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Analytical investigation of factors influencing the optimization of a solar adsorption cooling system using Moroccan climate data

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Abstract— **The analytical study to optimize a solar adsorption cooling system, dealt within this paper, is based on Moroccan climate data. In which, the critical factors affecting system performance are determined. In this research context, the main examined factors are the geometric parameters, the influence of the climate data and the working pair used in the reactor.**

The results show that the parabolic trough solar collector (PTC) provides a higher coefficient of performance (COP) compared to that achieved by the solar flat plate collector.

The system performances is improved using the pair Activated carbon-methanol and Activated carbon-ammoniac, by providing the effective temperature, with regard to the climate data which is the most important parameter. The study shows that the COP increase with high solar radiation and decrease when initial temperature is higher.

Keywords— ***Cooling systems, solar energy, adsorbate, adsorbant, parabolic trough collector, flat plate collector, climate data, Morocco.***

I. INTRODUCTION

Since the 1848s, considerable researchers are focusing on the study of adsorption cooling machines. Scientists have become aware about the traditional major refrigerator systems problems. In addition to the environmental pollution, These machines are heavy consumers of electrical energy. So, adsorption cooling researches have gained a renaissance in a strong direction [1] [2] [3].

Solar adsorption refrigerator system can be defined as a process based on the phenomenon of adsorption that occurs when a balance is established between a couple of adsorbate / adsorbent called working pair. When solar energy is used as the main energy source, activated carbon, zeolite, and silica gel are the common materials used as an adsorbent. Environmental-friendly materials including ammonia, methanol, or water can be a refrigerant. The adsorbent-refrigerant pairs used in this kind of system are considered as zero ozone depletion potential as well as zero global warming potential [4] [5].

Despite their potential advantages, the existing solar adsorption cooling systems are not yet competitive enough to replace electricity-driven refrigerators because of their low efficiency, intermittent operation, and high initial cost.

However, in this study, we will focus on the critical factors that affect the performances of this system, which will make it possible to highlight the variation of the critical parameters influencing the behavior of this machine, and improve the overall performance of the system.

The rest of this paper is organized as follow: in section 2, the system description is given, and then we discuss the modelization in section 3, followed by results and discussion and conclusion in section 4 and 5 respectively.

II. SYSTEM DESCRIPTION

A. *Solar adsorption refrigeration machine*

The solar adsorption refrigeration machine (figure 1) is a process that produces cold using solar thermal heat energy; it's constituted by three main elements [6]:

- The reactor (adsorber) enclosed in a solar collector, containing the adsorbent/adsorbate mixture, where the phenomenon of adsorption and desorption are produced;
- The condenser, is the unit used to condense the adsorbent from its gaseous to its liquid state so in this element where the refrigerant is liquefied ;
- The evaporator which is the unit used to turn the liquid form of the refrigerant to its gaseous-form, so in this element where the refrigerant evaporates, producing cold ;

When solar radiation is available, the solar collector captures the solar thermal energy, which is transferred to the adsorber reactor located inside the collector. The heated adsorber reactor releases the refrigerant from its adsorbent in desorption process, and pushes it into the condenser, so when the hot gas meets the cooler air temperature of the outside, it becomes liquid, this liquid form is at its high pressure, the adsorbent cools down as it flows into the evaporator located

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inside the coldroom, so the adsorbent absorbs the heat inside the coldroom, cooling down the air, the cycle starts all over, when the adsorbent evaporates to a gas, then flows back to reload the adsorber.

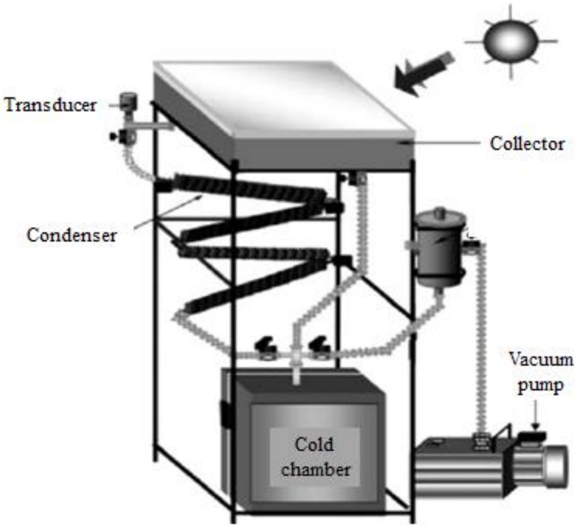

Figure 1: Layout of an experimental solar adsorption cooling machine [7]

The suitability of this configuration has been already assessed by several authors [8] [9] [10].

B. *Adsorption refrigeration cycle description*

An ideal cycle (1-2-3-4) of solar adsorption cooling machine is represented on the diagram (Figure 2). The cycle represents the evolution of the mixture adsorbent-adsorbate contained in the adsorber, It consists of two isosteric phases (1-2 and 3-4), where the adsorbed mass remains constant, and two isobaric phases (2-3 and 4-1) where the pressure remains constant [6].

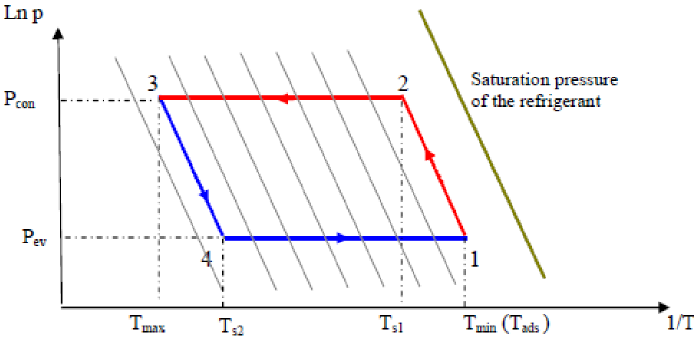

Figure 2: Thermodynamic cycle of solar adsorption cooling system

In the following, we present the different phases of an ideal cycle [6]:

Phase (1→2): isosteric heating

At the beginning of the cycle, the mixture adsorbent-adsorbate is at its minimal temperature T_{ads} and at the pressure of evaporation P_{ev}. When the reactor is heated, the pressure and temperature of the mixture increase, and when the pressure reaches the condensation pressure prevailing in the condenser (point 2). The temperature reached the temperature of desorption T_{s1}. The adsorbed mass remains constant during this phase.

Phase (2→3): isobaric condensation-desorption

The mixture adsorbent-adsorbate pressure reaches the saturation pressure of the refrigerant at the condenser's temperature. The desorption begins and the pressure remains constant until the temperature of the mixture increases and reach the maximum temperature where the refrigerant condenses, T_{max}.

Phase (3→4): isosteric cooling

In this phase, the reactor is cooled, the pressure decrease and follows an isoster. The pressure of the reactor decrease until it reaches the evaporator pressure evaporator, P_{ev}, the temperature reached is called adsorption temperature threshold T_{s2}. During this phase the adsorbed mass remains constant.

Phase (4→1): isobaric evaporation-adsorption

When the mixture reaches the point 4, the evaporation of the refrigerant begins producing the cold in the evaporator, until the moment where the temperature reaches the minimal temperature, T_{min}. During this phase, the mixture follows an isobar imposed by the evaporator pressure, which corresponds to the saturation pressure of the evaporator, T_{ev}.

C. *Working pairs*

A number of studies have been carried out both experimentally and theoretically, for the selection of adsorbent-adsorbate materials. In this kind of system the working pair requires the following characteristics:

1. A refrigerant with a large evaporation latent heat.
2. A working pair with high thermodynamic efficiency.
3. A small heat of desorption under the considered operating pressure and temperature conditions.
4. A low thermal capacity of the adsorbent material.

So, the most widely used working pairs in this kind of systems are: zeolite – water, activated carbon – methanol, silica gel – water and activated carbon – ammonia.

D. *Solar collectors*

As a part of solar adsorption cooling system, solar collector provides the driving energy for system operation. Flat plate collectors are commonly used in this kind of systems [11] [12]. Some attention has also been given to use concentrator collector [13] [14]. So in this study we made a comparison of the coefficient of performance of this system using two kind of collector: flat plate collector and parabolic trough collector.

1) Flat plate collector

A solar flat plate collector (Figure 3) typically consists of a large heat absorbing plate exposed to solar radiation, and painted black to absorb as much as possible solar radiation for maximum efficiency, this surface exchange with calorific fluid the calories produced by the absorption of the incident radiation. This blackened heat absorbing surface has several parallel copper pipes or tubes that contain the working pair.

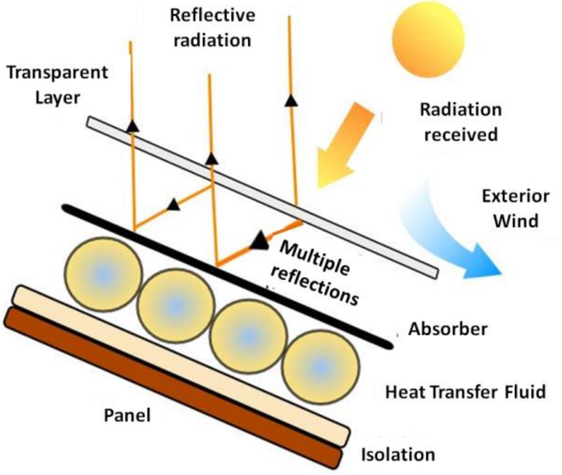

Figure 3: Flat plate collector

2) *Parabolic trough solar collector*

The parabolic trough collector (Figure 4) consists of a parabolic trough and a linear evacuated tube which is located in the focal line of the parabolic trough. The main idea of the parabolic trough collector is that the reflected radiation over the parabolic trough is directed to the focal point and so all the solar energy is concentrated in the evacuated tube.

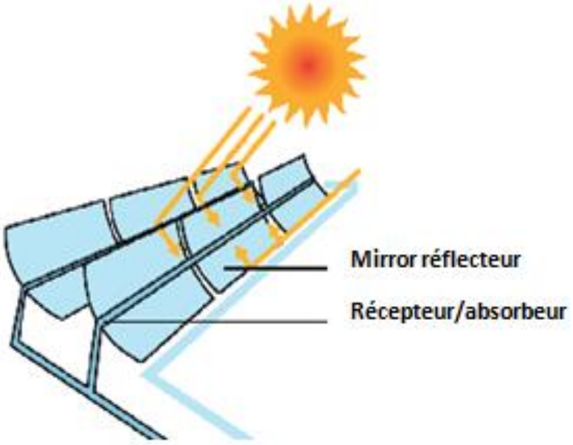

Figure 4: Cylindrical-parabolic collector

III. MODELIZATION

For this modelization, the following assumptions have been taken into account [6]:

1) The porous medium properties have a cylindrical symmetry;
2) All the phases are in local thermal all the time, mechanical and chemical balance;
3) The pressure is uniform;
4) The heat transfer is radial and the convection heat transfer owing to the radial mass transfer is neglected;
5) The conduction heat transfer in the medium can be characterized by an equivalent thermal conductivity coefficient.

A. *Equations of heat and mass transfer*

1) *The energy conservation equation combined with the masse conservation equation*

The transient behavior of the temperatures in the reactive medium is expressed by the energy conservation equation, combined with the mass conservation equation which is written at the position r and at time t by the following equation [15]:

$$A(t)\frac{\partial T}{\partial t} = B(t) + \lambda_e\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right] \qquad (A.1)$$

Where:

$$A(t) = \left[(1-\varepsilon)\rho_s C_s + \theta\rho_a C_a + (\varepsilon-\theta)\rho_g C_g\right] \qquad (A.2)$$

$$B(t) = \left(\frac{p}{\rho_g}\right)\frac{\partial}{\partial t}\left((\varepsilon-\theta)\rho_g\right) + \left(\frac{1}{V_t}\right)\left(\frac{p}{\rho_a} + \Delta H_{ads}\right)\frac{\partial m_a}{\partial t} \qquad (A.3)$$

Where:

T absolute temperature (°C)
ε porosity of adsorbent bed
ρ_s density of the solid phase (kg/m^3)
C_s specific heat of solid phase (J/kg K)
θ volume fraction of the adsorbed phase
ρ_a density of the adsorbed phase (kg/m^3)
ρ_g density of the adsorbed phase (kg/m^3)
C_a specific heat of adsorbed phase (J/kg K)
C_g specific heat of gas phase (J/kg K)
p pressure in the reactor (bar)
m_a adsorbed mass in kg of ammonia per kg of activated carbon (kg/kg-CA)
ΔH_{ads} adsorption heat of ammonia on activated carbon (J/kg)
λ_e equivalent thermal conductivity

2) *Quantity of cold produced*

It's important to know the quantity of cold produced in each cycle, to evaluate the performance of the system. Its expression is:

$$Q_f = \Delta m\left[L(T_{ev}) - \int_{T_{ev}}^{T_{cond}} C_{p,l}\,dT\right] \qquad (A.4)$$

Where Δm is the cycled mass, given by:

$$\Delta m = m_a\left(T_{ads}, P_s(T_{ev})\right) - m_a\left(T_g, P_s(T_{cond})\right) \qquad (A.5)$$

Where m_a (T,P), is the adsorbed mass of ammonia at temperature T and pressure P, calculated using the BET model.

$L(T_{ev})$ latent heat at evaporation temperature (J/kg)
T_{cond} condension temperature (°C)
T_{ev} evaporation temperature (°C)
$C_{p,l}$ liquid specific heat (J/kg K)

3) *Solar performance Coefficient*

The performance evaluation of solar machine is determined from the amount of heat Q_f and Q_s the amount of global irradiation received by the collector surface of the collector, its expression is given by:

$$COP_{sol} = \frac{Q_f}{Q_s} \qquad (A.6)$$

Where $Q_s = S_c \int_{Sunrise}^{Sunset} G(t)dt$ (A.7)

And S_c is the collecting area sensor (m^2)

B. *Modeling using a flat plate collector*

The following dynamic equations are given for 1 m^2 of the surface of the planar solar collector [6]:

$$\begin{cases} C_v \dfrac{dT_v}{dt} = q_v - h_{va}(T_v - T_a) - h_{vs}(T_v - T_s) + h_{pv}(T_p - T_v) & (B.1) \\ C_p \dfrac{dT_p}{dt} = q_p - h_{pv}(T_p - T_v) - h_{pa}(T_p - T_a) + h_{pm}(T_p - T_m) & (B.2) \end{cases}$$

Where:

C_v , C_p are respectively thermal capacity of the glass and the wall (J/K.m2);

h_{va} coefficient of heat exchange (W/K. m^2) between the glass and the atmosphere;

h_{vs} coefficient of heat exchange between the glass and sky;

h_{pv} coefficient of heat exchange (W/K. m^2) between the wall and the galss;

h_{pa} coefficient of heat exchange (W/K. m^2) between the wall and the atmosphere;

h_{pm} coefficient of heat exchange (W/K. m^2) between the wall and the mixture;

T_v temperature of the glass (°C);

T_s sky temperature (°C);

T_a ambient temperature (°C);

T_p temperature of the wall (°C);

T_m temperature of mixed adsorbent-adsorbate (°C). And

$$\begin{cases} q_v = a_v.G; \text{ is the glass absorbed radiations} \\ q_p = a_p.G; \text{ is the wall absorbed radiations} \end{cases}$$

Where

G global irradiation (W/m^2)

a_v and a_p are respectively the glass and the wall absorption coefficients of global radiation

The convective exchange coefficient between glass and atmosphere is determined by the Correlation of Watmuff:

$$h_{va} = 2.8 + 3.0 \times V_v$$

Where

V_v wind speed (m/s)

The radiation exchange between glass and sky is given by [16]:

$$h_{vs} = \varepsilon_v.\sigma(T_s^2 + T_v^2).(T_s + T_v)$$

Where:

ε_v emittance of the glass;

σ Boltzmann constant = 5.68 10^{-8} (W/ m^2 .K^{-4})

Only radiation exchange between window and wall is taken into account [16]:

$$h_{pv} = \sigma.\frac{(T_p^2 - T_v^2).(T_p - T_v)}{\dfrac{1}{\varepsilon_p} + \dfrac{1}{\varepsilon_v} - 1}$$

Where

ε_p emittance of the wall

Only heat conduction exchange between wall and atmosphere is taken into account.

$$h_{pa} = \frac{\lambda}{e_p}$$

Where

λ equivalent thermal conductivity

e_p insulation thickness(m)

The heat coefficient exchange between wall and porous medium h_{pm} was determined experimentally [17], the value found is equal to 33.65 W/m^2.K .

C. *Modeling using a parabolic trough collector*

The equation of the energy balance of the glass tube, surrounding the absorber, is written under the form [18]:

$$\overbrace{\rho_{ve} C_{ve} A_{ve} \frac{\partial T_{ve}}{\partial t}}^{(1)} = \overbrace{\gamma_r \alpha_{ve} \beta\, W I_b(t)}^{(2)} + \overbrace{\pi D_{vi} h_{ab-ve}(T_{ab} - T_{ve})}^{(3)} \\ \underbrace{- \pi D_{vo} h_{ve-amb}(T_{ve} - T_{amb})}_{(4)} \qquad (C.1)$$

The different terms of this equation are defined by [18]:

(1) Sensitive energy of the glass tube; where :

ρ_{ve}: Density of the glass tube

C_{ve}: Specific heat capacity of the glass tube

T_{ve}: Temperature of the glass tube

(2) Solar energy absorbed by the glass tube; where:

γ_r: Reflectivity of reflective surface

α_{ve}: Absorptivity of the glass tube

(3) Heat exchanges with the absorber, where

D_{vi}: Inside diameter of the glass tube

h_{ab-ve}: refers to the heat transfer coefficient between the absorber and the glass envelope;

(4) Heat exchanges with atmosphere, where

D_{vo}: Outside diameter of the glass tube

T_{amb}: ambient temperature (°C)

h_{ve-amb}: refers to the heat transfer coefficient between the glass envelope and the ambient air;

The equation of energy balance of the absorber (heat pipe) is expressed as follows [18]:

$$\overbrace{\rho_{ab} C_{ab} A_{ab} \frac{\partial T_{ab}}{\partial t}}^{(1)} = \overbrace{\gamma_r \alpha_{ab} \beta\, WI_b(t)}^{(2)} + \overbrace{\pi D_l h_{ab-ve}(T_{ab} - T_{ve})}^{(3)} \underbrace{- \pi D_l h_T (T_{ve} - T_{cal})}_{(4)} \qquad (C.2)$$

The different terms of this equation designate respectively [18]:

(1) Sensitive energy of the Sensitive energy, where :

ρ_{ab}: Density of the absorber
C_{ab}: Specific heat capacity of the absorber
T_{ab}: Temperature of the ansorber

(2) Solar energy absorbed by the absorber, where :

α_{ve}: Absorptivity of absorber

(3) heat exchanges with glass, where :

D_l: Outside diameter of the absorber

(4) useful energy, transferred to the heat pipe, where :

h_T: refers to the heat transfer coefficient between the outer surface of the absorber and the vapor-liquid interface.

IV. RESULTS AND DISCUSSION

For this study, the porous medium used is a fixed bed of grains of activated carbon reacting by adsorption with ammonia.

The phases existing in the porous medium are: Solid phase constituted by carbon grains, gaseous phase and adsorbed phase.

A. *Geometric parameters*

We present the results of numerical simulation (Figure 5) [19] [20], obtained using the hourly solar data and climate (ambient temperature and overall solar irradiation) corresponding to a clear typical day of July in Tetouan (Morocco, 35°35’ N, 5°23’ W), from the climatological database [21] (Figure 5).

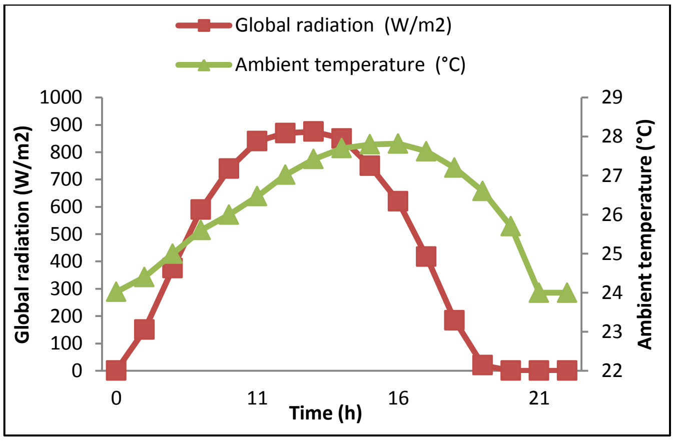

Figure 5: Climate data used in the study for a typical day of July in Tetouan [21]

We present in the figure 6, the COP as a function of the temperature of the working pair [22], we notice that the COPs increase respectively, from 0,06 to 0,15.

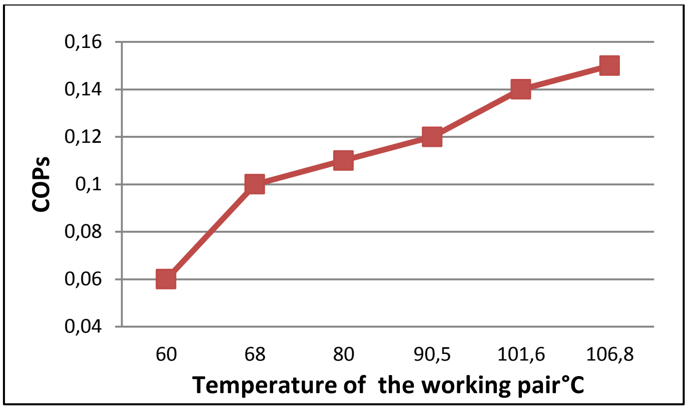

Figure 6: Variation of refrigeration production as a function of the temperature of the working pair [22]

We present in figure 7 the variation of COP as a function of the temperature of the hot source; we notice that the COP and the refrigeration production increase, respectively, from 0.025 to 0.22 per 0.8 m^2 of surface area of the concentrator [23].

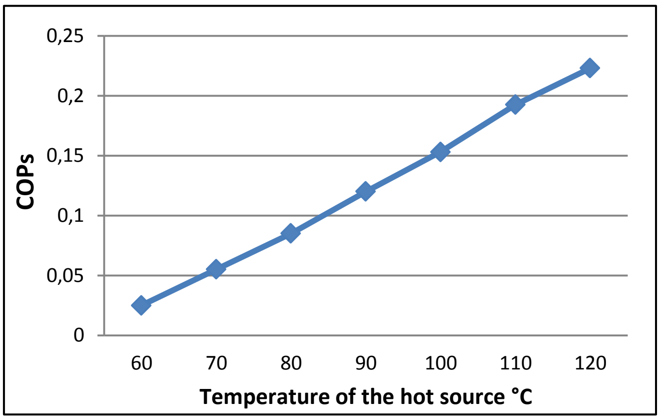

Figure 7: Variation of refrigeration production as a function of the temperature of the hot source [23]

A comparison of the coefficient of performance of each collector show that the parabolic trough solar collector makes it possible to obtain high enough coefficient of performance which is 22% compared with the flat plate collector 15%. So the geometric parameters can be adjusted to increase the energy efficiency of the system. In fact, numerous studies have reported that the parabolic trough solar collector has a high efficiency compared to other types of collectors [24] [25]. It has been tested in various applications, such as steam production [26] [27], sea-water desalination [28] and production of hot water [29] [30]. The result of this concentration is the high temperature levels in the absorber, because large amounts of energy absorbed in a small region. The use of an evacuated tube increases the thermal efficiency of the collector, and convection losses between the absorber and the cover are eliminated.

B. *Climate data*

In this study, we have used the hourly solar data and climate data (ambient temperature and global radiation on inclined surface) corresponding to a clear typical day of different months in three Moroccan cities located in different regions with different climate data Tetouan, Marrakech, Oujda, we have taken into account the climate data obtained in May, June, July and September [31]..

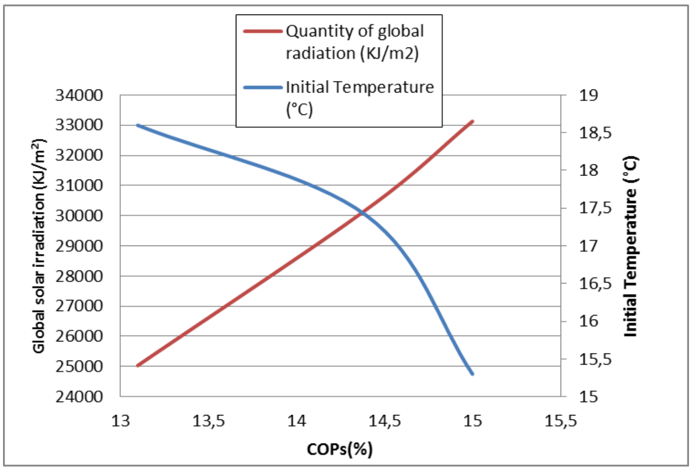

Figure 8: Variation of the COPs as a function of initial temperature and global solar radiation in Tetouan

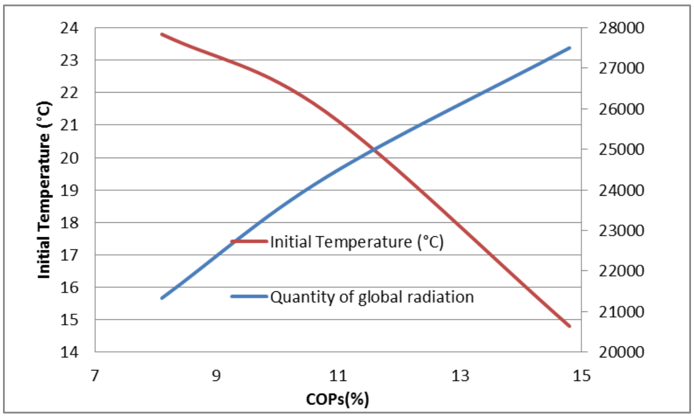

Figure 9: Variation of the COPs as a function of initial temperature and global solar radiation in Oujda

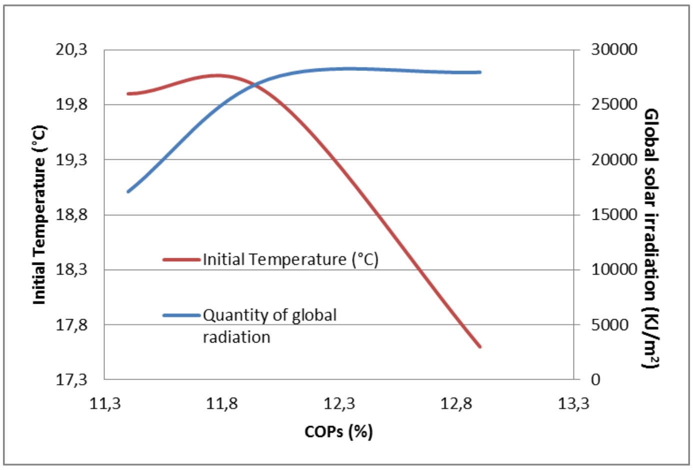

Figure 10: Variation of the COPs as a function of initial temperature and global solar radiation in Marrakech

So the coefficient of performance of this system is related to the initial temperature and the global solar radiation of the area of study. The COP increase when global solar radiation increases and decrease when initial temperature increase.

C. *Working pair*

The performance of adsorbent-adsorbate pair is reviewed here based on heat source temperature.

TABLE 1: ADSORBENT –ADSORBATE PAIRS USED IN THE SOLAR ADSORPTION REFRIGERATION SYSTEM

Adsorbent-adsorbate pair	**System COP**
Zeolite-water [32]	0.1-0.40
Silica gel- Water [33]	0.2-0.3
Activated carbon-Methanol [34]	0.15-0. 23
Activated carbon-Ammonia [35]	0.2-0.7

The activated carbon-ammonia helps to improve system performance as we can see in Figure 11 and activated carbon-methanol is also a suitable working pair of solar energy because of its relatively low regeneration temperature and low freezing point & no corrosion problem.

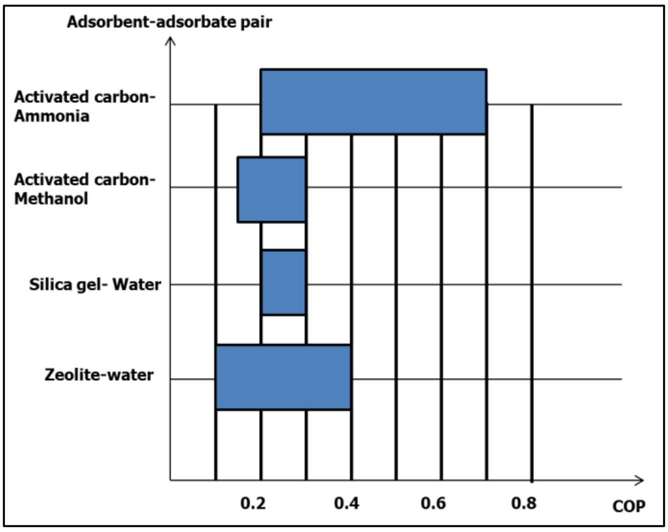

Figure 11: COP reached using different selected adsorbate/adsrbent

Methanol is considered as good adsorbate, its enthalpy of vaporization is high and its molecule is small enough to be easily adsorbed. Its working pressure is always lower than the atmospheric one, which means a safety factor in case of leakage. And it can operate at a cooling temperature below 0°C. As a result activated –carbon methanol is the most widely used adsorbent reported in the literature due to its extremely high surface area and micro pore volume.

V. CONCLUSION

Solar energy as a renewable energy source for cooling machine has long been a hot topic for many researchers, in this context, this article examines the evaluation of the mass adsorption treatment system with different Moroccan climate data.

- The parabolic trough collector helps to improve the performance of the system compared with the flat plate collector. Morover, we can get a higher COP with the parabolic trough solar collector if it’s oriented permanently towards the sun and follows its movement.
- The COPs increase with high solar radiation and when the initial temperature is lower.
- The activated carbon-ammoniac helps to get a higher COP.
- The Activated carbon-methanol is widely used due to its extremely high surface area and micro pore volume.

The main factors showed in this study help to improve and optimize the solar adsorption cooling systems, and it’s interesting to study the economic and the environmental aspect of the whole project as a future work, in addition to the safety factors.

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