Dynamic model of heat and mass transfer in rectangular adsorber of a solar adsorption machine

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Abstract. This paper presents the study of a rectangular adsorber of solar adsorption cooling machine. The modeling 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. To study the solar collector type effect on system’s performances, the used model takes into account the variation of ambient temperature and solar intensity along a simulated day, corresponding to a total daily insolation of 26.12 MJ/m² with ambient temperature average of 27.7 °C, which is useful to know the daily thermal behavior of the rectangular adsorber.

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 are 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, some 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. The influence of the type of solar collector on the system’s performance is also discussed using \( \text{COP}_\text{s} \) (solar performance coefficient) as an optimization criteria. The effect of the adsorbent mass, solar collector area and total solar radiation is also discussed.

2. Solar intensity and ambient temperature

In order to simulate the system in a more realistic manner, the solar intensity and ambient temperature are modelled in this study as varying 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:

\[
G(t) = G_{\text{max}} \sin\left(\frac{\pi t}{D_j}\right)
\]

(1)

Where \( G_{\text{max}} \) is the maximum solar intensity occurring at solar noon; \( D_j \) is the length of the day; \( t \) in equation (1) is the difference between the time of the day (at a given instant) and the sunrise time in hours.

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

\[
G_{\text{tot}} = \int_{\text{rise}}^{\text{set}} G(t) \, dt
\]

(2)

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

\[
T_{\text{amb}} = \left(\frac{T_{\text{max}} + T_{\text{min}}}{2}\right) + \left(\frac{T_{\text{max}} - T_{\text{min}}}{2}\right) \sin\left(\frac{\pi (t - 8)}{D_j}\right)
\]

(3)

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

The distribution of the solar intensity and ambient temperature during a whole day is shown in figure 1. This simulated day corresponds to a total daily insolation of 26,12 MJ/m² and an average ambient temperature of 27,7 °C.

![Figure 1. Variation of climatic data with the day time.](image)
3. Performance analysis
The performance of the adsorption cooling system considered in this study is evaluated by the solar performance coefficient \( COP_s \), which 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:

\[
COP_s = \frac{Q_c}{A \int G(t) dt}
\]

Where, \( A \) is the total solar collector area. \( Q_c \) is the cooling production, it is defined by the adsorbate latent heat of evaporation minus the sensible heat to cool the adsorbate from the condensation temperature to the evaporation temperature, between the period of time when isosteric and isobaric cooling is completed, respectively.

4. Results
A computer program was done on the basis of the numerical model, which is well discussed in our previous work by Chekirou et al. [5]. All the basic parameters used in the model are also cited in reference [5].

The estimates of the saturated vapour pressure, the adsorbed phase density and the latent heat of methanol are given by Weast [6] and Bejan and Kraus [7].

The figure 2 represents a schema of rectangular adsorber used in this study. The rear and the lateral insulation are used to limit the thermal losses. The activated carbon AC-35 is packed inside a rectangular adsorber.

Figure 2. Schema of rectangular adsorber.

The activated carbon/methanol pair has proved to be the best pair among those studies so far, because it is reasonably stable chemically, has a high performance coefficient and is less expensive than other pairs. Methanol has been selected as an adsorbate, because it can evaporate at a temperature largely
below 0°C, its enthalpy of evaporation is high (~ 1200 KJ/kg at -5 °C), its molecule is small enough (4. 10^{-4} \mu m) to be easily adsorbed into micropores, with a diameter smaller than 2. 10^{-3} \mu m. Its pressure is always lower than the atmospheric one, which means a safety factor in case of leakage. The activated carbon AC-35 has been selected as an adsorbent material, because of its affinity with methanol. It has high adsorptive capacity at ambient temperature and low pressures, maintaining small capacity of adsorption at high temperatures and pressures. It has a significant volume of micropores of convenient size for adsorption. The thermo-physical properties of the AC-35, is produced by CECA (France), its specific surface BET is 1150 m$^3$/g. The void space in the AC-35 adsorbent bed represents 78 % of its total volume (39 % of the volume is constituted by the interparticles space, and 39 % by the pores within the grains).

The average of the temperature inside the adsorber during one day is presented in figure 3. The temperature is considered equal to the ambient temperature in the morning before sunrise and under a low pressure of methanol (equal to the evaporation pressure $P_e = 28.72 \text{ hPa}$). When the adsorber is heated by solar radiation, the adsorbent bed temperature increases rapidly with time. The heating continues until the condensation pressure is reached (equals to $P_c = 216.76 \text{ hPa}$). The reached temperature is known as limit temperature of desorption. The heating continues also as much as the solar radiation is sufficient to increase the temperature of the adsorbent bed and until the maximum regenerating temperature is reached. This last is assumed as the temperature where the adsorbent bed and the adsorber wall temperature are the same. Consequently, there are no heat exchanges between the adsorber wall and the adsorbent bed at this temperature. We can observe also that the slope of the curve, during the first period of isosteric heating is larger than that during the isobaric heating period. This is explained by the fact that the heat absorbed from the heating of the adsorber by the solar flux goes mainly to increasing the temperature of the adsorbent bed and adsorber wall. While, in the isobaric heating, the absorbed heat not only increases the temperature of the adsorbent bed and adsorber wall, but also contributes to the heat of desorption.

Solar flux decreases and the cooling starts down after it reaches the maximum regenerating temperature. The temperature decreases until the pressure becomes equal to that which reigns in the evaporator ($P_e = 28.72 \text{ hPa}$). The reached temperature is known as limit temperature of adsorption. Cooling continues until the temperature 25 °C, which is determined by the temperature in which there is no heat exchange between the adsorber wall and the adsorbent bed at this temperature. This value corresponds to the adsorption temperature given at the beginning of the cycle ($T_a = 25 \text{ °C}$).

| Day time (h) | Single glazed | Double glazed | TIM |
|-------------|---------------|---------------|-----|
| 6           | 20            | 20            | 20  |
| 8           | 30            | 30            | 30  |
| 10          | 40            | 40            | 40  |
| 12          | 50            | 50            | 50  |
| 14          | 60            | 60            | 60  |
| 16          | 70            | 70            | 70  |
| 18          | 80            | 80            | 80  |
| 20          | 90            | 90            | 90  |

**Figure 3.** Effect of collector configuration on average temperature inside the adsorber during one cycle.
The knowledge of the behaviour of the adsorber allows study the effect of some parameters on the solar performance coefficient and cooling production such as the type of the solar collector (collector configuration). In this study, we choose three types of collector (simple, double glassed and TIM cover (Transparent Insulation Material)).

Usually, the increase of glazing cover number is limited by collector structure and dimension; in common practice, there is no more than two or three glazing. Figure 3 shows also the effect of the three types of collector on the average temperature inside the adsorber.

We can see that the average temperature inside the adsorber increases when the double glass cover or TIM cover are used, this result is due to the fact that the heat losses with the TIM cover is lower than those related to a single glass cover and double glass cover.

We represent in Figure 4 and 5, the effect of the solar collector surface area on the solar performance coefficient \( \text{COP}_s \) and cooling production \( Q_f \). It can be observed from Figure 4 that the \( \text{COP}_s \) decreases with an increase in the solar collector surface area.

This can be justified by the fact that the increase in solar collector surface area induces an increase in the cooling production \( Q_f \) (Figure 5) and once the solar collector surface area reaches an optimal value, the cooling production decreases (Figure 5). Moreover, the total solar energy absorbed by the collector throughout the whole day, also strongly increases. Consequently, the variation of cooling production \( Q_f \), relative to the variation of the total solar energy absorbed by the collector, will be lower contributing to a decrease in the solar performance coefficient \( \text{COP}_s \).

**Figure 4.** Effect of solar collector area and its configuration on system’s performance.
The adsorbent mass is an important parameter for system optimization. Its influence on the system’s performances is presented in Figure 6. It can be seen from this figure that the solar performance coefficient $\text{COP}_s$ increases as long as the adsorbent mass is less than an optimal value. Moreover, when the adsorbent mass is increased to higher values, the $\text{COP}_s$ decreases. This trend reflects the fact that the required amount of methanol is desorbed at this optimal value of adsorbent mass 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 desorption. And the same justification holds for the cooling production (Figure 7).
The solar refrigerator is powered by solar radiation energy, therefore the solar energy intensity determines the cooling power as well as the solar performance coefficient $COP_s$ value, and these effects are shown in Figure 8. We can see that both the cooling power $Q_f$ (Figure 9) and the solar performance coefficient $COP_s$ increase with the increase of the total solar energy absorbed by the collector. However, there is a minimum value of solar radiation intensity under which no ice can be produced in practical application, because the amount of desorbed methanol, when evaporated, is just enough to provide cooling to evaporator. This minimum value of solar intensity depends on the variations of the atmospheric temperature during the day and characteristics of solar refrigerator device, this minimum value is about 11 MJ/m² [8].
5. 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, using a meteorological data of Constantine for a hypothetical clear day. The performance of the system considered in this study is evaluated by solar performance coefficient, $sCOP$. The obtained results show that the solar performance machine increase when a TIM or double glass cover is used. For fixed operating conditions, the solar performance coefficient presents a maximum for an optimal adsorbent mass per square meter of solar collector surface area. The solar collector surface area plays an important role in determining the performance of the system. $sCOP$ decreases with an increase in the solar collector surface area. Solar performance coefficient $\text{COP}_s$ increases with the increase of the total solar energy absorbed by the collector.

6. References
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