



Performance Optimization Study of an Adsorption Solar Refrigerator System with Special Reference to the Effect of the Collector-Adsorber Tilt Angle

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Type of Work: Peer Reviewed.

DOI: <https://dx.doi.org/10.21013/jas.v17.n1.p2>

Review history: Submitted: Dec. 07, 2021; Revised on: Jan. 15, 2022; Accepted: Jan. 17, 2022

How to cite this paper:

Tubreoumya, G.C. et al. (2022). Performance Optimization Study of an Adsorption Solar Refrigerator System: Effect of the Collector-Adsorber Tilt Angle. *IRA-International Journal of Applied Sciences* (ISSN 2455-4499), 17(1), 7-16. DOI: <https://dx.doi.org/10.21013/jas.v17.n1.p2>

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This paper is peer-reviewed under IRA Academico Research's [Peer Review Program](#).

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ABSTRACT

This paper presents an optimization study of an adsorption solar refrigerator through dynamic modeling and simulation of the system behavior using the zeolite/water couple. Thus, a mathematical model representing the evolution of heat and mass transfer at each component of the adsorption solar refrigerator has been developed. The results of this study showed that increasing the angle of inclination of the collector from 0° to 13° with respect to the horizontal causes an increase in the temperature of the zeolite. The result is an increase in the mass of water vapor cycled, but also an improvement in the performance of the solar refrigerator. When the value of the angle of inclination exceeds 13°, the mass of water vapor cycled decreases and subsequently leads to a decrease in the performance of the refrigeration system.

Keywords: Solar cooling, Adsorption, Zeolite/Water, Heat and mass transfer, Simulation

Introduction

Compressor machines are used to cover cold needs such as for the preservation of food products, pharmaceutical products and also for the search of thermal comfort in buildings through air conditioning. These machines are energy consuming and use refrigerants that have a negative impact on the environment. Since the Montreal Protocol in 1987, international agreements have called for the reduction of emissions of these refrigerants such as CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons) [1].

The adsorption solar refrigeration machines appear as an ecological and energetic alternative since they use solar energy as a source of energy and also use refrigerants such as water, ammonia and methanol which have a low effect on the environment [2-4].

Moreover, for developing countries with favorable sunlight and also in areas beyond the reach of the electricity grid, solar adsorption refrigeration machines appear as a promising solution for improving living conditions and reducing electricity consumption [5].

Adsorption solar refrigeration units are suitable in countries like Burkina Faso, endowed with favorable sunshine with an average irradiation between 5.5 kWh.m².day⁻¹ and 6.5 kWh.m².day⁻¹ [6]. In addition, these machines operate without any moving parts, with no noise pollution. They use refrigerants which are non-polluting, their maintenance is easy and their material of manufacture is recyclable [7].

While adsorption solar refrigeration machines have certain advantages, the fact remains that certain disadvantages are obstacles to the popularization of these types of machines. Among these disadvantages we can cite:

- discontinuous operation of the cycle due to the intermittence of the solar energy source [8,9];
- the low coefficient of performance (COP) due to the poor transfer of heat and mass in the adsorbent bed [10], to the low thermal conductivity of the adsorbent [11,12] and also to the poor contact between the absorber surface and the adsorbent bed [13,14];

The development of adsorption solar refrigeration therefore requires optimization of the process at all levels. Thus, the main objective of this study is to improve the performance of the solar refrigerator through the search for the optimal angle of inclination of the collector-adsorber containing the zeolite / water pair.

2. Materials and methods

2.1. Presentation of the model

The adsorption refrigeration system which is the subject of this study is illustrated in figure 1. It presents three compartments which allow to produce cold by the use of the solar energy which are among others the collector-adsorber containing the bed of adsorbent, the condenser and the evaporator located in the refrigerating chamber. The adsorbent bed made of zeolite/water is the most essential element of the system. It plays the same role as a compressor in a compression refrigeration system.

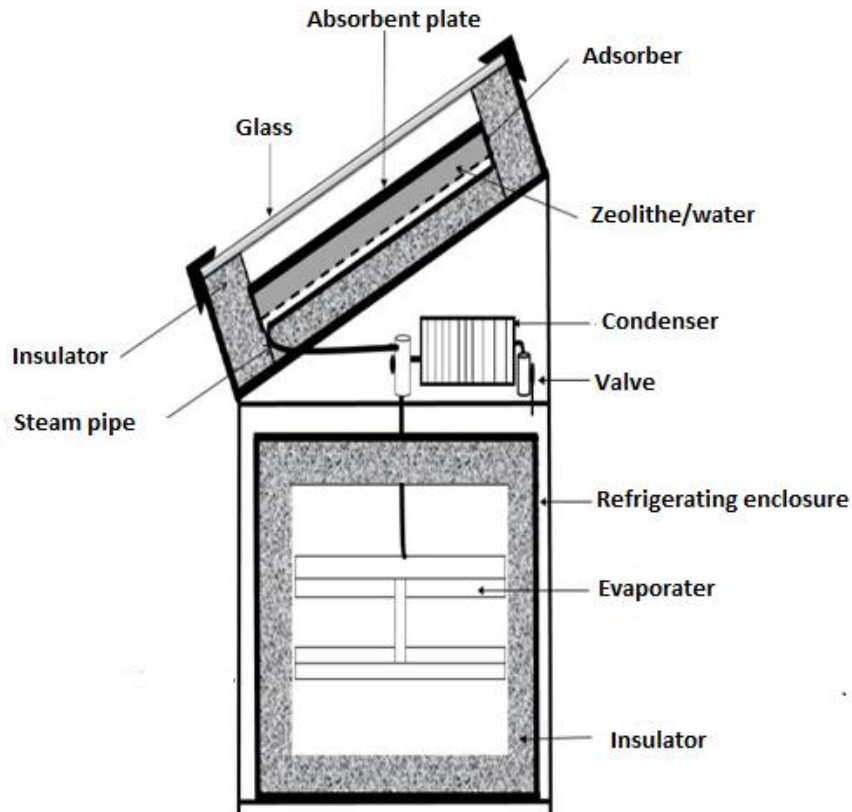


Figure 1: Schematic of the solar adsorption refrigerator

3. Mathematical modeling

3.1. Assumptions of the Mathematical Model

The main assumptions of the model are the following:

- the porous material (adsorbent) can be assimilated to a medium with temperature T and equivalent thermal conductivity;
- the heat transfer is unidirectional;
- the convective heat transfer and the pressure losses are negligible in the porous medium;
- the pressure remains constant in the condenser and in the evaporator;
- the total mass of desorbed adsorbate vapor condenses completely;
- the mass transfer resistance is negligible;
- the physical properties of the adsorbent and the metal walls of the adsorber, condenser and evaporator are considered constant.

3.2 Energy balance

The heat transfer equations at each part of the refrigerator can be written as:

→ **Energy balance of glass**

$$m_v C p_v \frac{\partial T_v}{\partial t} = \alpha_v \cdot G_n \cdot s_v + h_{p-v} \cdot s_v (T_p - T_v) - h_{cv-v-ext} \cdot s_v (T_v - T_{amb}) - h_{r-v-ciel} \cdot s_v (T_v - T_{ciel}) \quad (1)$$

T_v is the temperature of the glass, T_p the temperature of the absorber plate and T_{amb} the temperature of the ambient environment.

→ **Energy balance of absorber plate**

$$m_p C p_p \frac{\partial T_p}{\partial t} = (\alpha \tau)_{eff} s_p G_n - h_{p-v} s_v (T_p - T_v) - h_{p-a} s_p (T_p - T) \quad (2)$$

Where T is the equilibrium temperature of the zeolite/water mixture and h_{p-a} the heat transfer coefficient between the absorber plate and this mixture.

→ **Energy balance of adsorbent bed**

○ During the isosteric heating and desorption phase

$$m_{eq} C p_{eq} \frac{\partial T}{\partial t} = h_{p-a} \cdot s_p (T_p - T) + \delta \left(\Delta H_{des} \cdot m_a \cdot \frac{\partial m^{des}}{\partial t} + m_a \cdot C p_l (T - T_{cd}) \cdot \frac{\partial m^{des}}{\partial t} \right) \quad (3)$$

○ During the isosteric cooling phase and adsorption

$$m_{eq} C p_{eq} \frac{\partial T}{\partial t} = h_{p-a} \cdot s_p (T_p - T) + \delta \left(\Delta H_{ads} \cdot m_a \cdot \frac{\partial m^{ads}}{\partial t} - m_a \cdot C p_l (T - T_{ev}) \cdot \frac{\partial m^{ads}}{\partial t} \right) \quad (4)$$

With:

$\delta=0$: During isosteric heating and cooling.

$\delta=1$: During desorption and adsorption.

→ **Condenser energy balance**

$$\left[m_{cd} \cdot C p_{cd} + m_d(t) \cdot C p_l \right] \frac{\partial T_{cd}}{\partial t} = m_a \cdot \frac{\partial m^{des}}{\partial t} \left[L_{cond}(P_{cd}) + C p_l (T - T_{cd}) \right] - h_{r-cd-ciel} \cdot S_{cd} (T_{cd} - T_{ciel}) - h_{cv-cd-amb} \cdot S_{cd} (T_{cd} - T_{amb}) \quad (5)$$

Where $m_d(t)$ represents the total mass of adsorbate vapor desorbed, T_{cd} the temperature of the condenser and L_{cond} the latent heat of condensation.

→ **Evaporator energy balance**

$$\left[m_{ev} C_{p_{ev}} + (m_d(t) - \Delta m m_a) C_{p_l} \right] \frac{\partial T_{ev}}{\partial t} = -m_a \frac{\partial m^{ads}}{\partial t} \left[L_v(P_{ev}) - C_{p_l}(T - T_{ev}) \right] - h_{cv-ev-air} S_{ev} (T_{ev} - T_{air}) \quad (6)$$

Where T_{ev} is the temperature of the evaporator and L_v the latent heat of vaporization.

3.3. Model of adsorption kinetics

The Dubinin- Astakhov equation is successfully used to describe the adsorption of gas vapor on the adsorbent. Thus, this equation is used to calculate the rate of adsorbate (water) in the zeolite (adsorbent) as a function of temperature and pressure.

$$m = w_0 \rho_l(T) \exp \left(-D \left(T \ln \frac{P_s(T)}{P} \right)^n \right) \quad (7)$$

Where $\rho_l(T)$ is the density of the adsorbate (water), $P_s(T)$ the saturation pressure, w_0 the maximum adsorption capacity; D and n are constants depending on the adsorbent/adsorbate couple used. Using Antoine's equation giving the saturation pressure:

$$P_s(T) = 1000. \exp \left(16,89 - \frac{3803,9}{(T - 41,68)} \right) \quad (8)$$

Where T is the temperature in K.

3.4. Performance analysis

The solar coefficient of performance (COPs) of a solar refrigeration machine is defined as the ratio between the amount of cold produced at the evaporator and the total solar energy incident during a full day

$$COP_s = \frac{Q_f}{\int_{t_{sr}}^{t_{ss}} A_s \cdot G_n \cdot dt} \quad (9)$$

Where A_s is the collection area and G_n is the solar flux in W/m^2

Q_f the amount of cold produced at the evaporator, given by:

$$Q_f = m_a \Delta m \left[L(T_{ev}) - \int_{T_{ev}}^{T_{cd}} C_{p_l}(T) dT \right] \quad (10)$$

3.5. Boundary conditions

At the beginning of the cycle, we assume that the solar reactor is in thermal equilibrium with the ambient environment. As a result, the initial values of temperature, pressure and mass are defined as follows:

$$T_v(t_0) = T_p(t_0) = T_{ev}(t_0) = T_{cd}(t_0) = T(t_0) = T_{amb} \quad (11)$$

$$P(t_0) = P_{ev} = P_s(T_{ev}) \tag{12}$$

$$m = m(T, P) \tag{13}$$

3.6. Numerical resolution

The method of solving the system of equations that describes the transient behavior of the model is purely numerical, based on the implicit finite difference method and the iterative method of Gauss Seidel. A computer program written in Fortran language has been developed to model and simulate on the one hand the adsorption-desorption kinetics of the zeolite/water couple and, on the other hand, the operation of each element of the refrigerator during one day.

4. Results and discussion

4.1. Temporal behavior of the temperature of the different components of the adsorption solar refrigerator

The temporal evolution of the temperatures of the glass, the absorber plate, the adsorbent bed (zeolite), the condenser and the evaporator are shown in figure 2. At the beginning of the day, the temperatures are identical and equal to the adsorption temperature which, at sunrise, is equal to the ambient temperature. Under the action of the solar flux, the collector-adsorber heats up and the temperatures of its various components increase rapidly over time to reach a maximum value ($T_v=358\text{ K}$ (85°C), $T_p=396\text{ K}$ (123°C), $T_{zeo}=395\text{ K}$ (122°C), $T_{cd}=320\text{ K}$). At the end of the day, the solar flux decreases and it results in a cooling of the collector-adsorber which starts as soon as the temperature of the adsorbent bed has reached the regeneration temperature. It can be seen that the temperatures of the different compartments of the adsorber decrease up to 300 K (27°C). This value represents the temperature from which there is no heat exchange between the glass, the plate and the adsorbent bed. The temperature of the evaporator decreases from about 297 K (24°C) to about 276 K (3°C). This drop in temperature is due to the evaporation of the condensate (water) which turns into steam and then flows towards the adsorbent bed. These same trends were found by Umair et al, (2014) who developed a solar refrigerator model using the activated carbon-ethanol pair [16].

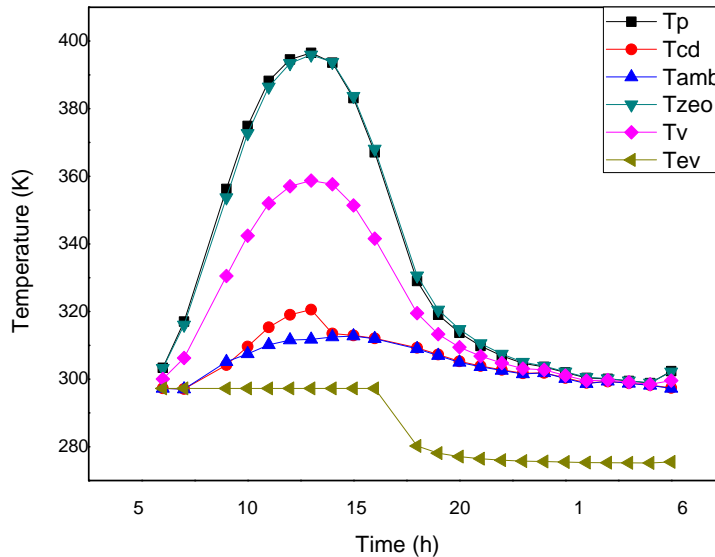


Figure 2: Temporal evolution of the temperature of the different components of the solar refrigerator.

4.2 Influence of the inclination on the performance of the solar adsorption refrigerator

The influence of collector tilt angle on the performance of the adsorption solar refrigerator is shown in figures 3-4. An examination of the curves in these figures shows that increasing the tilt angle from 0° to 13° with respect to the horizontal results in an increase in the temperature of the zeolite. This results in an increase in the mass of water vapor cycled, but also, an improvement in the performance of the solar refrigerator. However, when the value of the tilt angle exceeds 13° , the mass of water vapor cycled decreases and a decrease in the performance of the refrigeration system ensues (Figure 4). Thus:

- For 0° and 13° tilt angles, the amount of cold produced and COPs are 5.898 and 6.248 MJ and 0.251 and 0.258 respectively.
- For tilt angles of 30° and 45° , the amount of cold produced and COPs are 5.975 and 5.127 MJ and 0.252 and 0.233 respectively (Table 1)

These results show that for an optimal operation of the system, the angle of inclination of the collector-adsorber must be equal to the latitude of the place (approximately 13°) where the solar refrigerator is implanted. This allows to have maximum values of the solar flux, the amount of cold produced and the COPs. This trend was also observed by Qasem et al, (2013) who performed a numerical study on the performance optimization of adsorption solar refrigerator operating with activated carbon-methanol pair. To do this, they used a double-glazed TIM (Transparent Insulation Material) collector-adsorber, containing a thin stainless steel tubular adsorber with a selective coating and an optimal tilt angle. To do this, they used a double-glazed TIM (Transparent Insulation Material) collector-adsorber, containing a thin stainless steel tubular adsorber with a selective coating and an optimal tilt angle. The tilt angle of the collector-adsorber is changed every month to get the maximum value of the solar flux. Based on considering the climatic conditions of Dhahran (Saudi Arabia), modeling this prototype allowed them to find a value of the solar coefficient of performance (COPs) of the system of about 0.24 [17]. Similarly, Hassan et al, (2020) simulated the solar machine with a catchment area of 1 m^2 . The results showed that the variation of the thermal conductivity of the reactor is very small in space and time. The performance of this system (COPs) reaches a value of 0.21 under Canadian weather conditions.

Table 1: Performance of the solar refrigerator: Influence of the collector-adsorber tilt angle

Value of the angle of inclination of the collector-adsorber in relation to the horizontal.	0°	13°	30°	45°
Qf [MJ]	5.898	6.248	5.975	5.127
Qc [MJ]	23.532	24.230	23.707	21.963
COPs	0.251	0.258	0.252	0.233

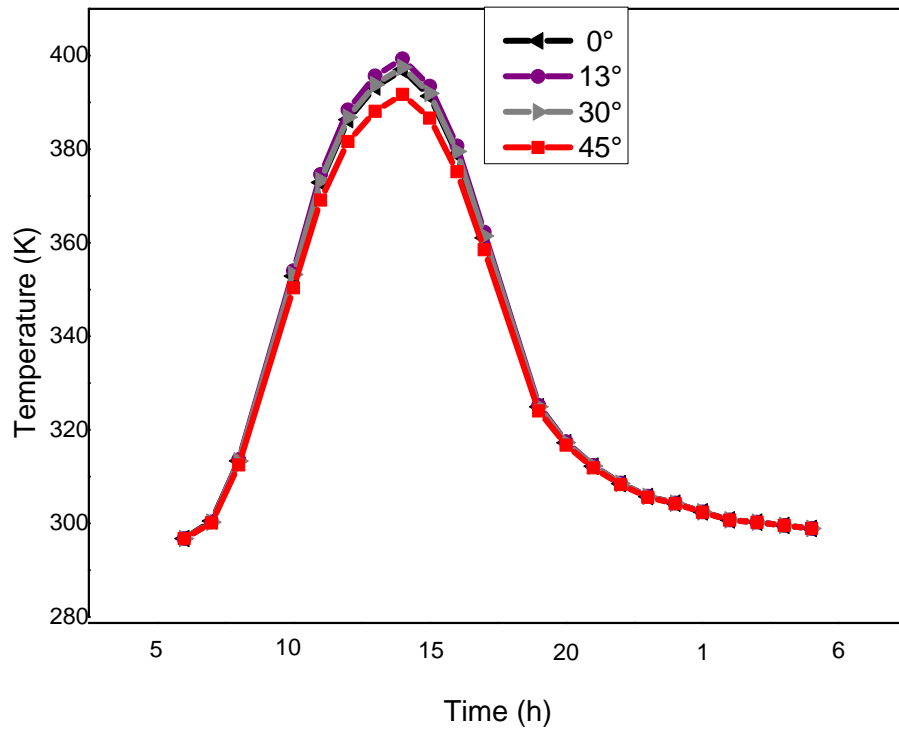


Figure 3: Influence of the tilt angle on the temperature of the zeolite

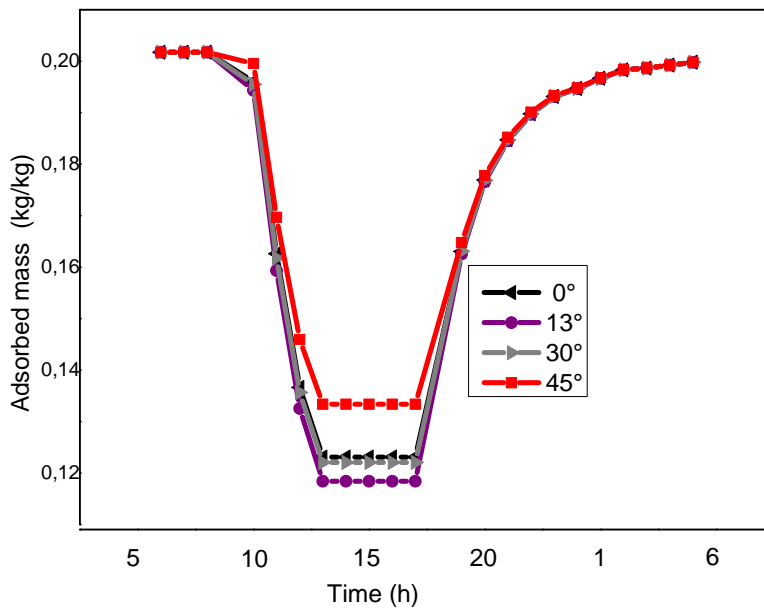


Figure 4: Influence of the tilt angle on the mass of adsorbed water vapor

5. Conclusion

In this paper, a performance optimization study of an adsorption solar refrigerator through modeling and simulation is presented. The results of this study show that for an optimal operation of the system, the angle of inclination of the collector-adsorber must be equal to the latitude of the location. This allows to have maximums of the solar flux, of the quantity of cold produced and of the COPs. The results found are satisfactory and can constitute a research platform whose goal is to improve the performance of solar systems on the one hand, and on the other hand, to master this process of solar cold production which is still poorly exploited in Burkina Faso.

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Nomenclature			
C_p	Spécific heat (J/kg.K)	ΔH	Heat of adsorption/desorption (J/kg)
D	Constant in the Dubinin-Astakhov equation	Subscripts	
G_n	Solar radiation (W/m ²)	a	adsorption
m	mass (kg)	ads	adsorbent
n	Constant in the Dubinin-Astakhov equation	d	desorption
P	Pressure (Pa)	cd	condenser
P_s	Saturation Pressure (Pa)	ev	evaporater
Q_f	Cold production (J)	v	glass
q	Water concentration inside the zéolithe (kg/kg)	ext	outside
S	Area (m ²)	amb	ambient
T	Température (K)	zeo	zeolithe
t	Time (s)	min	minimum
W_o	Parameter of Dubinin-Astrakhov equation (m ³ /kg)	max	maximum
L(T)	Latent heat of vaporization (J/kg)	g	generation
Greek Letters :		cv	convection
α	absorptance		
τ	Transmittance		
Δt	Time step (s)		