling on the Active Carbon + Methanol system. The average solar coefficient of performance (COP) is 0.114 and most of the time (75%) the daily cold production lies between 2.100 and 3.000 kJ/m^2. This type of refrigerator seems to be, at the moment, one of the most attractive solution for solar cooling.

Key Word: Solar refrigeration.

INTRODUCTION

After domestic water solar heaters, solar cooling seems to be the most promising application for solar energy. During the last twenty years, great efforts have been devoted to solar cooling using photovoltaic cells as using thermodynamical cycles. At the moment, these two directions are still in competition. The most important efforts concerning thermodynamical processes dialed with:

- solar air conditioning using LiBr–H_2O units coupled to solar collectors (1),
-solar open desiccant cycles (2),
- solar refrigerators operating intermittent cycles.

The efforts in the two first directions did not reach the level of commercialization when solar refrigerators operating intermittent cycles offer attractive solutions for commercialization.

First efforts in that 3rd direction had been devoted to the adaptation of well known liquid absorption cycles (3–5) but some technical problems could not be solved so that no commercialization occurred when corresponding efforts on solid gas systems succeeded. At the moment, three systems operating solid gas cycles are commercialized: Zeolite + Water (6) (Zeopower in USA), Active Carbon + Methanol (7) (Figure 1) and a chemical absorption system (8) (Sunice in Denmark).

Up to now, the technical feasibility of those systems has been proven but assessing their economic feasibility requires the study of their operation in actual meteorological conditions. The aim of that paper is to present the results of the numerical simulation of a year operation in Rabat (Morocco) of an adsorptive solar refrigerator using an Active Carbon + Methanol intermittent cycle.

ADSORPTIVE SOLAR REFRIGERATORS

The principle of such units can be described as follows (Figure 2).

Heating of the adsorber (day time)

First, heat is added to the adsorber from A to B (near isosteric line). At point B, vapor pressure of the refrigerant over the adsorbent equals to the saturation pressure at the condensing temperature. Addition of more heat from B to D desorbs refrigerant and increases the temperature of the adsorber. In an ideal cycle, the condensing temperature remains constant from B to D (isobaric line).

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Figure 1: View of a commercialized solar adsorptive refrigator operating with an Active Carbon + Methanol pair.

PERFORMANCES
*Inside effective content of isothermal enclosure: 2001.
*Inner temperature: ≤47°F (8°C).
*Accessory production of ice cubes.
*Conditions:
- Max external temperature: 109°F (43°C) (trpocal class/NF).
- Min average sun exposure: 4.5 kWh/m^2 per day.
- Insulation of isothermal coffer conforming with OMS specifications.

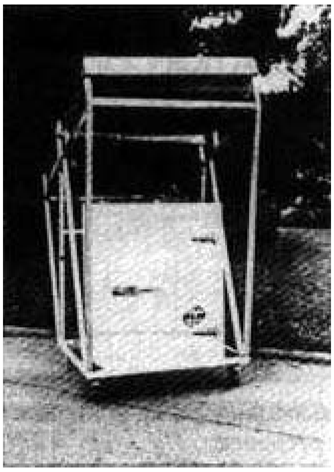
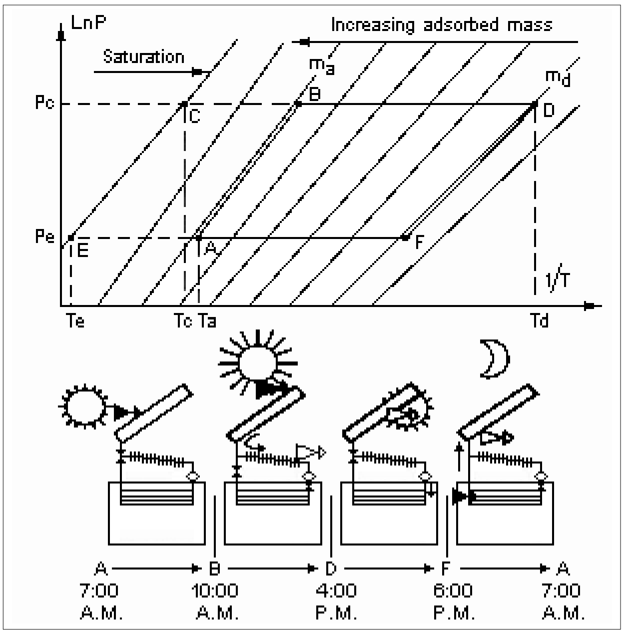


Figure 2: Schematic of solar adsorptive refrigerating cycle.



Cooling of the adsorber (night time)

When insolation decreases, the adsorber temperature decreases. The adsorber gradually cools discrading sensible heat from D to F (near isosteric line). At point F, vapour pressure of the refrigerant over the adsorbent equals to the saturation pressure at the evaporating temperature. From F to A evaporation proceeds, ideally at constant pressure (isobaric line), and refrigeration occurs when sensible and latent heat (resulting from adsoption) is extracted from the adsorber. To get an efficient cooling of the adsorber during the night, dampers may be open during the night, but the unit may as well operate without dampers (but with a lower efficiency).

To operate such a cycle, the unit needs either a manual valve (9) for a Zeolite + Water refrigerator and (10) for an Active Carbon + Methanol ice maker or a check valve (11).

The feasibility of adsorptive solar cooling units has been extensively studied in Orsay an a small solar refrigerator (9) and on a large cold store (12), for both operating with Zeolite + Water pair, and on an ice maker operating with the Active Carbon + Methanol pair (10, 13).

In this paper, the Active Carbon + Methanol pair was selected since it seems to present more advantages for commercialization than the Zeolite + Water pair.

MODELING

The physical model used in the two numerical models presented herein is the same and may be resumed as follows.

Physical model for heat transfer

Input solar radiation is converted into heat on the front plate of the solar collector

$$W = W_s - W_p \qquad [1]$$

where W is the collected heat flux, W_s is the input solar heat flux and W_p is the heat flux lost by conduction, convection and radiation.

Heat is transferred in the metallic parts of the collector according to Fourier's law

$$\rho_1 c_1 \frac{\partial T}{\partial t} = \lambda_1 \Delta T \qquad [2]$$

where $\lambda_1 / \rho_1 c_1$ is the thermal diffusivity of metal. Input solar energy and thermal losses (Equation 1), are taken into account as boundary conditions (15).

Then heat is transferred from the metallic parts to the adsorbent layer through a contact resistance

$$\lambda \frac{\partial T}{\partial n_s} = h(Tm_s - Ta_s) \qquad [3]$$

where the heat exchange coefficient is assumed to be constant. Tm_s and Ta_s are the metal/absorbent temperatures at the contact surface.

Finally, heat propagates within the adsorbent layer according to Fourier's law with a source term (dq / dt) due to adsorption or desorption

$$\rho_2(c_2 + mc_3)\frac{\partial T}{\partial t} = \lambda_a \Delta T + \rho_2 \frac{dq}{dt} \qquad [4]$$

The conductivity of the adsorbent λ_a is assumed to be constant and (dq / dt), the space-time heat source term, is given by a mass balance equation (Equations 6–7).

Physical model for mass transfer

In flat plate solar collectors, the value of the input heat flux is low enough for applying an equilibrium model, assuming completely negligible mass transfer resistances. This assumption was shown to be valid when the heat rate is less than 750 W/kg of adsorbent (14) in the case of the Zeolite + Water pair. Moreover, Guilleminot *et al.* (15) have shown experimentally that this assumption is realistic for solar reactors using the Active Carbon AC35 + Methanol pair.

The adsorption equilibrium law may be given in a functional notation:

$$m = m\,(T_c\,, T) \qquad [5]$$

where T_c is the saturation temperature in the condenser, T is the temperature of the adsorbent and m the amount of adsorbed refrigerant per kilogram of adsorbent.

When adsorbent and / or condensing temperature very adsorption or desorption occur, yielding a mass source term dm / dt :

$$\frac{dm}{dt} = \left(\frac{\partial m}{\partial T_c}\right)_T \frac{dT_C}{dt} + \left(\frac{\partial m}{\partial T}\right)_{TC} \frac{dT}{dt} \qquad [6]$$

The corresponding heat source term (dt / dq) used in Equation [4] is :

$$\frac{dq}{dt} = q_{st}\frac{dm}{dt} \qquad [7]$$

where q_{st} is the isosteric heat of desorption.

The temperature of an air cooled condenser is related to the condensed flow-rate :

$$LM_a \frac{dm}{dt} = h_C S_C \left(T_{ext} - T_C\right) \qquad [8]$$

where L is the latent heat of condensation, M_a the mass of adsorbent per square meter of collector, h_c is the heat exchange coefficient, S_c the exchange area of the condenser and T_{ext} is the ambient temperature. (It must be noticed that during desorption, dm / dt is negative).

Numerical simulation

The system of Equations [1–8] can be solved using a finite difference method when boundary and initial conditions are chosen.

The expenditure in computing time depends on the mesh of the spatial grid.

A detailed model (Sunice) takes 100 points for representing in details the heat transfers in the adsorber the influence of the fins is thus taken into account. The set of nonlinear equations is solved iteratively according to a Crank-Nicholson scheme (three iterations for a time step of 450s) (15). Sunice is implemented on IBM-AT Compatible's in Orsay, when only small micro computers (Apple//e) are available in Rabat. Simulation of one day of operation with a version of Sunice implemented on Apple//e would be several days long, which makes that numerical simulation prohibitive. Consequently Sunice was used only for determination of three global parameters that are data values of a simplified model: Mafrisol.

In Mafrisol, the modeled solar collector is one-dimensional, represented by only three points corresponding to the three elements: the front plate, the adsorbent and the rear plate. The temperature of each of these elements is assumed to be the mean temperature of each of these components. Each element is characterized by an equivalent Heat Capacity and the heat transfers between two of these three elements are characterized by equivalent conductance's assumed to be constant (all over the day and all over the year). These phenomenological conductance's globally include the heat transfer resistance at the metal-adsorbent interface, the conductive heat transfer through the packed bed and the effect of fins. These conductance's result from the detailed model Sunice: three test cases were studied, Sunice computes the temperature distributions in metallic volume and in the packed bed. Three global transfer coefficients, determined from average temperatures and heat fluxes, can be used as input data by Mafrisol.

By solving implicit equations with the Crank-Nicholson method (time steps of one hour with only one numerical iteration for each), Mafrisol computes the evolutions of the four temperatures (front, adsorbent, rear and condenser) all along the day, and thus the quantity of desorbed Methanol and finally the heat extraction at the evaporator and the overall solar COP.

Mafrisol is implemented on Apple//e, and the computing time is only one minute per calculated day. This allows calculations on one year of meteorological data, and studying dependence of performance on some characteristic of the modeled machine.

It was verified on few representative days that both models yield same results concerning performance of the machine.

METEOROLOGICAL DATA

The site is Rabat, a coastal town of Morocco with a latitude of $\varphi = 34°$ North.

The solar energy laboratory of the University of Rabat has a complete equipment for solar measurements:

- a pyrheliometer NIP EPPLEY equipped with a pursuit solar system measures the direct solar flux on a plane normal to solar beams.

- pyranometers EPPLEY, black and white. One of them is used for the measurements of the global solar radiation on a horizontal plane.

- thermocouples for the ambient temperature.

An HP 3794A, piloted by an HP9915 micro computer is used for data acquisition and storage. Measurements are performed every 0.6s, integrated over 6 mins and then stored. Measurements from July 1986 to 1987 are used in the following numerical simulation. During that period some data are missing due to electrical cuts. Fortunately other measurement devices allowed us to substitute missing data as follows: Solar fluxes were read on a graphical recorder, ambient temperature was either read on a mercury thermometer during day-time, or deduced from recorded relative humidity during night-time.

Then from these data, the global energy incident the collector according to its orientation had to be computed. We chose a tilt angle of the collector equal to the local latitude, 34° for Rabat. The Energy incident on the collector was computed from the measured data (horizontal and normal). Several models, which differ mainly by the way to compute the diffuse component of the solar radiation (which may be either isotrope or anisotrope (17, 18), have been elaborated. A study of those models, carried out on the data of Rabat, showed that the isotropic model (18), which is the simplest one, is correct (19). The global solar irradiation on a surface tilted by an angle β- I_b – is given by

$$I_b = I_{bn} \cos\theta + 0.5\, I_d \left(1 + \cos\theta\right) + 0.5\, \alpha I \left(1 - \cos\beta\right) \quad [9]$$

where I_{bn} and I_d are respectively the direct normal, the global horizontal (both measured) and the diffuse (deduced from I and I_{bn}) solar irradiations, α is the albedo and θ is the incident angle of the direct solar radiation.

Figure 3: Daily incident global energies (upper) and histogram (lower). Period: July 86 – June 87.

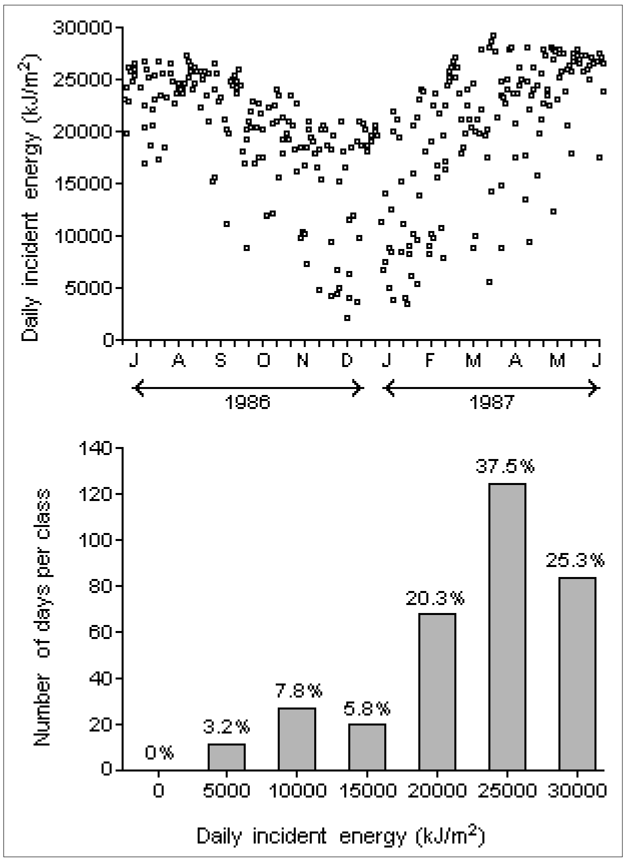


Figure 3 shows the variation of the daily global solar energy on collector as well as its repartition on class intervals of width 5.000 kJ/m^2 during the period corresponding to the numerical simulation. An accumulation of values (83%) between 15.000 and 30.000 kJ/m^2 and an important dispersion during winter are observed.

The ambient temperature (average value on 24 hours) is presented on Figure 4. The points are much more compact than on the former figure but the shape is the same. This figure shows a few days in wintertime with high values of temperature this is because of the 'Chergui', a warm wind blowing from the Sahara.

The statistical characteristics of the daily incident solar energy and of mean temperature are presented in the Table 1.

RESULTS OF SIMULATION

Optimization of the mass of adsorbent

An experimentation was conducted in Orsay, (13), involving two types of solar collectors with layers of Acti-

Table 1: Statistical characteristics of the daily incident energy received by a surface tilted by 34° and of mean ambient temperature.

	Average Value	Absolute Minimum	Absolate Maximum
Energy (kJ/m^2)	20.320	1.908	29.286
Temperature (°C)	18.4	9.9	27.2

vated Carbon respectively 5 and 6 cm thick. It showed that the 5 cm layer yields slightly better performance in the climate of Paris. These latter collectors contained 22 kg of A.C. per square meter of collector. That comparison was not exhaustive and meteorological conditions in Rabat are quite different. Thus five different thickness corresponding to 13, 15, 19, 23 and 27 kg/m^2 of A.C. were tested. For each value of thickness, the fins distribution is kept similar but the fin height is adapted.

Comparison of calculated performances was performed on the operation during summer-and wintertime. Figure 5 shows that the average Produced Cold is not very sensitive to the mass of adsorbent, the optimal value (for the geometry of collector here chosen) is 19 kg/m^2 all the following calculations herein will be performed with this value.

History of the COP along one year

The solar coefficient of performance (COP) is the ration between the heat extracted from the evaporator (evaporating load) and the daily solar energy incident on the plane of the collector. In previous works (7, 10, 12, 13) solar COP used to be presented as if the evaporated amount of refrigerant were exactly the same as the desorbed mass (one reason is the condensed amount of adsorbate was experimentally measured, but not the evaporated one). In actuality, the mass desorbed during the day-time is usually different from the mass adsorbed during the night, because the actual 'cycle' of a solar machine is not thermodynamically cyclic at the end of one night, most of the time, the temperature of the adsorber is not the same as at the end of the Solar COPa computed from the adsorbed mass, and the Solar COPd, computed from the desorbed mass.

Figure 4: Daily mean temperature. Period: July 86 – June 87.

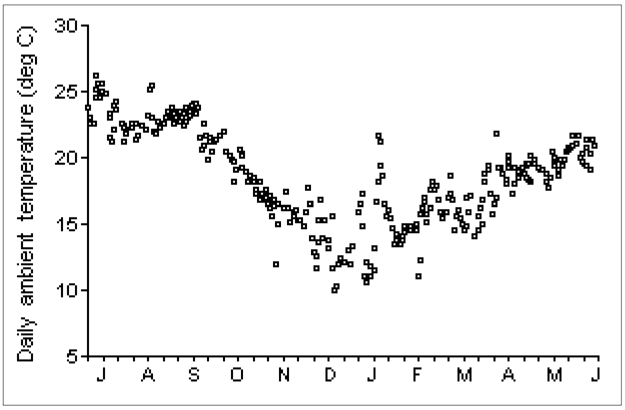
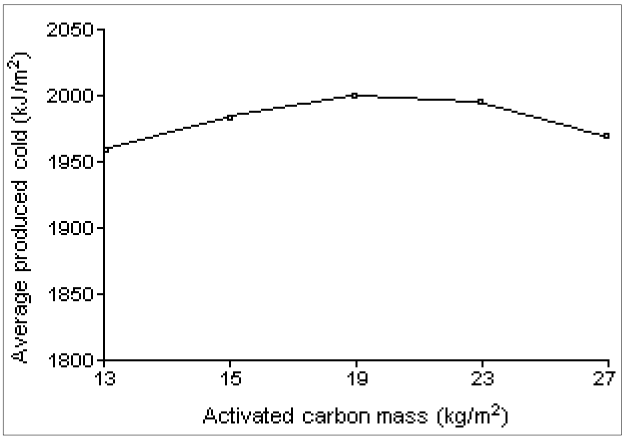


Figure 5: Influence of the mass of adsorbent on the produced cold.



COPa is roughly minimal in summertime (0.09) and maximal in winter (0.15) (Figure 6). A few days yield a COPa greater than 0.20. In fact the insolation for these seven days was very low (less than 5.000 kJ/m^2) when the previous days were always very bright. Consequently, at the morning of these 'grey' days the temperature of collector was much higher the ambient, and became much

Table 2: Influence of ambient temperature on solar COP.

Day	Solar Energy (kJ/m^2)	Ambient Temperature (°C)	Average Nocturnal Temperature	Solar COP (desorbed)	Solar COP (adsorbed)
24 July '86	20.509	23.1	22.1	0.102	0.094
30 July '86	20.783	23.6	22.7	0.098	0.091
27 Nov '86	20.254	15.4	14.2	0.142	0.124
30 Nov '86	20.207	15.2	13.9	0.135	0.136

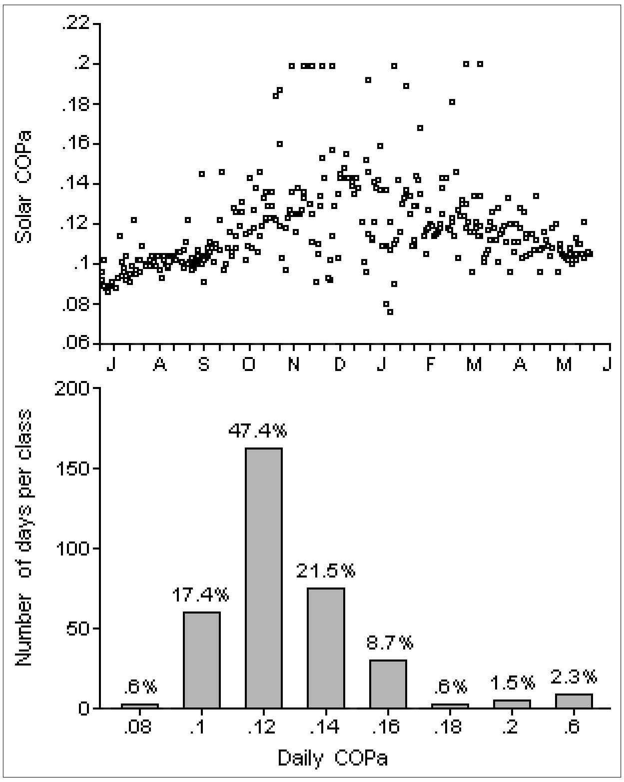


Figure 6: Solar COP (upper) and histogram (lower) (COP adsorbed).

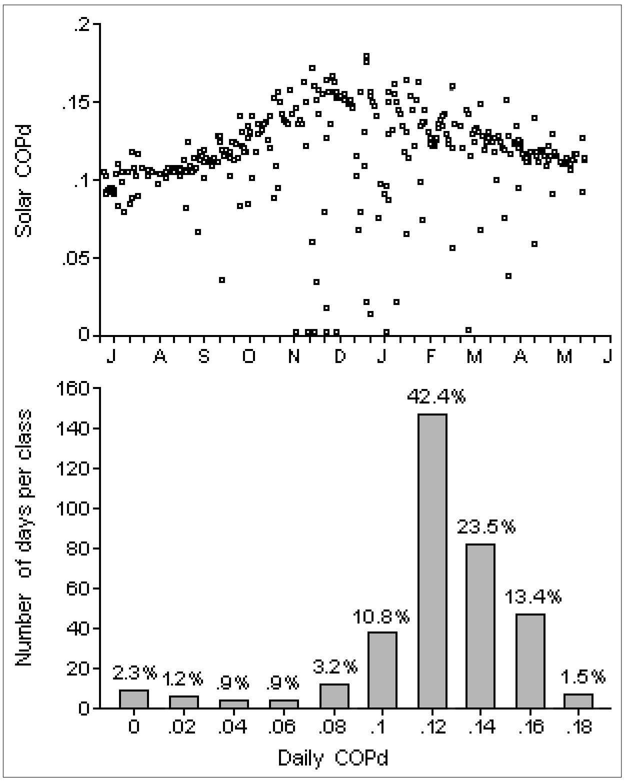


Figure 7: Solar COP (upper) and histogram (lower) (COP desorbed).

closer to the ambient at the end of the night. This difference of temperature between two successive morning causes some adsorption, inducing non-negligible heat extraction. This heat extraction almost does not depend on the incident energy, and if the latter is very low, the COPa reaches aberrant values. Moreover such very high values ‘hide’ the absence of desorption. This absence clearly appears when COPd is considered (Figure 7), where those days have a zero COPd. As well diagrams as histograms show that ‘normal’ days yield the same results for COPd and COPa: roughly 45% of days with COP between 0.10 and 0.12, roughly 35% with higher COP's (mainly up to 0.14), and 20% with lower values (mainly down to 0.08); the evolutions along the year are also roughly similar. The average value of COP (ratio of total heat extraction by total solar input) is 0.114.

Better values of COP's in winter although solar input is minimum, show the influence of ambient temperature on performance of a machine using Active Carbon + Methanol pair (20). In Table 2, four days are selected, with similar incident solar energies but with different ambient temperatures a decrease of 8.5°C of the latter one yields an increase by 40% of the solar COP.

History of the cold production along one year

The Cooling is presented on Figure 8. Compared with the isolation (Figure 3), it can be seen that.

- the dispersion of Produced Cold roughly reproduces the dispersion of insolation.

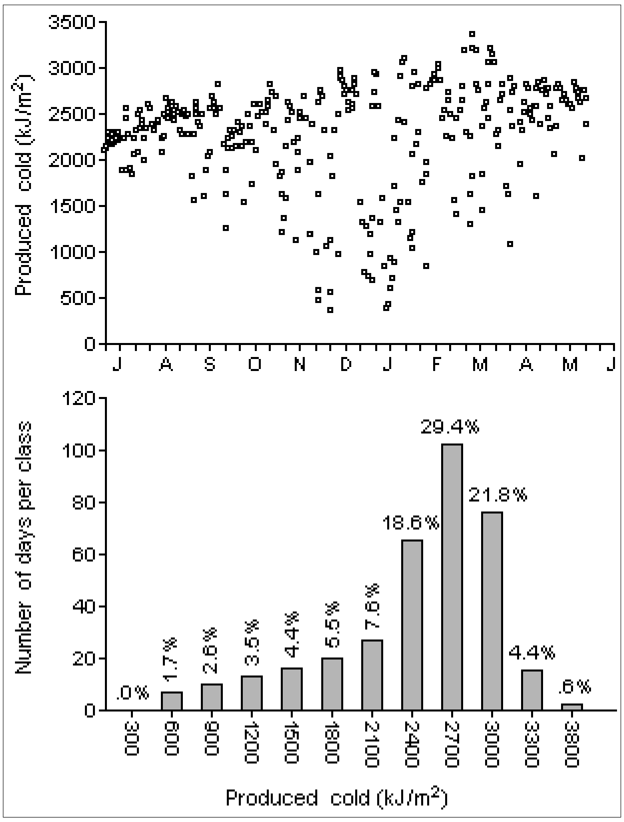
- as explained in former sub-section, the low ambient temperatures in winter ‘compensates’ the low values of insolation for the bright days, the heat extraction hardly depends on the season. For 70% of the studied days, Produced Cold lies between 2.100 and 3.00 kJ/m^2, and is higher for 5%. The average value is 2.050, minimum is 360 and maximum is 3.430 kJ/m^2.

It can be noticed that the Cold Production is always positive. But this is the Gross Cold Production. Some losses must now be accounted for e.g. thermal losses of cold store for a Refrigerator, or energy for cooling Water from ambient temperature down to 0°C for an Ice Maker.

CONCLUSION

For the present study, a special care was brought in gathering complete and accurate meteorological data all along one year. These data can be used for various simulations. A simplified model of an adsorptive solar

Figure 8: Daily cold production (kJ/m^2) and histogram (lower).



cooling unit yields reliable results. This allows optimization of characteristics of the machine and an analysis of COP's deeper than previously performed. Highest COP's are obtained during winter, showing the influence of ambient temperature on the thermodynamic efficiency of the cycle. In Robat, the Cold Production is rather regular at a satisfactory level Refrigerating machine using cycles with Active Carbon + Methanol are most probably well adapted to the climatic conditions of Rabat.

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