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Design and Analysis of a Solar Refrigeration System with a Rotating Generator

K. Bouhadef, S. Chikh, A. Boumedien, and A. Benabdesselam

Abstract**—**A solar refrigeration system based on the adsorption-desorption phenomena is designed and analyzed. An annular tubular generator filled with silica gel adsorbent and with a perforated inner cylinder is integrated within a flat solar collector. The working fluid in the refrigeration cycle is water. The thermodynamic analysis and because of the temperature level that could be attained with a flat solar collector it is required that the system operates under vacuum conditions. In order to enhance the performance of the system and to get uniform temperature in the silica gel and higher desorbed mass, an apparatus for rotation of the generator is incorporated in the system. Testing is carried out and measurements are taken on the designed installation. The effect of rotation is checked on the temperature distribution and on the performance of this machine and compared to the flat solar collector with fixed generator.

Keywords**—**Refrigeration cycle, solar energy, rotating collector, adsorption, silica gel.

I. Introduction

THE Humanity is facing a challenge of major importance. Its development and its evolution depend on a critical factor: the Energy. This last is mainly extracted from fossil fuels, which has many advantages, but unfortunately also many disadvantages including the long-term availability and more pollution and emissions of greenhouse gases.

Referral to other safer alternatives in terms of resources and in terms of environmental impacts is required. Alternatives commonly called renewable energy, including solar energy, which comes from an inexhaustible source, without any peril on the environment. Clean energy in short.

Algeria is a country that has very large potential solar energy. It is therefore important to develop the exploitation of this deposit, particularly in the field of cold production, intended for remote rural areas. For countries in the developing world, with a favorable sunlight, especially in areas without electricity, solar refrigeration with adsorption machines seems a promising way to improve living conditions in terms of health and economic as that:

- Reduction of wastage of food resources. Indeed, foodstuffs (meat, milk, eggs ...) can rot on the scene, because of the lack of storage conditions (refrigeration).
- Improvement of fish farming in rural coastal areas.
- Preservation of pharmaceutical products.

K. Bouhadef, S. Chikh, A. Boumedien, and A. Benabdesselem are with LTPMP Laboratory in the Mechanical and Process Engineering Faculty, University of Sciences and Technology Houari Boumediene, BP 32, El Alia, Bab Ezzouar, Algiers, Algeria (e-mail: kbouhadef@usthb.dz, schikh@usthb.dz, aboumedien@usthb.dz).

In addition to proper adaptation of this type of cooling, this technology has several advantages such as:

- It operates without any moving parts, with no noise
- It uses refrigerant (either ammonia, water or alcohols) whose the degree of environment pollution is weak
- Its maintenance is easy and simple
- Materials for its manufacture can be recycled.
- This type of system allows reaching storage temperature close to zero.

Studies undertaken on such systems have often been conducted on the case of plane or cylindrical static collectors. A literature review allowed us to retain the few following studies: Thus, Meunier, [1], [2], a pioneer in the field of adsorption, and his team [3], have analyzed theoretically and experimentally the couple zeolite-water, and showed that this couple is the most suitable for obtaining temperatures near 0°C. His team conducted some experimental studies as a solar cooler volume of 150 liters with a collector surface equal to $0.8m^2$, containing 23kg of zéolithe13X [4]. The average amount of ice produced in the evaporator was 7.5kg per m^2 of collector. The obtained coefficient of solar performance solar is of the order of 0.1.

Sakoda et al. [5] developed an experimental prototype using the silica gel-water pair. The collector was $0.25m^2$ of surface and 5cm of thickness, containing 1kg of silica gel. The unit was able to achieve a COP of 0.2 for heat on a clear solar day, equal to 19.3 MJ per m^2. According to this author, the thermal COP can reach 0.4 for a $0.4m^2$ of solar collector.

Turgut and Onur [6] have performed an analysis of heat transfer by convection above a flat solar collector. The study was both theoretical and experimental. The conclusion was among other things that the often used correlations to simulate heat losses due to the wind are not suitable and are to review and refined.

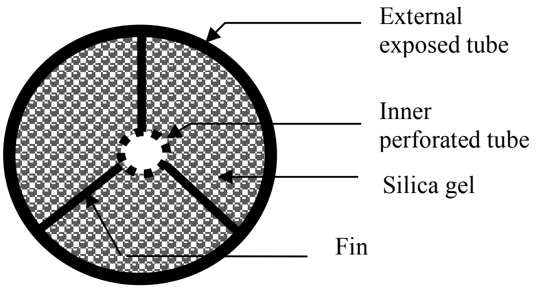
Otherwise, Al Mers and Mimet [7] simulated the performances of a cylindrical reactor contained in a flat solar collector using the adsorption principle with activated carbon-ammonia pair in a cooling loop. The obtained results obtained from the experimental data and the numerical simulations showed that introducing 5 or 6 fins can considerably increase the performances of the system.

The present study is undertaken for the design and realization of a solar collector using adsorption and the silica gel/water couple for supplying a refrigerant loop. Its performances are tested under actual weather conditions.

The development of this technology is a great initiative for countries with a large solar field. This will reduce the dependence on fossil fuels, protecting the environment and especially to allow the availability of refrigeration in remote areas and areas not supplied by electrical energy.

II. Physical Model and Thermal Load Calculation

The generator which has been designed is constituted by two concentric tubes forming an annular finned duct containing the silica gel. The outer tube receives the solar flux and the inner tube is perforated in order to collect the desorbed fluid (Fig. 1 (a) and 1 (b)).



(a)

(b)

Fig. 1 The generator section (a) Scheme of the section (b) View of the section on the realized device

The chosen adsorbent is silica gel (SiO_{2n} H_2O), which has great potential for water adsorption (400g/kg). It is widely used in solar cooling for the many benefits it offers, especially the fact that it has no harmful effect on the environment.

Cold quantity Qe produced at the evaporator is given by:

$$Q_e = M_{sg}.\Delta m.\left[L(T_e) - \int_{T_e}^{T_C} c_{pl}(T)dT\right] \quad (1)$$

where: L (T) and Cpl (T) are, respectively, the latent heat of vaporization and the specific heat of the adsorbate in the liquid state. Msg is the mass of the solid adsorbent contained in the adsorber. Δm is the mass of the cycled adsorbate, calculated as:

$$\Delta m = m_{max} - m_{min} = m\,(Ta, Pe) = m\,(Tg, Pc)$$

m_{max} is the adsorbed mass corresponding to the adsorption temperature Ta and the evaporation pressure Pe (Fig. 2). m_{min} is adsorbed mass corresponding to the regeneration temperature Tg and the condensation pressure Pc (Fig. 2). m_{max} and m_{min} are calculated by mean Dubinin-Astakov equation:

$$m(T,P) = X_0 \exp\left[-D\left(T\, Ln\frac{P_s}{P_v}\right)^n\right] \quad (2)$$

with: $X_0 = 0.35$ and $D = 6 \cdot 10^{-6}$

Results for two regeneration temperatures are shown on Fig. 6.

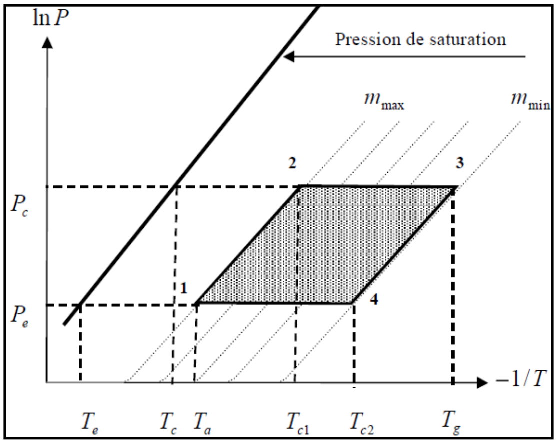


Fig. 2 Theoretical loop of adsorption

In a conventional achievement of such a generator, with static tubes, there is a heating which takes place only on the upper part of the tube exposed (directed) towards the sun, the lower part is not reached by the solar rays.

Due to fact that the heat distribution is not uniform around the circumference of the tube, and to remedy this, the suggestion is to provide a dynamic system where the tubes will be driven by a rotational movement.

This system will thus consist of two parts: a rotating part that includes collectors (tubes) exposed to the sun and a fixed part comprising the remaining components of the refrigeration system (condenser, evaporator ...).

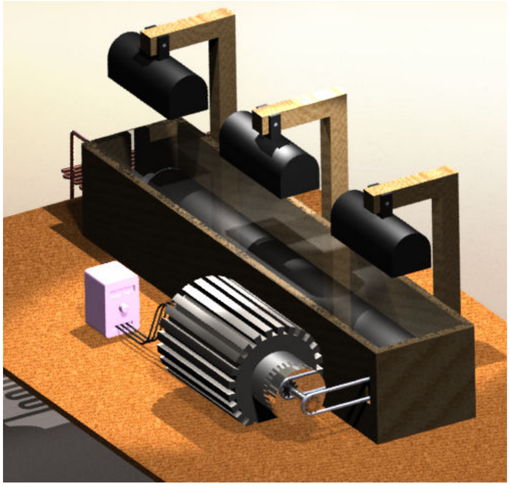


Fig. 3 Design with the rotating system and artificial lighting for the case of one tube

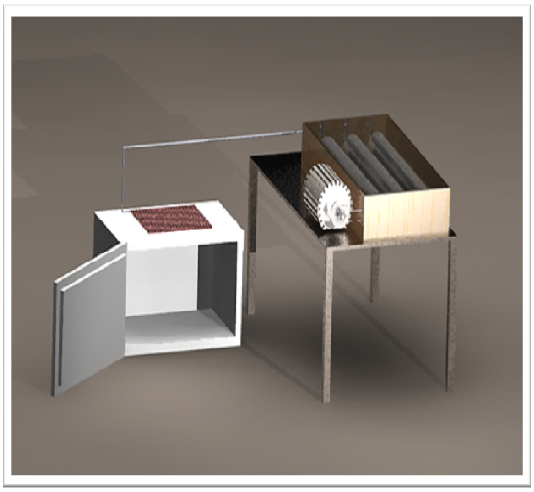


Fig. 4 Design of the apparatus with three rotating tubes

Otherwise, as the solar radiation received by the generator does not allow reaching very high temperatures, its operation requires the creation of a rather pushed vacuum into the system.

Such a system can offer, at first glance, better heating tubes, but it is still not without difficulties. The assembly of the fixed and rotary parts is very difficult because we have to prevent ingress of air into the system where the pressure should not exceed 10^{-3} bar.

In order to size the generator, calculating the load (cooling demand) is needed first. Indeed, this is what will determine the required mass of silica gel.

The refrigerated enclosure is a 60 litres box we want to cool to a temperature of 6°C. The calculation will be based on the cooling of various products (medicines, meat, drinks...) of different masses, from ambient temperature of about 30°C.

Fig. 5 View of the various elements of the realized apparatus for the case of one tube

III. Results

We present in what follows some results obtained during the experimental study.

Thus, Fig. 6 gives the influence of the silica gel mass on the cold quantity as calculated from (2).

As the value of the required load has been estimated by simulation to 2900 KJ with Tg= 80°C, so the corresponding mass of silica gel to use is about 25 Kg.

The experiences then focused on the influence of the rotating velocity on the temperature field.

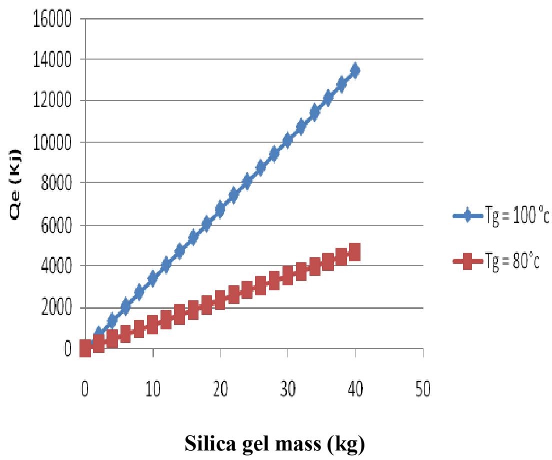


Fig. 6 Heat loads depending on the adsorbent mass

First, comparative graphs are presented below for the temperature value in the housing box (Fig. 7).

In this figure we can see that the temperature in the box where is enclosed the rotating tube is inversely proportional to the velocity of rotation, that is to say, the more speed, the slower is the evolution of temperature and inversely. This is due to movement of the tube that applies an effect of ventilation and therefore slower heating. However we find that whatever the speed of the tube, the temperature value will stabilize at a same value of about 57 ° C.

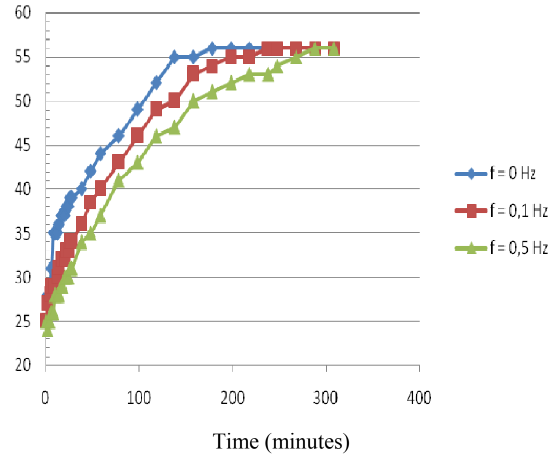


Fig. 7 Influence of the rotational velocity on the temperature evolution in the housing box

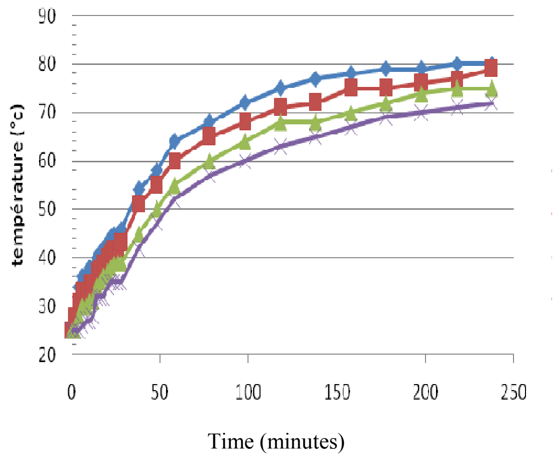


Fig. 8 Influence of the rotational velocity on the temperature evolution in the generator tube

The evolution of the temperature in the tube varies as a function of the rotational speed as shown in Fig. 8. The curves with squares and triangles corresponding respectively to the rotation frequencies of 0.1 Hz and 0.5 Hz show that the change in temperature is inversely proportional to the velocity of rotation. In addition, compared to the case without rotation, (curve with rhombuses corresponding to the high side of the tube and curve with crosses corresponding to bottom side) the temperature seems to be at an intermediate value, which suggests that the distribution in the product inside the tube is more uniform.

Moreover, if we observe the maximum value for the case at low velocities, for example, we see that it is of the same order of magnitude as that achieved for the static case. In the latter case, the temperatures were measured at the above of the tube (exposed to the heat source) and at the bottom of the tube (unexposed part).

The examination of the results shows that the upper heated faster and better compared to the lower part and to the other cases (dynamic). But, the difference being of the order of ten degrees, this suggests that the contribution of the product part located in the lower half of the tube would be less efficient.

These observations seems to go in the same way as our predictions which provide that the rotation will improve the uniformity of the thermal field in the silica gel contained in the tube and, therefore, improve the efficiency of the system.

IV. Conclusion

The aim of this work was the realization of a solar porous medium collector using the silica gel-water pair for supplying a cooling loop.

A preliminary study on the design has lead to the selection of a device that appeared to contribute to a potential improvement of performances of such systems.

The design of the installation has been made on the basis of thermodynamic data and constraints on the considered load.

The collecting system, designed and realised, is a set consisting of a housing box containing a tube filled with the adsorbent medium and adapted to operate under vacuum. Indeed, the sensor being called to receive solar radiation is to achieve very high temperatures, its operation requires the creation of a vacuum rather pushed. The generator tube is then adapted to a rotation to allow a uniform distribution of the solar flux over its entire thickness, and hence a greater contribution of the adsorbent product.

Thus, after completion of the installation, some of the thermal field surveys were conducted to verify the feasibility of the experiment and confirm the validity of assumptions, namely more uniform temperatures by the effect of a low turnover, which could mean better performance when the operating conditions are better controlled.

Acknowledgment

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