Design and realization of a solar adsorption refrigeration machine powered by solar energy

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Abstract

This work aims to the experimental realization of a refrigerator prototype that uses an adsorption tube collector for cooling, in which solar energy can be directly absorbed. The development of a software giving an estimate of the activated carbon and methanol quantities in the refrigeration system, the quantities of energy used in its various parts, their design, the refrigeration and solar performance coefficient was carried out, and this according to the temperature data, total radiation and the dimension of the refrigeration compartment to be cooled. The thermal COP of the prototype was founded equal to 0.49 depending thus on the refrigerating effect and the energy absorbed in the collector-adsorbor. The solar COP was founded equal to 0.081 depending on the refrigerating effect and the solar radiation.

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*Keyword: refrigeration, adsorption, solar energy, solar COP, activated carbon, methanol.*

1. Introduction

Among the thermal processes of solar energy, solar refrigeration is one of the most suitable processes for storage, transport and marketing of energy. Among its numerous applications, the adsorption refrigerating machine seems to be an interesting alternative to conventional refrigeration systems in isolated regions, where conventional electrical power is unavailable. However, these machines are not fully automatic because of manual interventions needed for its operation.

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The adsorption refrigeration system using an adsorbent/adsorbate working pair, is composed by different elements: a solar collector which contains the adsorbent/adsorbate working pair (in our case it is the activated carbon/methanol), a condenser where the adsorbate vapor condenses, an evaporator where water plates are laid out to be transformed into ice, in order to store cold for deferred use, and a refrigeration compartment.

The development of solar adsorption refrigeration systems appeared in the late 1970s, following the needs of non-oil countries, and several studies have been undertaken \cite{1, 2, 3, 4 and 5} since that time. Marmottant \cite{1} have studied and manufactured in 1990 a solar ice maker based on adsorption/desorption phenomena which operates intermittently and uses the working pair activated carbon/methanol. A solar adsorption refrigerator was built and tested in 2000 by Hildbrand \cite{3} in Switzerland using the pair Silica gel-Water. The system does not contain any movable part, and the author has obtained a COP between 0.12 and 0.23.

Mayor \cite{6} made an adsorption refrigerator working with the pair silica gel/water. This refrigerator is characterized by its compactness and its ability to be transported. The working volume of this refrigerator is 100 liters, the surface of the solar collector is 1m² and its mass reaches 150 kg. This machine was built with materials to minimize the mass of the system. For better insulation of refrigeration compartment, vacuum panels (VIPS) were used, while a large storage volume capacity was maintained. An independent valve was developed to eliminate any human manipulation. Abu-Hamdeh \cite{7} investigated some work on solar adsorption refrigerator using parabolic trough collector and uses olive waste as adsorbent with methanol as adsorbate. The author showed, from the COP values, that the optimal adsorbent mass varied between 30 and 40 kg while the optimum tank volume varied between 0.2 and 0.3 m³. Wang \cite{8} developed a novel two-stage adsorption freezing machine, which is powered by the heat source with the temperature below 100°C. The composite adsorbents of CaCl₂ and BaCl₂ developed by the matrix of expanded natural graphite were chosen as adsorbents. The experimental results showed that the optimal coefficient of performance (COP) and specific cooling power (SCP) at 15 °C refrigeration are 0.127 and 100W.kg⁻¹, respectively. COP and SCP increased with the increasing heat source temperature and decreased with the decreasing evaporating temperature.

The goal of this work is to develop an adsorption refrigeration system for cold production under Algeria’s climate. Experimental test was done on a prototype elaborated in laboratory in order to test the feasibility of the machine. Software was elaborated, giving an estimate of the activated carbon and methanol quantities in the adsorption refrigerator, the energy balance and the design of its various components, as well as performance coefficients of the machine.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_v</td>
<td>latent heat of evaporation</td>
<td>(kJ/kg)</td>
</tr>
<tr>
<td>m_f</td>
<td>evaporated mass of fluid</td>
<td>(kg)</td>
</tr>
<tr>
<td>Δ_m</td>
<td>quantity of fluid desorbed per unit of mass of the adsorbent</td>
<td>(kg/kg)</td>
</tr>
<tr>
<td>Q_G</td>
<td>quantity of heat received by the adsorbent</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>Q_EV</td>
<td>cooling load</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>Q_CD</td>
<td>quantity of heat yielded by the condenser</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>Q_A</td>
<td>quantity of heat yielded by the adsorbent during adsorption</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>δQ_1</td>
<td>sensible heat of metal</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>δQ_2</td>
<td>sensible heat of adsorbent</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>δQ_3</td>
<td>sensible heat of adsorbate fluid</td>
<td>(kJ/jour)</td>
</tr>
<tr>
<td>I_G</td>
<td>daily Solar Irradiance</td>
<td>(kJ.m⁻²)</td>
</tr>
<tr>
<td>τ</td>
<td>Sunshine duration</td>
<td>(sec)</td>
</tr>
<tr>
<td>τ_adsorption</td>
<td>duration of adsorption estimated</td>
<td>(hour)</td>
</tr>
<tr>
<td>COP_th</td>
<td>thermal coefficient of performance</td>
<td></td>
</tr>
<tr>
<td>COP_solaire</td>
<td>solar coefficient of performance</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>(K)</td>
</tr>
</tbody>
</table>
2. Description of the prototype and its operation principle

The following figure shows the prototype of the machine adsorption in semi pilot scale manufactured. The realization and test of a prototype at this scale allows evaluating the feasibility of the pilot scale adsorption refrigerator and its operating parameters. The prototype has the following components: a thermally insulated refrigeration compartment, an evaporator, a condenser and an adsorption tube collector (see Fig.1).

The operation principle of the machine consists in heating by solar radiation the adsorbent contained in the adsorption collector, which is disposed horizontally. This energy should be sufficient to desorb the molecules of the adsorbate (methanol) and to be transformed from its liquid phase into vapour. Then, the methanol vapours are condensed in a condenser and collected in a tank then evacuated towards the evaporator in a liquid phase. The adsorbent starts to cool gradually when solar radiation begins decrease in the evening to reach the ambient temperature. This decrease in temperature involves the adsorption phenomenon of the activated carbon with the methanol. Cold production is the result of the energy needed to evaporate the methanol in the evaporator, which will be adsorbed by the activated carbon. This phenomenon will cease when the adsorbent is completely saturated with methanol for a temperature slightly higher than the environmental temperature and the initial vacuum pressure.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_p)</td>
<td>specific heat</td>
<td>(kJ kg(^{-1}) K(^{-1}))</td>
</tr>
<tr>
<td>(T_{reg})</td>
<td>regeneration temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>(T_{ads\ (initial)})</td>
<td>initial adsorption temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>(T_{ads\ (final)})</td>
<td>final adsorption temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>(T_{des})</td>
<td>desorption temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>(T_{cond})</td>
<td>condensation temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>(T_{evap})</td>
<td>evaporation temperature</td>
<td>(°C)</td>
</tr>
</tbody>
</table>

Fig.1. the adsorption refrigerator Prototype with semi pilot scales.
3. Calculation programme

A calculation programme under Excel was elaborated in order to define the parameters of the refrigerating installation, and this before starting the manufacture of the adsorption refrigerating system with its various components. The program takes into account the initial climatic parameters of the site where the installation must be installed and the dimensions of the refrigeration compartment to be cooled. The principal input parameters are:

- Length, width and the height of the refrigeration compartment.
- Temperature and relative humidity of the ambient and refrigeration compartment air.
- Insulation thickness of the refrigeration compartment and its thermal conductivity.
- Quantity of ice stored in the refrigeration compartment.
- Quantity of the food products and their initial temperature in the cold room.
- Thermodynamics properties of the selected adsorbent/adsorbate pair.

From these data, the program calculates:

- The total daily refrigerating load of the refrigeration compartment.
- The initial and adsorbed quantities of methanol and activated carbon used to satisfy the cooling needs of the refrigeration compartment.
- The energy balance of the refrigeration system during the adsorption and desorption phases.
- Design of the different components of the refrigeration system (an adsorption plane collector, an evaporator and a condenser).

3.1. Calculation of the cooling load

The cooling load of a refrigeration compartment with given refrigerator dimensions was determined according to various heat inputs and thickness of its insulation: heat input through the insulating walls, heat input due to the renewal of air, heat due to the food products, ice thermal storage.

3.2. Mass estimation of desorbed fluid and of adsorbent

Using the parametric equation of Dubinin-astaknov developed for AC35/methanol pair, it was estimated the mass of the initial fluid as well as the quantity of the adsorbent in the adsorption tube collector.

\[
m_{\text{ff}} = \frac{Q_E}{L_v} \quad \text{[kg/day]} \tag{1}
\]

\[
Q_E: \text{ total daily cooling load [kJ/jour]}
\]

\[
L_v: \text{ latent heat of evaporation [kJ/kg]}
\]

\[
m_{\text{ads}} = \frac{m_{\text{ff}}}{\Delta m} \tag{2}
\]

\[
m_{\text{ff}}: \text{ evaporated mass of fluid [kg]}.
\]

\[
\Delta m: \text{ quantity of fluid desorbed per unit of mass of the adsorbent [kg of fluid desorbed /kg of adsorbent].}
\]

The quantity \(\Delta m\) is obtained from the isosteric diagram on which we trace a cycle characterized by four temperatures \(t_{\text{ads}}, t_{\text{reg}}, t_{\text{evap}}\) and \(t_{\text{cond}}\) or calculated from the equation of Dubinin-astaknov, which is written in the following way [9]:
\[
\ln \left( \frac{q}{w_0} \right) = -D \left[ T \ln \left( \frac{P_s}{P} \right) \right]^{n}
\]

Where: \( w_0 = 0.425 \text{ l/kg} \); \( D = 5.02 \times 10^{-7} \); \( n = 2.15 \)

### 3.3 Energy balance of the refrigeration system

An estimate of the amounts of heat used in the system, in order to calculate numerically the thermal COP and the solar COP of the refrigeration machine [9]:

\[
COP_{th} = \frac{Q_{EV}}{Q_G}
\]

\[
COP_{solaire} = \frac{Q_{EV}}{T_{G} \cdot S_{cap}}
\]

The heat balance is written in the following way:

\[
Q_G + Q_{EV} = Q_{CD} + Q_A
\]

- \( Q_G \): quantity of heat received by the adsorbent
- \( Q_{EV} \): cooling energy
- \( Q_{CD} \): quantity of heat yielded by the condenser
- \( Q_A \): quantity of heat yielded by the adsorbent during adsorption

\[
Q_G = \int_{T_{ads}}^{T_{reg}} T \sum m_i c_{pi} dT + \int_{T_{ads}}^{T_{reg}} T \sum m_i c_{pi} dT + \Delta H \Delta m m_{ads}
\]

\[
Q_{EV} = L v (T_{evap}) \Delta m m_{ads} - \Delta m c_p (T_{cond} - T_{evap}) m_{ads}
\]

\[
Q_{CD} = L v (T_{cond}) \Delta m m_{ads} + \Delta m c_p (T_{reg} - T_{cond}) m_{ads}
\]

\[
Q_A = \int_{T_{reg}}^{T_{reg(new)}} T \sum m_i c_{pi} dT + \int_{T_{ads(new)}}^{T_{ads(new)}} T \sum m_i c_{pi} dT
\]

\[
+ \int_{T_{ads(new)}}^{T_{ads(new)}} \Delta H \Delta m m_{ads}
\]

\[
\sum m_i c_{pi} dT = \sum Q_i = \delta Q_1 + \delta Q_2 + \delta Q_3
\]

Where: \( \delta Q_1 \): sensible heat of metal.
- \( \delta Q_2 \): sensible heat of adsorbent.
- \( \delta Q_3 \): sensible heat of adsorbate fluid.
3.4. Design of the various components

3.4.1. Adsorption solar collector

The entire area of the adsorption collector is determined from the knowledge of the solar collecting surface (given according to the cooling load) by the following formula [9]:

\[ S_{\text{captation}} = \frac{Q_E}{I_G \cdot 0.1} \]  

(12)

3.4.2. Condenser

The condenser should be designed so that it must evacuate the quantity of heat \( Q_{CD} \) by the collecting surface, at least over duration equal to that of the sunshine duration [9].

\[ Q_{CD} = \frac{I_G \cdot \text{COP_solaire} \cdot S_{\text{captation}}}{\tau} \]  

(13)

\( I_G \): daily Solar Irradiance (kJ.m\(^2\)).
\( \tau \): Sunshine duration (sec).

3.4.3. Evaporator

The surface of the evaporator is estimated by the following formula:

\[ S_E = \frac{Q_E}{K \cdot \Delta T} \]  

(14)

Since the system works in an intermittent way, the capacity of the evaporator is estimated according to the adsorption time which is evaluated at 6 hours:

\[ Q_E = \frac{Q_E}{\tau_{\text{adsorption}}} \]  

(15)

With \( \tau_{\text{adsorption}} \) is the duration of adsorption estimated in hours.

3.5. Calculation Result

The calculation results example is done for the case of the adsorption refrigerator at pilot scale, which is under construction in laboratory, and presented in the following table, according to meteorological data for the region of Algiers and for typical day in July. The COP values were calculated numerically from the values of temperature of the adsorption cycle and daily solar radiation, for a useful refrigerator volume of 100 L and a polyurethane insulation thickness of 10 cm. Daily Solar Irradiance is chosen for a typical day in July, equal to 27966 kJ.m\(^2\). The temperature of the refrigerated compartment is supposed equal to 4 °C while the exterior temperature equal to 34°C:
Table 1. Parameters of the refrigeration machine (pilot scale)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling load of the refrigeration room (W.k/day)</td>
<td>679.77</td>
</tr>
<tr>
<td>Mass of activated carbon (kg)</td>
<td>10.6</td>
</tr>
<tr>
<td>Mass of methanol (kg)</td>
<td>2.86</td>
</tr>
<tr>
<td>Surface collector (m²)</td>
<td>1.06</td>
</tr>
<tr>
<td>Evaporator area (m²)</td>
<td>0.41</td>
</tr>
<tr>
<td>Condenser area (m²)</td>
<td>2.4</td>
</tr>
<tr>
<td>Thermodynamic COP</td>
<td>0.49</td>
</tr>
<tr>
<td>Solar COP</td>
<td>0.081</td>
</tr>
</tbody>
</table>

4. Realization and test of the adsorption refrigeration prototype

The adsorption collector comprises two (2) external tubes with a diameter of 40 mm containing each one a coaxial tube with a diameter of 14 mm and a length of 450 mm. The external tubes are covered with black paint to increase the absorptivity at their surfaces. The coaxial tubes are drilled and wrapped with a metal grid so that it lets diffuse the methanol vapours without the penetration of the activated carbon grains in the tube (Fig.2). The quantity of activated carbon is estimated at 630 g for a volume of 120 ml of methanol. A movable insulation on the lower side of the adsorption collector is designed in order to permit quick cooling of the tubes during the adsorption phase.

![Fig.2. (a) Adsorption solar collector scheme; (b) Coaxial tubes of adsorption.](image)

A horizontal tubular evaporator is used in our case, and is immersed in water which is intended to form ice during adsorption phase. The role of ice is to maintain the temperature of the refrigeration compartment to be cooled during the desorption phase and night. A coil condenser must be long enough to condense all the overheated vapours of methanol, which are released from the adsorption collector during desorption (heating phase).

The goal of the test is to observe the change of the temperature at the collecting surface and into the activated carbon, during selected days, and to test its effectiveness of the collector. The tubular form was chosen because the vacuum produced in the tubes is easier to maintain than another form. The tubular form of the collector provides also a notable reduction of the surfaces number to be welded, and thus, reduction of the risk of leakage.
K-type thermocouples connected to data acquisition system were placed on various components of the tubular adsorption collector. The tests carried out in the laboratory enabled the acquisition of the temperatures values reached at various prototype elements for various solar irradiance values. This experimental study has been the subject of a further article [10].

5. Simulation

Due to the intermittent operation of the solar adsorption refrigerating machine, cold thermal storage is used in order to store cooling energy in night period. Ice is the phase change material used for cold thermal storage (Fig. 3).

Simulation of the phase change phenomena is undertaken in order to determine the adequate quantity of PCM required counteracting the heat losses at the walls during its melting cycle (night period). The evaporator is immersed directly into water for an efficient heat transfer.

The amount of ice formed, as a consequence of the adsorption of methanol by the activated carbon, will be used to cool the refrigeration compartment during night. The quantity of water chosen for cold storage is 2 kg, which takes more than 4 hours to melt totally. The following figures show the temperature evolution of the ice during its melting phase, assuming that the initial temperature of the ice is -4°C. Figure 4 illustrates the fusion of the total mass of PCM in direct contact with the evaporator. Figure 5 presents the fusion of a portion of PCM only.
Figure 4. Fusion of the total mass of PCM (study case)

Fig. 5. Temperature evolution of ice used for cold thermal storage (time simulation: 4 hours 30 min).
Conclusion

The goal of this work is to develop an adsorption refrigeration system for cold production able to answer the socio-economic requirements, in particular in terms of total low costs (solar collector, equipment, maintenance) and technological simplicity (system without valve and self-adapting in the external conditions). A prototype on a semi-pilot scale was elaborated, and the experimental tests were carried out in a laboratory. Cold thermal storage is used in order to store cooling energy use while shifting. Simulation of the phase change phenomena is undertaken in order to determine the quantity of PCM (ice) required to counteract the heat losses at the walls during its melting cycle (night period).

Computation programme was elaborated, giving an estimate of the activated carbon and methanol quantities in the adsorption refrigerator, the energy balance and the design of its various components, as well as the thermal and solar performance coefficients of the system. A manufacture and optimization work is being done for an adsorption refrigeration machine on a pilot scale, for a refrigeration compartment volume of 100 L.

References