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Optimal Design Study of Tubular Adsorber for Solid Adsorption Solar Cooling Machine Working with Activated Carbon–Methanol Pair

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Abstract : This paper presents the study of a tubular adsorber of solar adsorption cooling machine. The modelling and the analysis of the adsorber are the key point of such studies, because of the complex coupled heat and mass transfer phenomena that occur during the working cycle. The adsorber is heated by solar energy and contains a porous medium constituted of activated carbon AC-35 reacting by adsorption with methanol.
The simulation technique takes into account the variation of ambient temperature and solar intensity along a simulated day, which is corresponds to a total daily insolation of 26,12 MJ/m^2 and an average ambient temperature of 27.7 °C. The obtained solution allows to know the daily thermal behaviour of the tubular adsorber.The dimensioning of the solar reactor (internal adsorber radius and collector surface area) is done after an optimization study. It has been found that the solar and the thermal performance coefficient of the system are 0.135 and 0.308, respectively.

Keywords: Solar refrigeration machine; Adsorption; Heat and mass transfer; Activated carbon AC-35/methanol; Numerical simulation.

1. Introduction

Since the Montreal protocol called for a ban on the use of CFCs, the research efforts have been increased over the last twenty years on the development of refrigeration technologies which address the environmental concerns of Ozone layer depletion and global warming. Solar adsorption cooling machines constitute very attractive solutions. They are of significance to meet the needs for cooling requirements such as air conditioning, ice-making, and medical or food preservation in remote areas far from electric grid.

Compared with the electric driven vapor compression refrigerator systems, these machines are advantageous because: They are noiseless; They usually employ environmentally friendly substances as refrigerant, such as water, methanol and ammonia; They operate with no moving part; No compression work. They are also advantageous if they compared with the absorption systems, mainly because: Their cycle is intermittent, which is well adapted to solar energy; The adsorbent bed can be implanted directly in the solar collector; There is no need for circulation pump or rectifier; They can drive by low temperature heat sources, which can be provided by solar energy with single solar flat plate collector. Although, the adsorption solar cooling systems have all the advantageous discussed above, certain drawbacks have become obstacles for its real applications and commercialization, such as: The discontinuous operation of the cycle;The large volume and weight relative to traditional refrigeration systems; The low coefficient of performance [1-3] and The long cycle time.

The adsorber is the most important component in an adsorption cooling systems and the enhancement of heat and mass transfer inside it is the most important factor to improve the performance of such systems. Thus, great efforts have been made to investigate the transfer occurring in the adsorption and desorption process.

The model presented in this study simulates a transitory behaviour of the solar reactor (adsorber). For this purpose a mathematical model based on uniform pressure and non uniform temperature distribution inside the adsorbent bed has been developed, using the meteorological data of Constantine. Moreover, to find the optimum geometrical parameters of the adsorber (internal adsorber radius and collector surface area), which maximize the performance machine, we used COP_{th} and COP_s as an optimization criteria.

2. System description and working principle

The solar refrigeration system presented in this study consists of the following main elements (Figure 1):
solar collector, condenser, evaporator, receiver and valves establishing the link between the different components (Vc, Ve, throttling valve).

The adsorptive reactor coupled to the solar collector which has 1m^2 surface area (Figure 2), consists of transparent single glass cover, lateral and rear insulation in order to limit the thermal losses, and 8 connected parallel copper tubes, where the total sum of external diameters tubes is equal to 1 m.

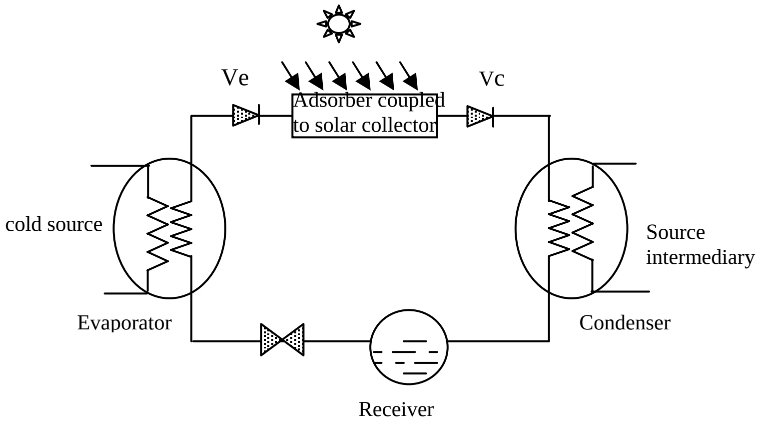

Figure 1: Schematic diagram of simple solar adsorption machine

These tubes are coated with a selective painting to allow a good absorption of solar radiation and low emission. The porous medium consists of a fixed cylindrical bed of activated carbon grains reacting by adsorption with methanol. It is packed in the annular space between two coaxial tubes. Consequently, the size of adsorbent bed in each tube is defined by (R_2-R_1) and L_t, corresponding to 4,8 kg of activated carbon in each tube and 38,4 kg in all tubes. The inner tube is perforated in order to ease the flow of methanol into and out from the activated carbon granules and to avoid pressure drops and temperature differences along the tubes.

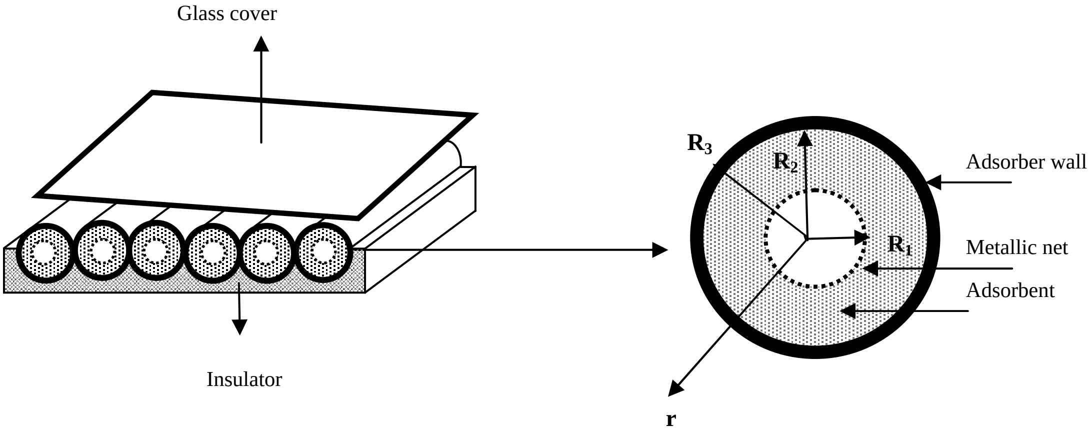

Figure 2: Scheme of the adsorptive reactor coupled to the solar collector

The principle working of the basic cycle associated to this kind of machines is represented in the Clapeyron diagram (Figure 3). Theoretically, the cycle consists mainly of four phases:
Pressurization process at a constant adsorbed mass (isosteric heating phase), desorption at constant pressure (isobaric heating phase), depressurization at constant adsorbed mass (isosteric cooling phase), and adsorption at constant pressure (isobaric cooling phase). At the beginning of the day, point 1, the adsorber is isolated from both the condenser and the evaporator by valves Vc and Ve (Figure 1), and it is completely charged with the porous medium. The pressure inside the adsorber initially equals the evaporator pressure P_e, and the temperature is uniform and equals the ambient temperature at sunrise (or the adsorption temperature T_a). When the adsorber starts to heat up by the incident solar radiation, both pressure and temperature inside the adsorbent bed are elevated along the isoster, but the adsorbed mass remains constant at m_{max}. The adsorber still isolated until the pressure reaches the condenser pressure at point 2 (the temperature reached known as the critical temperature of desorption T_{c1}). The valve Vc is opened and the adsorbate starts to desorb and flow towards the condenser, collected in a receiver. During this isobaric heating phase, the temperature continues to increase, and

the adsorbate mass continues to decrease as more adsorbate is being freed from the adsorber. When the adsorbent temperature reached the maximum value $\mathrm{T_g}$ at point 3, the valve Vc is closed and the adsorber starts the cooling phase. When the solar flux decreases, the adsorber is cooled down along the isoster at a constant adsorbate mass $\mathrm{m_{min}}$, till the pressue inside the adsorber decreases to the evaporator pressure $\mathrm{P_e}$ (point 4). The temperature reached known as the critical temperature of adsorption $\mathrm{T_{c2}}$. The last phase of the cycle starts at night. When the valve Ve is opened and the adsorber is connected with the evaporator, both adsorption and evaporation occur, the adsorbent is cooled from point 4 to point 1, the adsorbed mass increases to $\mathrm{m_{max}}$ at point 1, and the adsorbent cools to the adsorption temperature $\mathrm{T_a}$. During this phase the cold is produced.

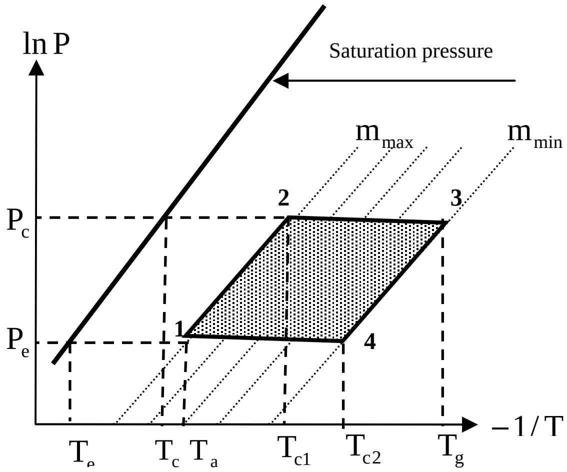

Figure 3: Clapeyron diagram of ideal solid adsorption cycle

3. Solar intensity and ambient temperature

In order to simulate the system in more realistic manner, the solar intensity and ambient temperature are modelled in this study as variant along the day (hypothetical clear day). These meteorological conditions are taken for Constantine region, which is situated at the north- east of Algeria, at 6°,37’ East (longitude) and 37°,17’ North (latitude), with an average altitude of about 625 m [4].

The solar intensity is assumed to vary sinusoidally from sunrise to sunset according to:

$$G(t) = G_{\max} \sin\left(\frac{\pi\,\theta}{D_j}\right) \quad (1)$$

Where, $G_{\max}$ is the maximum solar intensity occurring at solar noon; D_j is the length of the day and θ is the difference between the time of the day (at a given instant) and the sunrise time in hours.

The total solar intensity G_{tot} per $1\,\mathrm{m}^2$ of collector area is obtained by:

$$\mathrm{G_{tot}} = \int_{\mathrm{Sunrise}}^{\mathrm{Sunset}} \mathrm{G(t)\,dt} \quad (2)$$

The ambient temperature is calculated by the following equation [4]:

$$T_{amb} = \frac{\left(T_{\max} + T_{\min}\right)}{2} + \frac{\left(T_{\max} - T_{\min}\right)}{2} \sin\left(\frac{\pi\,(t-8)}{D_j}\right) \quad (3)$$

Where, $T_{\max}$ and $T_{\min}$ are the maximal and minimal daily temperatures.

The distribution of the solar intensity and ambient temperature during a whole day is shown in figure 4. This simulated day corresponds to a total daily insolation of 26,12 MJ/m^2 and an average ambient temperature of 27,7 °C.

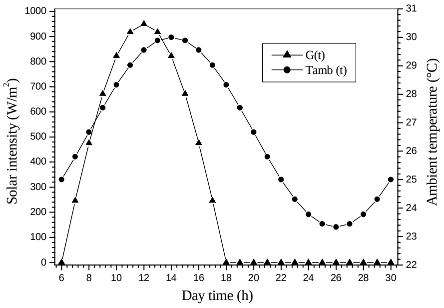

Figure 4: Variation of climatic data with the day time

4. Mathematical model and performance analysis

In order to analyse the evolution of the heat and mass transfer process in the adsorbent bed, which is the heart of the system, and to identify the parameters that influence the system performance, a simplified mathematical model has been developed using the following assumptions:

- The thermodynamic equilibrium of the adsorbent / adsorbate system is verified in all points of the adsorber and any given moment;
- The diffusion occurs only in the gaseous phase;
- The resistance to mass diffusion though the interparticle voids and the pore is neglected;
- The adsorbate –adsorbent system is treated as a continuous medium for the thermal conduction effect;
- The pressure is assumed to be uniform in the reactor (grad p = 0);
- The convection effects within the porous bed are negligible;
- In the adsorption-evaporation and desorption- condensation phases, the vapour pressure equals the saturation pressure at the evaporation and condensation temperature, respectively.

For the adsorbent layers, the heat transfer is governed by the one dimensional Fourier equation including the heat source term of sorption [5]:

$$\rho_2\left(cp_2 + m\ cp_1\right)\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \rho_2\, q_{st}\,\frac{\partial m}{\partial t} \quad (4)$$

The mass source term is obtained from the state equation of the bivariant solid-vapour equilibrium using Dubinin- Astakhov model, which is expressed as [34]:

$$m = w_0\,\rho_1(T)\exp\left[-D\left(T\ln\frac{P_s(T)}{P}\right)^n\right] \qquad (5)$$

Q_f is the cooling power, which can be written as:

$$Q_f = m_a\,\Delta m\left[L(T_e) - Cp_1(T_c - T_e)\right] \qquad (6)$$

The performance of the adsorption cooling system considered in this study is evaluated by two performance factors, such as the solar performance coefficient COP_s and the thermal performance coefficient COP_{th} .

The solar performance coefficient COP_s is calculated as the ratio between the cooling production and the total daily solar energy absorbed by the collector during the whole day.
It is given by:

$$COP_s = \frac{Q_f}{A\displaystyle\int_{sunrise}^{sunset} G(t)\,dt} \quad (7)$$

Where, A is the total solar collector area.

The thermal performance coefficient is defined by the ratio of cooling production Q_f, to the heat Q_c necessary for heating the full solar reactor to the maximum temperature T_g, taking into account the necessary heat for methanol desorption:

$$COP_{th} = \frac{Q_f}{Q_c} \quad (8)$$

The heat Q_c is given by:

$$Q_c = \sum_i \int_{T_a}^{T_g} m_i \, Cp_i \, dT + Q_{des} \quad (9)$$

Q_{des} is the necessary desorption heat of methanol.

5. Numerical results and discussion

The numerical tool developed computes for each value of the solar collector area ranged between 1 and 10 m^2, the variation of the thermal pe!rformance coefficient COP_{th} and the solar performance coefficient COP_s. The figure 5 shows these variations. It can be observed from this figure that both COP_{th} and COP_s decrease with an increase in the solar collector surface area. Accordingly, it results that the best performances ($COP_{th} = 0{,}308$ and $COP_s = 0.135$) correspond to a solar collector area of 1 m^2. This result is used for the optimization study of the internal adsorber radius R_2. The internal adsorber radius R_2 is an important parameter for system optimization. Its influence on the system's performances for values in the range 25 mm-105 mm is depicted in figure 6. It can be seen, that the solar performance coefficient COP_s increases with the internal adsorber radius in all the range 25 mm-105 mm. While, the thermal performance coefficient COP_{th} increases as long as the internal adsorber radius R_2 is less than 60 mm. moreover, increasing the internal adsorber radius R_2 to more than 60 mm, the COP_{th} decreases.

This tendency reflects the fact that the required amount of methanol is desorbed at this optimal value of radius and beyond this value the energy consumed by the adsorber increases only the sensible heat of its components (adsorbent, adsorbate and wall adsorber) and doesn't contribute to the desorption.

On the other hand, the increase in the internal adsorber radius involves an increase of the adsorbent mass. As we know, for a larger adsorber radius (bed thickness), there are more adsorbent in the adsorber and consequently more adsorbate can be cycled in the cycle. Finally, we can say, for the given system that, a maximum COP_s of 0.135 and COP_{th} of 0.308 are achieved for an internal adsorber radius of 60 mm correspond to a solar collector area of 1 m^2.

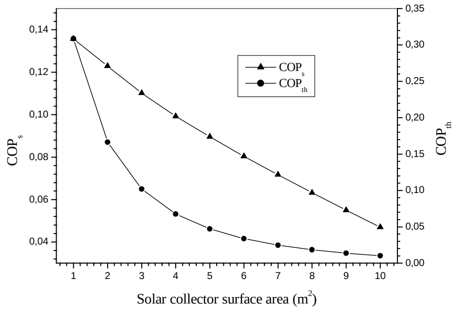

Figure 5: Effect of solar collector area on the system's performances

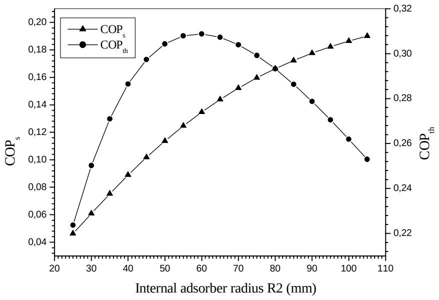

Figure 6: Effect of internal adsorber radius on the system's performances

6. Conclusion

A theoretical model and a numerical program have been developed in order to evaluate the performance of the adsorption cooling system powered by solar energy. The system uses the activated carbon AC-35/methanol as a working pair. The ambient and solar radiation time variations are taken into account. A uniform pressure and non uniform temperature model is proposed, in order to describe the behaviour of heat and mass transfer in the adsorbent bed. This model used the state equation of the bivariant solid- vapour equilibrium, using the Dubinin-Astakhov model. The obtained equation set is solved by a fully implicit finite difference method using a meteorological data of Constantine for a hypothetical clear day.

The performance of the system considered in this study is evaluated by two performance factors, such as the solar performance coefficient $\mathrm{COP_s}$ and the thermal performance coefficient $\mathrm{COP_{th}}$.

Through the analysis of the prediction results a number of conclusions can be drown as follows:

- The solar collector surface area plays an important role in determining the performance of the system. Both COP_{th} and COP_s decrease with an increase in the solar collector area.
- For a fixed condition of functioning, the thermal performance coefficient presents a maximum for an optimal internal adsorber radius tube per square meter of collector surface area. This implies the existence of the optimal dimensioning of the solar reactor.

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