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A NEW SOLAR POWERED ADSORPTION REFRIGERATOR WITH HIGH PERFORMANCE

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ABSTRACT

An adsorptive solar refrigerator was built in September 2000 in Yverdon-les-Bains, Switzerland. The adsorption pair is silicagel + water. The machine does not contain any moving parts, does not consume any mechanical energy except for experimental purposes and is relatively easy to manufacture. Cylindrical tubes function as both the adsorber system and the solar collector (flat-plate, 2 m^2, double glazed), the condenser is air-cooled (natural convection) and the evaporator contains 40 litres of water that can freeze. This ice is a cold storage for the cabinet (320 litres).

The first tests (September 2000) showed very promising performance, with a gross solar cooling COP_{SR} of 0.19. After minor modifications, a second test campaign was carried out during summer 2001. This test campaign shows how the external parameters influence the machine on the COP_{SR} (irradiation and external temperature). The latter varies between 0.10 and 0.25 with a mean value of 0.16. These values are higher than the ones obtained by former solar-powered refrigerators (0.10-0.12).

This paper describes the principle of the cycle, the different components of the machine, and the test procedure. The test procedure includes a constant daily cooling requirement. The experimental results will be presented over a period of two months.

KEYWORDS

Solar energy, silicagel, water, adsorption, cooling, refrigerator, flat-plate solar collector

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1. INTRODUCTION

The concept of using solar energy for powering a refrigerator arose forty years ago [1] with a prototype using a liquid sorption cycle. Solar-powered refrigeration can also use solid sorption, either chemical reaction [2-4] or adsorption. Meunier has published a comparison of those three sorption systems for solar cooling [5]. The solid-gas system used in the present study is adsorption.

All the machines reported in the articles [6-18], either with chemical reaction or with adsorption, follow an alternative cycle heating/cooling, also known as 'intermittent', the period of which corresponds to the alternation of day and night.

Regarding performance, the highest values of COP_{SR} (0.10-0.12) were obtained with the adsorption systems zeolite + water [13] and activated carbon + methanol [9, 10, 16]. As methanol can easily evaporate at temperatures below 0°C, thus favouring the production of ice, water must be the most environmentally friendly refrigerant. With water, ice can be produced *within* the evaporator, acting as a ‘cold storage’. Both refrigerants, water or methanol, operate at under-atmospheric pressure and therefore require vacuum technology.

The main purpose of the present study is to obtain, with a technically speaking simple machine, better performances than the ones reported above. This aim seems reasonably achievable with an adsorptive machine, operated in a 100% solar-powered 24 hour cycle with flat-plate solar collector containing the adsorbent. However, when referring to the work reported above, both the efficiency of the solar collector and that of the adsorption thermodynamic cycle could be improved. These requirements lead to the design of the 'advanced' machine.

The laboratory of solar energy of the Engineering school of the Canton de Vaud (EIVD, Yverdon-les-Bains, Switzerland) has been developing adsorptive solar refrigerators since 1999. The first systems built used the adsorption pair activated carbon + methanol. For reasons of reliability and respect of the environment, this pair has been abandoned in favour of silicagel + water pair.

The solar adsorption refrigerators have been developed mainly to be used in hot regions with no electricity supply. An urgent need exists in the domain of health (conservation of medicines and vaccines). These systems have the advantage of not requiring any other energy than solar.

The prototype described and analyzed in this article has been working since the summer of 2000 on the site of the EIVD. A complete system of measurement allows us to characterise it in a complete way. During the summer of 2001, a constant procedure of thermal load in the cold cabinet allowed us to observe the behaviour of the adsorption system over a continuous period of 68 days. The coefficient of performance (COP_{SR}) and the temperature of the ice storage in the evaporator are studied according to external meteorological conditions (external temperature and daily irradiation). Previously, few articles were interested in the analysis of the storage.

2. DESCRIPTION OF ADSORPTION AND OF THE ADSORPTION COOLING CYCLE

Adsorption, alias physisorption, is the process by which molecules of a fluid are fixed on the walls of a solid material. The adsorbed molecules undergo no chemical reaction, they simply lose energy when being fixed : adsorption, the phase change from fluid to adsorbate (adsorbed phase) is exothermic. Moreover it is reversible. In the following, we will focus on adsorption systems mainly used in cooling (or heat-pumping) machines : a pure refrigerant vapour that can easily be condensed at ambient temperature and a microporous adsorbent with a large adsorption capacity.

The main components of an adsorptive cooling machine are the adsorber (in the present case, the solar collector itself), the condenser, the evaporator and a throttling valve between the last two devices, see figure 2. An ideal cycle is presented in the Dühring diagram (LnP vs. –1/T), figure 1.

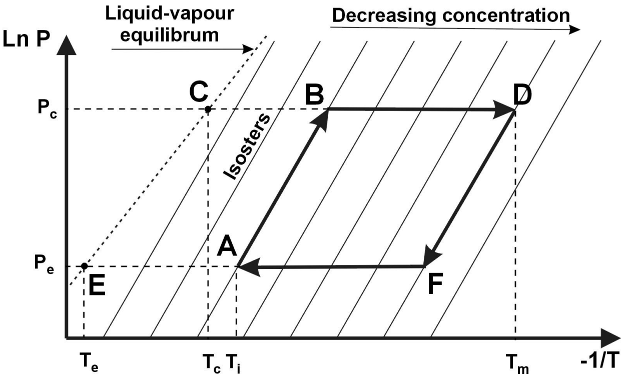

Figure 1 : An ideal adsorption cooling cycle in the Dühring diagram. Saturation liquid-vapour curve for the refrigerant (EC dashed line), isoster curves (thin lines), adsorption cycle (thick lines). Heating period : step AB (7 a.m.? 10 a.m.) and step BD (10 a.m.? 4 p.m.) ; cooling period : step DF (4 p.m.? 7 p.m.) and step FA (7 p.m. ? 7 a.m.).

The cycle is explained in detail in [19]. We can summarize it in four steps :

Step 1 : Isosteric heating (A? B ; figure 1) :
System temperature and pressure increase due to the solar irradiance.

Step 2 : Desorption + condensation (B? D) :
Desorption of the water steam contained in the silicagel ; condensation of the water steam in the condenser ; drainage of water in the evaporator through the valve.

Step 3 : Isosteric cooling (D? F) :
Decrease of the period of sunshine ; cooling of the adsorber ; decrease of the pressure and the temperature in the system.

Step 4 : Adsorption + evaporation (F? A) : Evaporation of water contained in the evaporator ; cooling of the cold cabinet ; production of ice in the evaporator ; readsorption of water steam by the silicagel.

3. DESCRIPTION OF THE MACHINE TESTED IN YVERDON-LES-BAINS, SWITZERLAND (this text derives in part from [19])

Adsorptive pair : The refrigerant is water, and the adsorbent is a microporous silicagel (*Actigel SGÒ*, *Silgelac*).

Collector-adsorber : The solar collector (2 m^2, tilt angle of 30°) is double-glazed : a Teflon film is installed between the glass and the adsorber itself. The adsorber consists of 12 parallel tubes (72.5 mm in diameter) that contain the silicagel (78.8 kg). The tubes are covered with an electrolytic selective layer (Chrome-black, *Energie Solaire SA*), which absorbs 95% of the visible solar radiation while presenting an emissivity of 0.07 in the infrared wave-lengths. The tubes are layered with a material of good conductivity but low specific heat capacity (sheets of graphite : *PapyexÒ*, *Le Carbone Lorraine*). A central tube is made out of a grid (diameter 15 mm, mesh 1 mm, wire 0.45 mm diameter). The ventilation dampers mentioned in the previous sections consist of a mechanism that allows the thermal insulation to be opened on the rear side of the collector (50 mm glass fibre), to provide efficient cooling by natural convection during the night.

Condenser : Eight parallel finned tubes make a condenser, cooled by natural convection of air. The total fin area is 6.9 m^2.

Evaporator, ice storage and cold cabinet : The evaporator consists of three rings made of square tubes. The total heat exchange area is 3.4 m^2. The evaporator contains 40 litres of water which can be transformed into ice during the evaporation step. The cold cabinet is chest-type. It is well insulated (170 mm of expanded polystyrene) and the internal volume available is 320 litres.

Valves : In the present configuration, a check valve is needed on this machine, the one located between the graduated tank and the evaporator. The other valves have been installed for experimental purposes only.

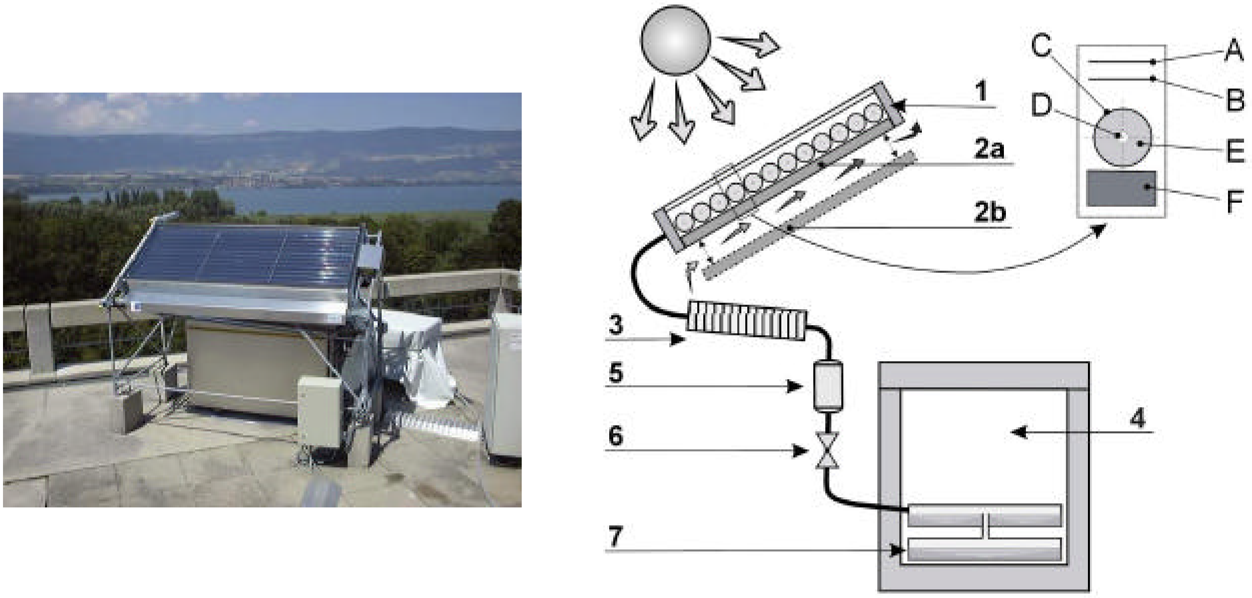

Figure 2 : Photography and scheme of adsorptive solar refrigerator : solar collector-adsorber (1) with detail : glass cover (A), teflon film (B), tube covered with selective surface (C) and internally layered with Papyexâ, central tube for vapour transport (D), silicagel bed (E), thermal insulation around the collector (F) ; ventilation dampers (2) closed (2a) and open (2b), condenser (3), cold cabinet (4), graduated tank (5), check valve (6), evaporator and ice storage (7).

4. MEASUREMENTS AND OPERATIONS

The objective of the 2001 measurement campaign is to obtain a great deal of measurements continuously in order to characterise the working of our adsorption machine. To do this, a system of measurement and a constant procedure of load was established.

4.1 Measurements

The temperature is measured (probes Pt 100) in the silicagel of a central tube of the collector-adsorber (7 sensors), on two condenser tubes and three evaporator tubes ; the ambient air temperature is also measured. The vapour pressure is measured by a piezo-gauge in the collector-adsorber, in the condenser and in the evaporator. The global irradiance in the plane of the collector is recorded by a pyranometer. A graduated tank (6.5 litres) collects the condensed water. The level of liquid water is automatically measured by a level detector.

A water bottle system in series allows a daily renewal of the load to be introduced into the cold cabinet. The total volume of these bottles is 32 litres. Three sensors (thermocouples K) measure temperature in the input, in the middle and in the output of the storage ; the temperature of the input is adjusted using a thermostatic system. A flow-meter allows the flow to be controlled. All these sensors are connected to the data acquisition unit, which also drives the daily renewal of the load.

4.2 Acquisition system and command

A Labview program takes measurements and administers various commands (valve, dampers and load). The interval of acquirements is 30 seconds.

4.3 Automatic load

In the order to simulate a thermal load in the refrigerator, every day at 1 a.m. a quantity of water is introduced, allowing to be renewed the load. The input temperature is about 35°C. The load introduced daily corresponds to 4.1 MJ. The water flow is stopped when the difference between the input and the output temperatures is lower than 0.5 K. It guarantees a good homogeneity of the temperature on the bottles.

4.4 Check valve management

Closing : when solar irradiance is above to 100 W/m^2.

Opening : when, at the end of afternoon, the difference of pressure between evaporator and condenser is lower than 100 Pa.

4.5 Ventilation damper management

Closing : when the irradiance goes above 100 W/m^2.

Opening : at the end of afternoon when the angle of incidence is above 50°.

5. METEOROLOGICAL CONDITIONS

The campaign of measurement took place from July 25th to September 30th 2001 (68 days) in Yverdon-les-Bains (altitude : 433 m, longitude : –6.38°, latitude : 46.47°). The figure 3 shows observed weather conditions (daily irradiation and mean external temperature).

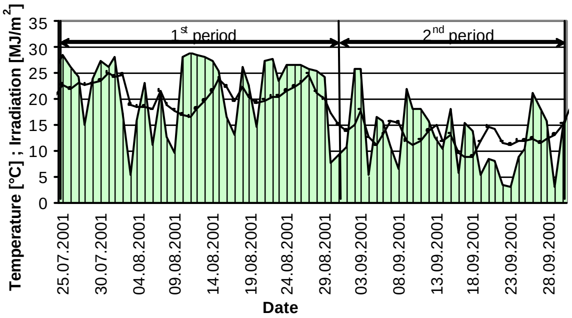

Figure 3 : Evolution of the daily irradiation and mean external temperature during campaign of measurement (from 25th July to 30th September 2001). 1st period : Summer meteorological conditions with high mean external temperature and irradiation. 2nd period : Autumnal meteorological conditions with reduced mean external temperature and irradiation.

This graph shows two different periods :

1) From July 25th to the beginning of September : during this summer period, the mean external temperature is above 20°C and the mean daily irradiation reaches 22 MJ/m^2. This fine weather period is interrupted between the 3rd and 9th August by less favourable weather.

2) From the beginning of September to the end of the measurement : the mean external temperature and the daily irradiation are distinctly lower (13°C and 13 MJ/m^2). Furthermore, the conditions are very variable from one day to the next.

6. PERFORMANCE OF THE TESTED UNIT

For each day, a gross solar COP_{SR} can be defined as the ratio of the heat extracted by evaporation of water to the solar heat supply, see equation 1. The first one, Q_e, is obtained by multiplying the mass of processed water, m_L, by the enthalpy difference between the saturated vapour at T_e and the saturated liquid at T_c. The second one, Q_h, is the product of the surface S of collector and the solar irradiation obtained by integrating the solar irradiance G from sunrise to sunset. This yields the following expression for the gross solar COP_{SR} :

$$COP_{SR} = \frac{Q_e}{Q_h} = \frac{m_L \cdot [L - Cp_L \cdot (T_c - T_e)]}{S_{fs} \cdot \int_{\text{sunrise}}^{\text{sunset}} G(t) \cdot \mathrm{dt}} \qquad (1)$$

The figure 4 presents the COP_{SR} measured during the period of measurement according to the daily irradiation. In addition, an indication of the mean external temperature is given.

This figure shows a threshold : below a daily irradiation of 7 MJ/m^2, the COP_{SR} is equal to 0. Over 20 MJ/m^2 the COP_{SR} varies between 0.12 and 0.23. This shows that the coefficient of performance varies from day to day. Furthermore, for two days with identical irradiance, the COP_{SR} is not necessarily the same. The main reason for this variation is the influence of the external temperature on the cycle. Most days situated in the zone I are characterized by a mean external temperature lower than 20°C. Most days situated in the zone II are at a temperature higher than 20°C. This intervenes several levels of the cycle :

- **At nightime** : the lower night-temperature is, the better the readsorption of water in the silicagel will be. When the readsorption is high, so is evaporation, and consequently a large amount of ice is produced in the evaporator. Furthermore, the next morning, the adsorber is in a favourable state for a good desorption during the day which follows.
- **In the daytime** : The temperature of the ambient air defines the level of pressure of condensation (P_c in figure 1). The lower the day temperature is, the lower this pressure is and the earlier in the day condensation will begin. To sum up, for two days with equal irradiation, the performance will be better for the day characterised by the lower external temperature.
- **During night and day :** the heat losses from the cold cabinet are linked directly to the external temperature.

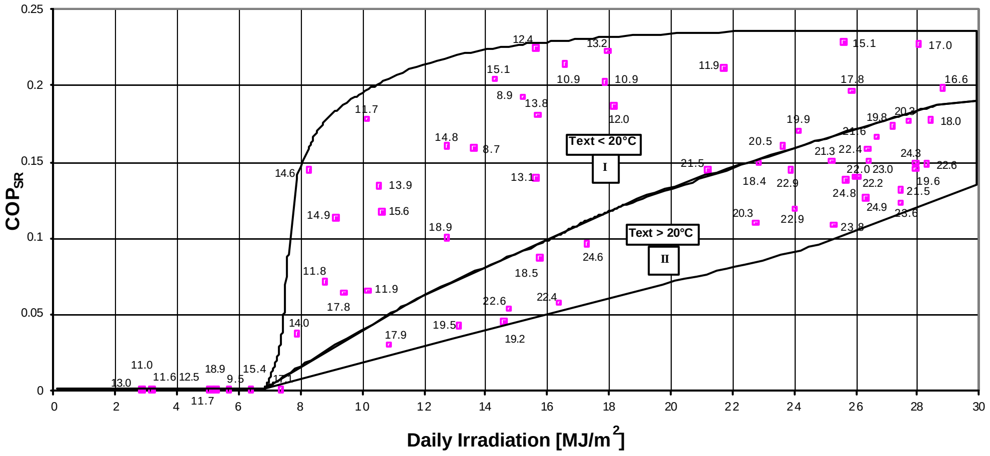

Figure 4 : Evolution of the COP_{SR} according to the daily irradiation between 25th July to 30th September 2001. The label of every point is the mean external temperature.

This variation of COP_{SR} is illustrated in the graphic of figure 5. For these few days, a decreasing COP_{SR} (0.22 to 0.10) corresponding to an increasing external mean temperature (17°C to 24°C) can be observed while the daily irradiation is almost constant. The COP_{SR} falls while the outside temperature increases.

In addition to the temperature and the daily irradiation, we could note that the state of the storage (completely, partially or not at all frozen) influences the value of the COP_{SR} of the next day.

The figure 6 shows the evolution of the temperature in the evaporator during the period of measurement.

During this period, three series of days appeared where the machine did not satisfy the demand. This resulted in the defrosting of the ice storage and the increase of the temperature in the cold cabinet.

We see that these increases in temperature do not necessarily correspond to a same sequence of non-period of irradiation. On the one hand, these variations can be explained by the evolution of the COP_{SR} as described previously (figure 5). On the other hand, we note that the load imposed daily on the refrigerator corresponds to the mean of daily net production of cold in the evaporator (equations 4 and 5). It explains the sensitivity of the system to the meteorological conditions.

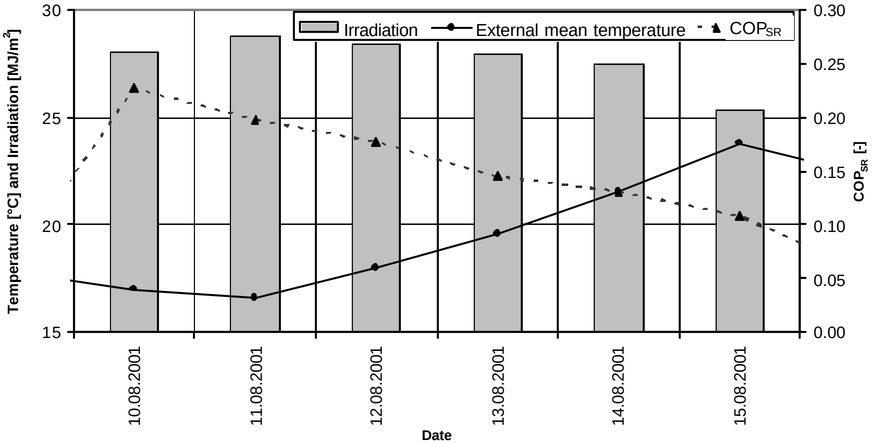

Figure 5: Evolution of the COP_{SR} according to the daily irradiation + mean external temperature between 10th and 15th August 2001.

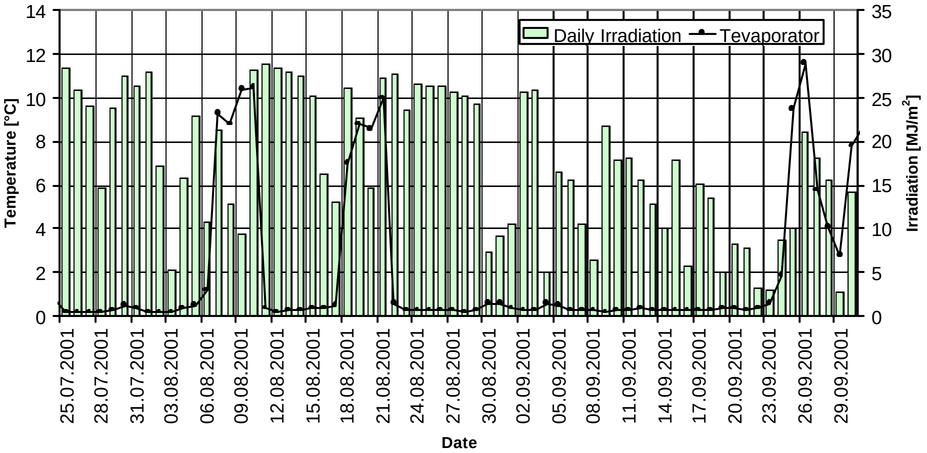

Figure 6: Evaporator temperature and daily irradiation (from 25th July to 30th September 2001).

There follow some values permitting to draw up a balance sheet of energy over a period where the temperature of the evaporator remained virtually constant from August 24th to September 22nd 2001 (30 days) :

- Irradiation Q_h : 923 MJ
- Cold energy produced Q_e : 146 MJ
- Cabinet thermal losses Q_{tl} : 26 MJ
- Load energy Q_l : 123 MJ

The difference observed between the sum of the cold cabinet thermal losses and the load energy (Q_{tl} + Q_l) and the cold energy produced (Q_e) corresponds to the variation of the ice storage in the evaporator between August 24th and September 22nd (-3 MJ/-9 kg of ice).

The rough and net COP_S can be defined :

$$\overline{COP_{SR}} = \frac{Q_{tl} + Q_l}{Q_h} = \frac{26 + 123}{923} = 0.16 \tag{2}$$

$$\overline{COP_{SN}} = \frac{Q_l}{Q_h} = \frac{123}{923} = 0.13 \tag{3}$$

The mean net production on this period is :

$$\overline{Q_e}_{24.08 \rightarrow 22.09} = \frac{Q_e - Q_{tl}}{n_d} = \frac{146 - 26}{30} = 4\,\mathrm{MJ} \tag{4}$$

and the mean load :

$$\overline{Q_l}_{24.08 \rightarrow 22.09} = \frac{Q_l}{n_d} = \frac{123}{30} = 4\,\mathrm{MJ} \tag{5}$$

It should be remembered that the load was maintained constant during the whole measurement period. This procedure did not favour the system. During a real-life use of a sun refrigerator (adsorption or photovoltaic), it is necessary to adapt the load to the meteorological conditions. In fact, when the weather are not good, the user has the choice between :

- not loading the refrigerator and losing one day of production
- loading the refrigerator and letting the temperature of the whole stock rise above the temperature desired (5-10°C), thus risking damaging the contents if the unfavourable meteorological conditions persist.

7. CONCLUSIONS

This campaign of measurement carried out over a long period reveals the influences of the meteorological conditions (external temperature and irradiation) on the performance of the system. Our adsorption solar refrigeration system presents very interesting performance coefficients ($\overline{COP_{SR}}$: 0.16 ; $\overline{COP_{SN}}$: 0.13). These values are better than other adsorptive system (the highest values of COP_{SR} (0.10-0.12) were obtained with the adsorption systems zeolite + water [13] and activated carbon + methanol [9, 10, 16]).

Our dimensioning approaches aim to store cold by freezing water during sunny days for 3 successive days with bad weather. The data presented in this paper show that we are near to obtaining this.

The meteorological conditions of the climate in which the tests took place (Switzerland) are relatively favourable. The use of such systems being essentially intended for a Sahel climate type, it is necessary to take into account the influence of the external temperature by selecting the size of the condenser and insulating the cold cabinet well. On the other hand, in these regions, the high level of daily irradiation encourages the use of the solar refrigerator based on adsorption.

Besides the developments made in Switzerland, a technology transfer to Sahel country (Burkina Faso) is to be carried out. An activated carbon + methanol refrigerator was built in 1999 in Ouagadougou for a NGO (Centre Ecologique Albert Schweitzer). It has worked well so far [20]. A new compact silicagel + water refrigerator is to be tested in summer 2002 in Ouagadougou.

We should emphasize that the behaviour of the users of a solar refrigeration system without auxiliary energy resource must be adapted to the variable solar resource.

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NOMENCLATURE

COP	Coefficient of Performance	[-]
C_p	Specific heat	$[J\cdot kg^{-1}\cdot K^{-1}]$
G	Irradiance	$[W\cdot m^{-2}]$
H	Irradiation	[J]
L	Evaporation latent heat for water	$[J\cdot kg^{-1}]$
m	Mass	[kg]
n	Number	[-]
P	Pressure	[Pa]
Q	Heat quantity	[J]
S	Surface	$[m^2]$
T	Temperature	[K]
t	Time	[s]

Indexes

c	condenser
d	day
e	evaporator
fs	collector front side
h	solar heat supply
l	load
L	liquid
m	maximum
N	net
R	rough
S	solar
tl	thermal losses (of the cabinet)
w	water