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Experimental analysis of the operation of a solar adsorption refrigerator under Sahelian climatic conditions: case of Burkina Faso

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***Abstract*—*This work is an experimental analysis of the operation of a solar adsorption refrigerator designed for the conservation of pharmaceutical products. The experiment consisted to measure incident solar radiation on the collector-adsorber, temperature of all the components of the collector-adsorber, of the condenser, the evaporator and the storage tank. Experimental results indicated that the maximum temperature of the front face of the absorbent plate varied from 70 °C to 80 °C and that of the condenser varied from 45 °C to 53 °C. The minimum temperature reached by the evaporator was + 4 °C. With a total energy received of about 19 MJ/m*^{2}*, this solar adsorption refrigeration device can provide a SCOP ranging from 0.09 to 0.185. These results demonstrate the technical feasibility of the prototype solar adsorption refrigerator that we have experimented*.
Keywords*—*Solar energy; Refrigeration; Adsorption; Experimentation; Zeolite / Water.

I. INTRODUCTION

The conservation of food and pharmaceutical products is a real problem in some regions of Burkina Faso. These different regions are not connected to the national electricity grid. This problem results from the lack of electrical energy to cover the whole country. However, Burkina Faso has a very important solar potentiel with an average irradiation between 5.5 kWh.m^{-2}.day^{-1} and 6.5kWh.m^{-2}.day^{-1}and an annual sunshine duration of 3000 hours running up to and 3500 hours [1]. Thus, solar adsorption refrigeration machines are an alternative to meet this energy problem. In fact, solar adsorption refrigeration units operate without moving parts and do not require another source of energy out of solar energy. The technology of these machines is simple, maintenance is easy and the materials used, are recyclable [2]. In addition, they use refrigerants that have no effect on the environment such as water [3-5], methanol [6-8] and ammonia [9]. As a result, several researchers have focused their work on its machines because they have several advantages and the different demands of cold coincide in most of the time with the availability of the sun [10-15].

In this article, the solar adsorption refrigerator using the zeolite-water pair is presented, described and tested under the climatic conditions of Yako, Burkina Faso. The main objective of this study is to evaluate the behavior and overall performance of the prototype. Therefore, in the first part of our work, the operating principle and design criteria are described. Then, the experimental results of a few days of operation are presented.

II. OPERATIONAL PHASES OF THE SOLAR ADSORPTION REFRIGERATOR

A solar refrigerating adsorption machine operates in a cycle. It consists in a flat plate collector containing the zeolite/water mixture and plays a role of capturing and releasing the heat. It is connected to a condenser and an evaporator. The principle of operation of these machines is based on the phenomena of adsorption- desorption of a gas (water vapor) in a solid (zeolite). This chemical reaction is exo or endothermic according to its direction of unwinding. The basic adsorption cycle for refrigeration consists of four processes represented in Fig. 1. In the first one 1–2, the adsorbent is heated by solar energy until the pressure reaches a level that enables desorption of refrigerant (state 2). During process 2–3 addition of heat from solar energy results in desorption of vapor refrigerant, which condenses in an air-cooled condenser. At state 3, when the adsorbent rises up to its maximum temperature, solar irradiance starts to decrease. The

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collector, cut off from the condenser, drops in temperature. Cooling of the adsorbent provokes a drop of pressure in the collector (process 3–4). Meanwhile, the liquid refrigerant is transferred into the evaporator. When the pressure reaches the value of the pressure at the evaporator temperature, the collector is connected to the evaporator (state 4). The adsorbent continues to decrease in temperature and pumps the liquid refrigerant, which evaporates and extracts out heat from the evaporator (process 4–1) generating a cooling process inside the chamber. The cycle is said intermittent because the evaporation–cooling process happens only during the night.

III. IMPLEMENTATION OF THE PROTOTYPE

The prototype of the solar adsorption refrigeration machine that we have experimented is installed in Yako, a village located in the province of Passoré, about 100 km far from Ouagadougou (Burkina Faso). It is located between latitudes 12 ° 90 and 12 ° 96 North and between longitudes -2 ° 17 and -2 ° 26 west. This prototype consists of a collector-adsorber, a condenser and a refrigerating enclosed containing the evaporator (Figure 2). The adsorbent / adsorbate pair used is the zeolite / water pair.

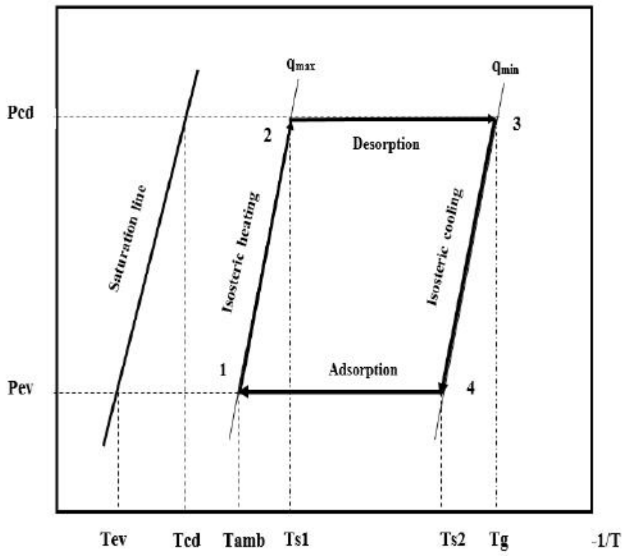

Fig.1. Theoretical cycle of an adsorption machine

Fig. 2. Photography of solar adsorption refrigerator

3.1 The collector-adsorber

The collector-adsorber is an essential element of the solar adsorption refrigerator. It is a parallelepipedic box of $1m^2$ surface and 20 cm high, closed on its upper face by a 5 mm thick glass cover. The side faces and the back face are insulated by 10 cm thick of layer of glass wool. The adsorber, enclosed in the housing, is composed of:

- 8 cm of 32 kg of zeolite in contact with thirteen (13) fins provide heat transfer between the front face and the inside of the adsorber.
- a channel of rectangular section 2 cm high, arranged between the zeolite bed and the back plate of the adsorber with a grid to allow the water vapor desorbed from the bed of zeolite of flow to the condenser through the flexible tube.

The front face of the adsorber, intended to receive the solar flux, was previously coated with a black paint of low emissivity allowing good absorption of solar radiation. The absorbed solar flux is converted into heat for heating the adsorbent (the zeolite). The collector-adsorber assembly has a tilt angle of 13° to the horizontal (Fig.3).

3.2 The condenser

The condenser consists of an aluminum tube 65 cm long, 5 mm thick and 10 cm in diameter. It has 52 fins spaced 15 cm apart. Each aluminum fin has a square shape of 20 cm of coast and thickness 1 mm. The total exchange area of the condenser is 3.5 m^2. The condenser is cooled by natural convection generated by the difference between the temperature of the outer face of the condenser wall and that of the ambient air. It is positioned in the solar refrigeration plant so that the condensate flows through one of the orifices easily under the effect of gravity towards the evaporator.

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3.3 The evaporator

It is installed in a thermally insulated cold chamber with internal dimensions 50x50x30 cm. It consists of a parallelepiped tank whose walls are insulated with 20 cm thick of layer of glass wool. It has two tubes 25 mm in diameter allowing the passage of water vapor during adsorption. The total exchange area of the evaporator is 0.7 m^2. A part of the evaporator contains a sufficient quantity of distilled water which does not participate in the cycle of the refrigerating machine. It is constantly present to form a mass of ice that serves as cold storage for the day and the periods without sun. The storage of cold latent form allows a constant evaporator temperature and very low.

3.4 Connecting accessories

The different components of the experimental prototype (the collector-adsorber, the condenser and the evaporator) are connected by connecting accessories namely: the flexible tube and the valves(Fig.4).

Fig.3. Detailed photograph of the collector-adsorber.

IV. MEASUREMENT PROCEDURE

To verify and evaluate the performance of our experimental device in a more realistic way, we tested it in the weather conditions of a city in Burkina Faso. This experimental study is based mainly on the measurements, over time, of the temperature of the components of the collector-adsorber, the condenser, the evaporator and the solar flux incident on the inclined plane of the collector-adsorber. The various tests on the solar refrigerator took place in Yako (Burkina Faso). We used (08) eight type K thermocouples placed on the various compartments of the refrigerator (glass, front and back side of the adsorber, condenser, ...). We did not introduce a thermocouple inside the adsorber for the sake of sealing. These thermocouples are connected to a data logger of the Midi Logger GL220A type thus allowing the acquisition of measurements with an accuracy of $\pm 0,5\ °C$ (Fig.5). In addition, we measured the overall illumination on the inclined plane of the adsorber sensor with a KIMO brand solarimeter ($\pm 0.38\ \mathrm{W}/m^2 °C$). Measurements were done all the day long with a timestep of fifteen (15) minutes.

Fig.4. Detailed photograph of the condenseur and the refrigerating enclosure

V. EXPÉRIMENTAL RESULTS AND DISCUSSION

5.1 Evolution of solar irradiance and ambient temperature

Figs.6-8 present the hourly evolution of the ambient temperature and solar irradiance measured during the different days of experiments. We found that the global solar irradiance increases from 6:00 h and reaches a maximum value around 12:00 h,then gradually decreases until the end of the day. The maximum value of solar irradiance varies between 750 and 830 W / m^2. Moreover for the days considered, we observe a difference in the shape of evolution during the day of solar irradiance. This difference is due to the passage of clouds and the environment of the experimental site (the shadow of the building). The maximum value of the recorded ambient temperature was approximately 38 ° C and the minimum value was 21 ° C.

Fig.5. Acquisition of experimental data.

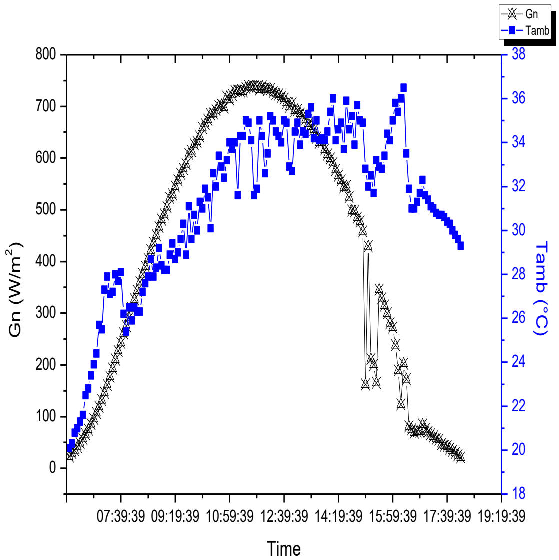

Fig.6.Evolution of solar irradiance and ambient temperature for 12/15/2016

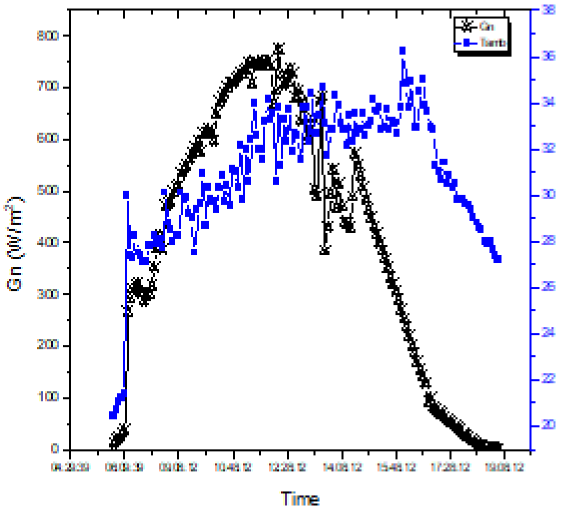

Fig.7. Evolution of solar irradiance and ambient temperature for 14/12/2016.

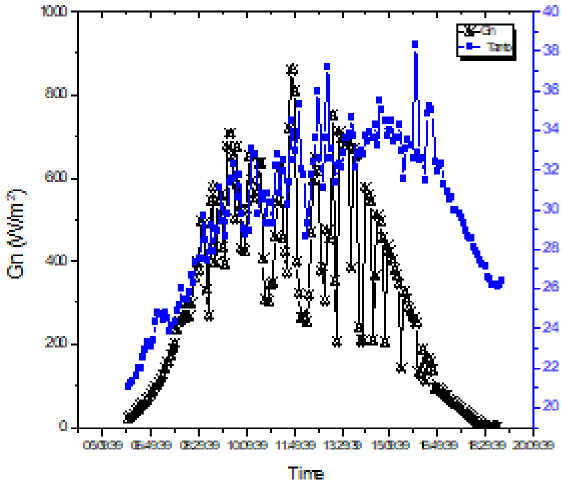

Fig.8. Evolution of solar irradiance and ambient temperature for 04/08/2016

5.2 Evolution of the temperature of the various components of the collector-adsorber

The hourlyevolution of the temperature of the various components of the collector-adsorber (glass, front and back of the absorbent plate, zeolite) are shown in Figs .9-11. Initially, the temperature of each of the components matches the ambient temperature, then they follow during the day the same shape as that of the of solar irradiance. The hourly evolutions of the temperature of the front (Tp-av) and back (Tp-ar) of the absorbent plate show that they reach a maximum value at 12:00 h,corresponding to the maximum solar irradiation of the day of 15/12/ 2016. Thus, the maximum temperature of the front face of the absorbent plat is of the order of 80 °C and 40°C for the back face. The temperature of the zeolite is assumed equal to the average of the temperatures of the front and back of the absorbent plate. Its maximum value is therefore 60 °C.

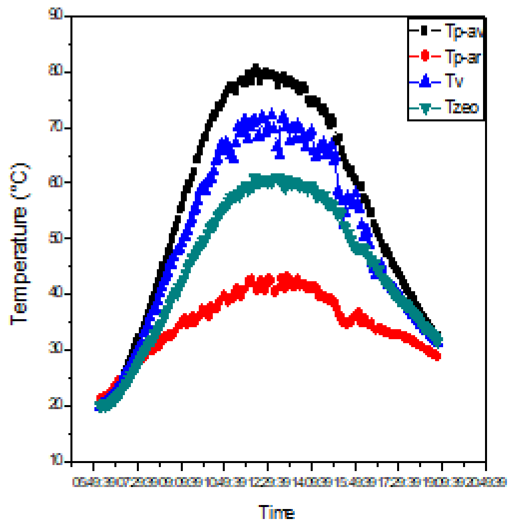

Fig.9. Evolution of the temperature of the various components of the collector-adsorber for 15/12/2016

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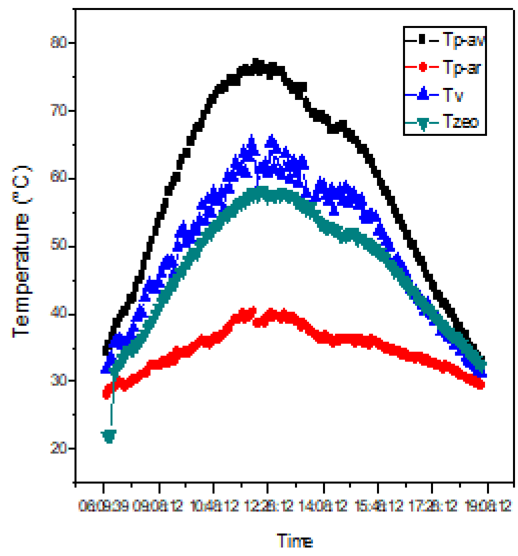

Fig.10.Hourly evolution of the temperature of the various components of the collector-adsorber during the day of 14/12/2016

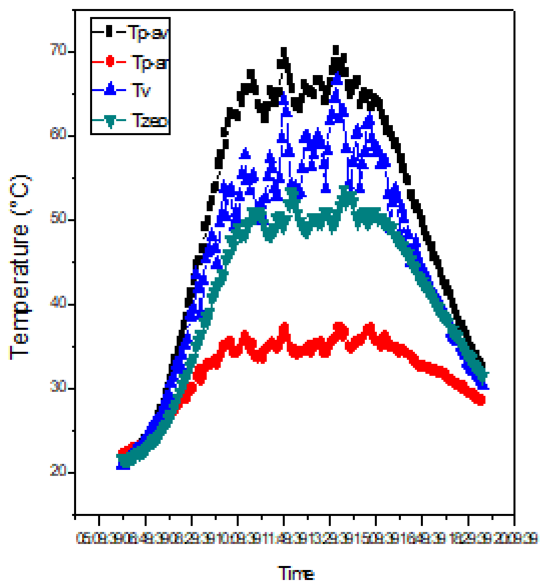

Fig.11. Evolution of the temperature of the various components of the collector-adsorber for 04/08/2016

5.3 Evolution of the condenser temperature

Figs. 12-14 show the hourlyevolution of the condenser temperature during the different days of experimentation. It should be noted that the temperature of the condenser is equal to the ambient temperature up to 9h. Then, it gradually increases over time until the maximum difference with the ambient temperature is equal to 17 ° C (15/12/2016). This increase of the temperature results mainly from the amount of heat released during the water vapor condensation on the walls of the condenser. The amount of water vapor desorbed is all the more important that the difference between the temperature of the condenser and that of the ambient is large. After 12:00 h, the temperature of the condenser decreases along with the reduction of solar irradiance. It follows that the flow rate of the desorbed water vapor decreases with time, which causes a decrease in the temperature of the condenser. At approximately 16:00 h, the hourly evolution of the condenser temperature is similar to that of the ambient temperature.

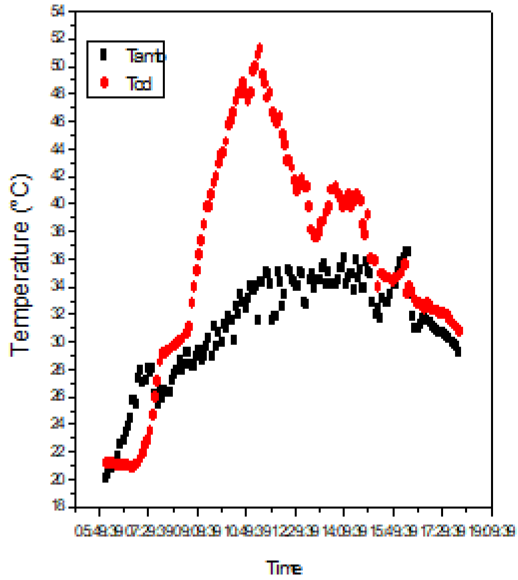

Fig.12 Evolution of the condenser and ambient temperature for 15/12/2016

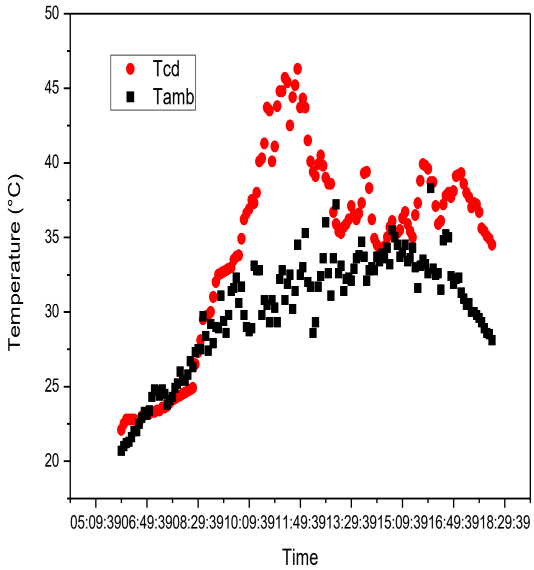

Fig.13 Evolution of the condenser and ambient temperature for 14/12/2016

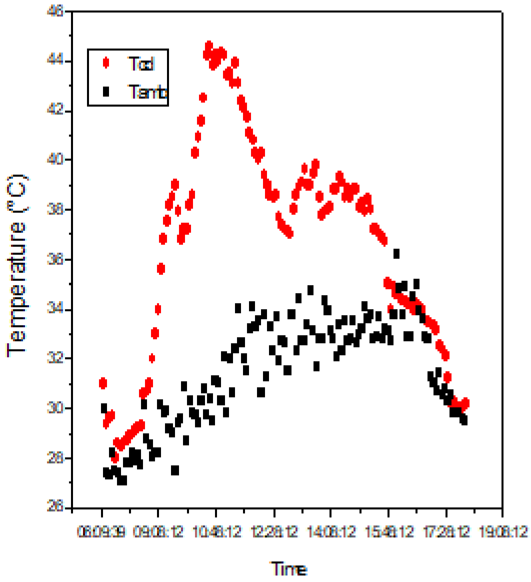

Fig.14 Evolution of the condenser and ambient temperature for 04/08/2016

5.4 Evolution of the evaporator and the storage tank temperature

We have shown in Fig. 15-17 the hourly evolution of the evaporator (Tev) and the storage tank (Tst) temperatures. We note that the hourly evolution for these two temperatures, during the test days, is similar between 18:00 h to 6:00 h. During this period, the amount of cold is produced by the evaporation of water at low pressure. The high adsorption capacity of the zeolite makes it possible to adsorb large amounts of water vapor, which allows the continuation of the vaporization of the water and thus the production of cold in the refrigerating enclosure.

The evaporator tempearture and that of the storage tank begin to decrease from 18:00 h until reaching a temperature about +4°C at about 6:00 h. However, during the day, the evaporator tempearture and that of the storage tank gradually increase until reaching maximum values of 22°C (14/12/2016). This increase of the temperature is partly due to the infiltration of air into the refrigerating enclosure and also the energy losses and the climatic conditions.

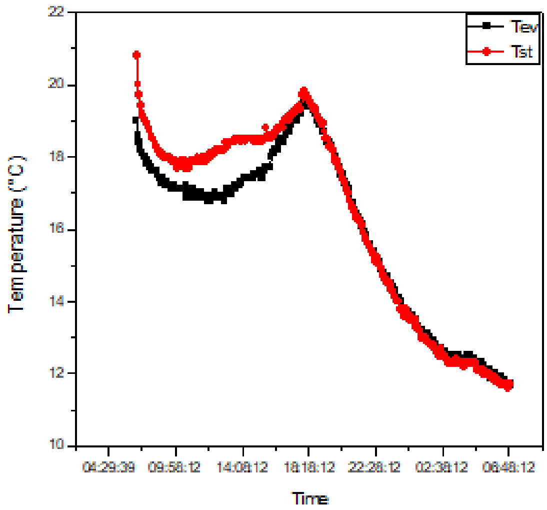

Fig.15 Evolution of the evaporator and the storage tank temperatures for 14/12/2016

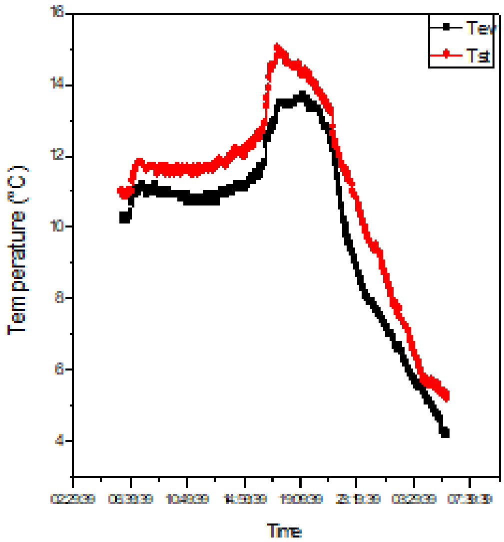

Fig.16 Evolution of the evaporator and the storage tank temperatures for 15/12/2016

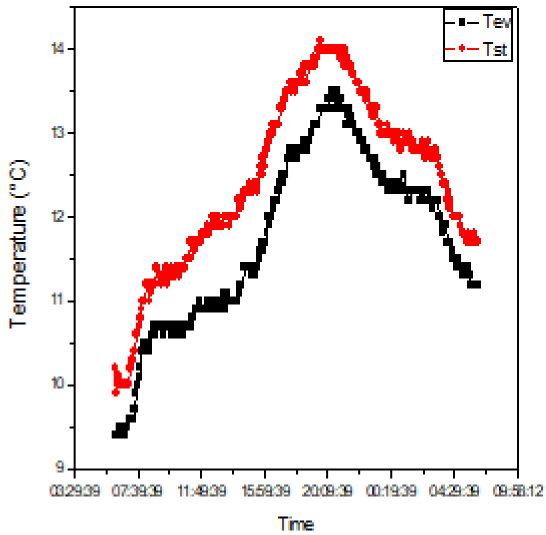

Fig.17 Evolution of the evaporator and the storage tank temperatures for 04/08/2016

VI. PERFORMANCE OF ADSORPTION REFRIGERATION SYSTEM

The thermal performance of the solar adsorption refrigerator is characterized by the solar performance coefficient (SCOP). This coefficient is the ratio between the amount of the cooling production to the heat input more precisely the total solar energy captured by the collector-adsorber during a day.

$$SCOP = \frac{Q_f}{\int_{t_{sr}}^{t_{ss}} A_s.Gn.dt} \qquad (3.1)$$

Where A_s is the collecting surface and G_n is the solar irradiation

Q_f is the amount of cold product at the evaporator :

$$Q_f = m_{ad}.\left[L(Tev) - Cp_l\left(T_{cd} - T_{ev}\right)\right] \qquad (3.2)$$

The prototype that we have experimented is not equipped with a device for measuring the cycled condensate mass during a cycle of operation of the solar adsorption refrigerator. This quantity is an important parameter because it allows the calculation of the amount of cold Q_f produced at the evaporator. Thus, we used the correlation of Errougani, A. (2007) [19] to estimate the mass of cycled condensate (m_{ad}) as a function of the ambient temperature and the incident daily solar irradiation. This correlation is given by equation (3.3):

$$\log(m_{ad}) = 2,44859 * \log\left(\frac{Gn}{Tamb}\right) - 4,0886 \qquad (3.3)$$

Where Gn is kJ / m^2 and Tamb in (K).

Table 3.1 gives the solar performance coefficient (SCOP) estimates for the different days of experimentation. The experimental SCOP of our solar adsorption refrigeration system varies between 0.09 to 0.185 and the total energy received by the adsorber-collector varies between 15 and 19 MJ. The low SCOP value obtained can be explained by the small amount of cold produced due to the small amount of adsorbed refrigerant compared to the solar thermal energy received by the adsorber collector.

Table.1: Coefficient of performance of the solar adsorption refrigerator.

Day	Solar radiation energy (MJ)	Amount of cold produced(MJ)	Evaporator temperature (°C)		Condenser temperature (°C)		SCOP
			Max	Min	Max	Min	
03/08/2016	15,519	1,40	16	11	47	26	0,09
04/08/2016	21,86	2,21	14	9,5	44	28	0,101
05/08/2016	18,15	1.87	18	8	42	25	0,103
11/12/2016	15,77	2,69	16	11	47	26	0,171
12/12/2016	15,12	2,40	14	9,5	44	28	0,158
13/12/2016	19.66	3.30	18	8	42	25	0,167
14/12/2016	21,32	3,78	21	12	45	21	0,177
15/12/2016	19,60	3,63	15	4	52	20	0,185
16/12/2016	19,66	3,30	16	6	49	23	0,167

Table.2: Comparison SCOP of some solar refrigerator adsorption system

	adsorbent/adsorbate	SCOP	Total energy received
Present experimental study	Zeolithe/water	0.09-0.185	15-20 MJ/m^2
Hildbrand et al. (2004)	Silicagel/ water	0.12-0.23	> 20 MJ/m^2.
Philippe Dind et al. (2005)	Silicagel/ water	0.19	Artificial sunshine
A.Boubakri et al. (1992)	AC/methanol	0.12	19.54 MJ/m^2
Hildbrand et al. (2005)	AC/methanol	0.09-0.13	19-25 J/m^2

We compared the obtainedresults with those of the literature (Table 3.2). We found that these values are of the same order of magnitude as in the literature [16-18] using the zeolite-water or silica gel-water pair. This validates our experimental protocol and demonstrates the technical feasibility of the solar adsorption refrigerator prototype that we used.

VII. CONCLUSION

In this paper, an experimental solar adsorption refrigerator, using the zeolite/water pair, is presented.

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Designed for the conservation of pharmaceutical products, several experimental tests have been carried out in order to test the reliability of the solar adsorption refrigeration system. Thus, the hourly evolution of the temperature of the different components of the system was presented and discussed:

- The maximum value of solar irradiance varies between 750 and 830 W / m^2. Tthe maximum value of the recorded ambient temperature was approximately 38 °C and the minimum value was 21 °C.
- The maximum temperature of the front face of the absorbent plat is of the order of 80 °C and that of the back face is 40°C. The temperature of the zeolite is maximum value is therefore 60 °C.
- The temperature of the condenser reaches a maximum temperature of 52 °C and that of the evaporator, a minimum temperature of 4 °C.

The SCOP of the solar adsorption refrigeration system varies between 0.09 to 0.185 and the total energy received by the adsorber-collector varies between 15 and 19 MJ.

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Nomenclature

Cp	Specific heat (J/kg.K)
Gn	Solar radiation (W/m^2)
m	mass (kg)
Q_f	Cold production (J)
q	Water concentration inside the zéolithe (kg/kg)
A	Area (m^2)
L(T)	Latent heat of vaporization (J/kg)
T	Température (K)
P	Pressure (Pa)

Indexes

amb	ambient
zeo	zeolite
ev	evaporator
cd	condenser
v	glass
p	plaque
st	storage
t	Time (s)
g	generation
ad	adsorbent

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