Journal of Renewable Energy and Sustainable Development (RESD) Volume 11, Issue 1, June 2025 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2025.11.1.1224

Received on, 10 February 2025 Accepted on, 10 April 2025 Published on, 13 April 2025

Modeling and Optimization of a Solar Adsorption Cooling System under Weather Conditions in Algeria

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ABSTRACT

In order to optimize and Aim for the efficiency improvements of a solar adsorption refrigeration system, the present work evaluates the influence of the operating parameters, the solar collector location, and the working pair type on the performance of a solar adsorption refrigeration system. As a test case, five solar collector sites in Algeria were investigated on a representative day in April. The model used for this study is the thermodynamic Dubinin-Astakhov (D-A) model, which takes into account the variation of the solar intensity and the adsorption capacity of the selected working pairs, which were AC/methanol, Zeolite/water, and composite/ethanol. The performance considered in this study was the system coefficient of performance COP. The pressure-temperature-concentration (P-T-X) diagram of the selected pairs is presented for a temperature range from 27˚C to 127 ˚C and an adsorption process pressure of 2 bars. The maximum adsorption capacity was found to be 0.31, 0.25, and 0.62 kg of adsorbate/kg of adsorbent, respectively, for the selected working pairs. Results show that the maximum COP of 0.314 was achieved with Zeolite/water while the minimum COP of o.107 was achieved with the AC/Methanol working pair.

Index-words: *Solar adsorption refrigeration, Adsorption capacity, Dubinin-Astakhov (D-A) model, COP.*

Nomenclature	
A	solar collector area, m^2
AC	activated carbon
COP	coefficient of performance
Cp	specific heat, kj/kg.k
D	D-A equation parameter
I	solar intensity w/m^2
$I_{c.max}$	maximal Solar intensity, W/m^2
G	Solar global irradiance, W
L	latent heat, kj/kg
M_a	adsorbate mass, kg
n	exponential constant
P	pressure, bar
P_s	saturated pressure, bar
T	temperature, ◦c
t	time, s
X	adsorption capacity, $kg.kg^{-1}$
indices	
amb	ambient
max	maximum
min	minimum
Greek Symbols	
α	collector absorptivity
γ	collector reflectivity
η	solar collector efficiency

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I. INTRODUCTION

Due to the highly increasing demand and consumption of energy, including electrical and fossil energy resources, without forgetting the exhaustion and the polluting character with the harmful emissions of the traditional resources (natural gas, oil, coal ...), which accelerates the environmental damage, use of the renewable energy has received more and more attention. Currently, it is estimated that 80% of electricity is generated by fossil fuels [1], whose 30-40% of the total energy consumption is in the building sector [2], and refrigeration and air-conditioning account for approximately 40% of the total energy [3]. Energy demand for refrigeration and air-conditioning is increasing. Hence, solar energy is the more appropriate and highly promising renewable solution for cooling and refrigeration, among other options of renewable energies due to the coincidence of peak cooling load with the available solar power, the use of environmentally friendly refrigerants like water, which eliminates global warming concerns [4-6]. One of the world's most pressing concerns is satisfying the rising energy demands in an eco-friendly and sustainable manner. [7]

Solar cooling can be classified as electrical and thermal cooling systems. The electrical cooling systems uses the PV cells to convert the solar energy to electricity then using the conventional cycles to produce cooling power.

Research has shown that solar energy is an excellent alternative to fossil fuels. All of these systems require minimal or no mechanical energy consumption, and they can operate using low-temperature heat from various sources, such as waste heat or solar energy. Absorption cooling systems, such as those using LiBr-H_2O or H_2O-NH_3 as working pairs, offer numerous advantages for specific applications. They offer higher cooling system efficiency than adsorption systems.

The most known solar thermal cooling technologies are absorption and adsorption. Adsorption cooling technology has attracted attention in recent years more than any other systems due to its advantages: the ability to work with a wide range of driving temperature levels, noiseless, non-corrosive, and environmentally friendly [8-9]. The technology and performance of solar adsorption cooling systems have reached maturity, enabling them to meet the growing demand for air conditioning. High upfront and operating costs have, however, hindered the commercial spread of solar adsorption cooling systems. Comparing the solar adsorption cooling system with commercial air conditioners, the solar thermal system offers superior efficiency. [10]

This technology is mainly used for ice making, air conditioning and refrigeration. The main advantages of adsorption system are: ability to work with wide range of driving temperatures, noiseless, non-corrosive, and environmentally friendly refrigerants [11, 12, 13]. On the other hand, this technology suffers from the high cost of adsorption chillers, the low performance of the adsorption chiller, and the size of the system.

The research activities in adsorption solar cooling sector are still increasing to allow them to compete with the well-known vapor compression system. The research has focused on solving the technical, economical, environmental problems, and achieve high performance and low cost.

II. DUBININ-ASTAKHOV (D-A) MODEL

The Dubinin-Astakhov (D-A) model is often used for adsorption studies, especially when dealing with microporous materials. The rationale for using this model over other adsorption models, as well as a development of the assumptions associated with adsorption kinetics and heat transfer calculations, is as follows:

1. Rationale for Choosing the D-A Model

- Adaptability to Microporous Materials
- Physical Interpretation
- Energetic Heterogeneity
- Behavior at High Pressure and Low Temperature
- Robustness and Flexibility

2. Assumptions in Adsorption Kinetics

- Equilibrium Conditions
- Homogeneous Surface Sites
- Absence of Resistance to External Mass Transfer

3. *Assumptions in Heat Transfer Calculations*

- Constant Heat Capacity
- Negligible Temperature Gradients
- Steady-State Conditions
- Negligible Heat Loss

In this paper, the focus is on the adsorption cooling system with its simplest cycle, viewing the effect of the working pair type, the solar collector location, and operating parameters variation. All this is due to its mature state of the art in the field of solar adsorption cooling. The effect of the thermal conductivity of the adsorbent, the flow rate, and the inlet temperature of the heat transfer fluid on the performance of the adsorption solar cooling system were analyzed by Shu Xu [14]. Leite et al. l. Presented a numerical simulation for an adsorption solar cooling system with activated carbon–methanol as a working pair. The effect of the TIM cover system was studied and found to be 40% more efficient than the single cover [15].[16] Experimentally, the effect of the type and amounts of adsorbents filled in a solar adsorption refrigeration system using activated ammonia and activated carbon was evaluated. The results showed that a higher COP was found with the utilization of an adsorbent of 100% AC. [17] A numerical study was carried out to evaluate the influence of the design parameters on the overall performance of a solar adsorption refrigerator using a flat plate collector and silica gel-water pair. The main parameters in this study were the mass of silica-gel and the orientation of the solar collector. The influence of collector area and cycle time on the performance of a single-stage, two-bed adsorption chiller is studied by Kumar et al. They used a dynamic model with silica gel/water on two different days. They found that both daily average and cyclic average COP increase with the increase in solar collector area and the cycle time [18].

Tubreoumya et al. An adsorption solar refrigeration system with silica gel water was simulated as a working pair using a dynamic model. The effect of the adsorbate/adsorbent working pairs, the solar flux, and the ambient temperature on the adsorption and desorption process was studied [19].[20] Experimentally tested the influence of adsorption time on the performance of solar adsorption cooling systems using silica gel and water as working pairs. The results showed that the optimal COP was 0.258 for an adsorption time of 45 min. Li and Ji designed, analyzed, and optimized a large-diameter aluminum-alloy finned-tube adsorbent bed collector to enhance heat transfer and reduce uneven temperature distribution in the collector/adsorber. The adsorbent bed efficiency was improved between 31.64% and 42.7%, the maximum COP was 0.122, and the maximum daily ice-making can achieve 6.5 kg [21]. Jaiswal et al. (2016) evaluated the effect of variation of the collector area and the adsorption cycle time on the performance of a single-stage, two-bed silica gel + water adsorption chiller for representative days in summer and winter [22].

The possibility of using solar heat as a source for a different adsorption chiller with a variety of collectors and working pairs has been reviewed by Dieng and Wang [23]. Zhang et al. [24] simulated the performance of a solar-driven chiller with different storage volumes and cycle times with a fixed collector area. A solar-powered adsorption cooling system was carried out by Almohammadi et al to determine the optimal operating conditions by using a multi-objective genetic algorithm. The results showed that the system performance improved by 21% compared to the rated operating conditions [25]. Basdanis et al. [26] investigated the performance of a solar adsorption chiller in Athens, Greece, by simulating the system by dynamically adjusting the half-cycle time for a single-stage tow-bed adsorption chiller and the results show that the dynamically optimized adjusted half-cycle time provides higher cooling capacities compared to constant ones.

All the above-mentioned studies indicate a strong dependency of system performance on the operating parameters of the system and heat source temperature, which, in turn, depends on the solar collector area and system location in addition to the working pair adsorbent/adsorbate. One needs to account for a combined effect of all these parameters in order to optimize the system operation. The present work evaluates the influence of the operating parameters of the adsorption refrigeration system, the solar collector location, and the working pair type on the performance of a solar adsorption refrigeration system. As a test case, five solar collector locations in Algeria varied on a representative day in April. The model used for this study is the D-A model.

Volume 11, Issue 1, June 2025 - ISSN 2356-8569
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III. MATHEMATICAL MODELLING

A schematic of solar driven adsorption cooling system in its basic cycle is shown in Fig. 1. Major components are an adsorber, an evaporator, a condenser and a solar collector field.

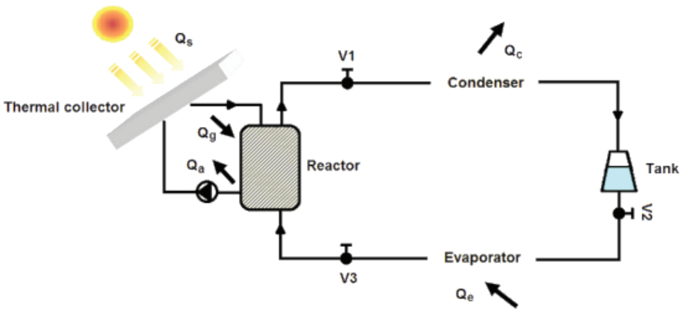

Fig. 1. Schematic of solar adsorption refrigeration system [27]

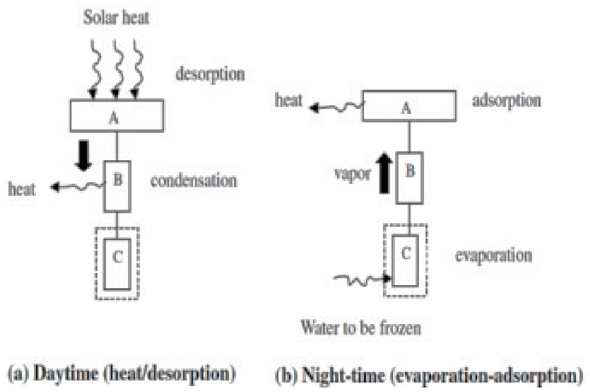

Fig. 2. Cycle timing scheme [28]

The adsorber bed timing scheme is shown in Fig. 2. The operation of a basic cycle adsorption chiller is as described by [29].

For the present study, we pose the following assumptions:

- the heat transfer of the system components is not taken into account;
- the adsorbate mass is considered totally desorbed of the adsorbent and then condenses completely;
- the pressure remains constant during condensing and evaporation;
- no pressure losses are taken into account during the fluid motion;

In order to simulate the system, metrological data was modeled for five solar field locations in Algeria. The ambient temperature and solar intensity during a day in April were presented. During one day of the study, we considered that the solar incidence was collected by a flat plate collector without a tilt angle system.

The transient variation of solar irradiation [4] from sunrise to sunset is evaluated in Eq. (1).

$$I(t) = I_{c.max}\sin\left(\frac{\pi(t-t_{sunrise})}{(t-t_{sunset})}\right) \quad (1)$$

The total solar irradiation received by the solar collector is given by the equation. (2) as follows:

$$G(t) = A\alpha\gamma\eta\int_{sunrise}^{sunset} I(t)dt \quad (2)$$

Where: A is the surface area of the collector, α, η, and γ are the absorptivity, efficiency, and reflectivity of the collector [5].

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

$$T_{amb}(t) = \frac{T_{amb.max}+T_{amb.min}}{2} + \frac{T_{amb.max}-T_{amb.min}}{2}\sin\left(\frac{\pi(t-t_{sunrise})}{(t-t_{sunset})}\right) \quad (3)$$

Where $T_{amb.max}$ and $T_{amb.Min}$ are the maximum and minimum ambient temperatures.

The metrological data used in this study were obtained from Meteonorm software.

TABLE I. INPUT DETAILS ARE USED TO CALCULATE THE DAILY VARIATION OF IRRADIANCE AND AMBIENT TEMPERATURE

City	$I_{c.max}$, w/m^2	$T_{amb.max}$	$T_{amb.min}$	$t_{sunrise}$, h	t_{sunset}, h
Algiers	975	29	15	6:00	18:00
Tlemcen	980	30	18	6:00	18:00
Constantine	940	28	12	6:00	18:00
Ghardaïa	1060	36	22	6:00	18:00
Tamanrasset	1074	39	25	6:00	18:00

The studied system is an adsorption solar refrigerator in its simplest form, the diagram of which is shown in Fig. 2. The performance considered in this study is the coefficient of performance COP. The COP can be calculated as follows:

$$COP = \frac{Q_f}{G(t)} \quad (4)$$

With Q_f is the cold produced, it is defined by the latent heat of evaporation of the adsorbate minus the sensible heat to cool the adsorbate from the condensation temperature to the evaporation temperature, and it is given by [6]:

$$Q_f = M_a \Delta X[l(T_e) - \int_{T_e}^{T_c} Cp(T)dT] \quad (5)$$

Where M_a is the mass of the adsorbate, ΔX is the instantaneous absorption calculated by the Dubinin-Astakhov D-A equation [8]. It can be defined as:

$$\Delta X = X_{max} - X_{min} \quad (6)$$

$$X = X_0 \exp\left[-D\left(T ln \frac{P_s(T)}{P}\right)^n\right] \quad (7)$$

Where X_0 is the maximum absorption capacity, D and n are the parameters of the D-A equation, and $P_s(T)$ is the saturated pressure of the adsorbate.

TABLE II. D-A PARAMETERS FOR THE SELECTED WORKING PAIRS [30] [31] [32].

AC/ Methanol	Zeolite/Water	Composite/Ethanol
n = 2,15	n = 2	n = 1.8
D = 5.02.10^{-7}	D = 1,8.10^{-7}	D = 2,67.10^{-7}
X_0 = 0,425 (l/Kg)	X_0 = 0.265 (l/kg)	X_0 = 0.81 (l/kg)

The estimates of the saturated vapour pressure, the specific heat and the latent heat of the selected working pairs are given by Weast [33] and Bejan and Kraus [34].

IV. PRINCIPLE OF OPERATION

Adsorption is a reaction that occurs between the adsorbent and the adsorbate, which is characterized by molecules attached to a surface. According to the installation instructions above, the operating principle of this machine for the production of cold can be described as follows [35,36].

A. Process

The adsorption cycle consists of four processes, two of which are isosteric and the other two are isobaric. The cycle is illustrated by the Clapeyron diagram in Fig. 3.

The processes in the basic adsorption cycle are as follows:

1. Isosteric heating (processes 1-2)
2. Isobaric heating (processes 2-3)
3. Isosteric Cooling (Process 3-4)
4. Isobaric Cooling (Process 4-1)

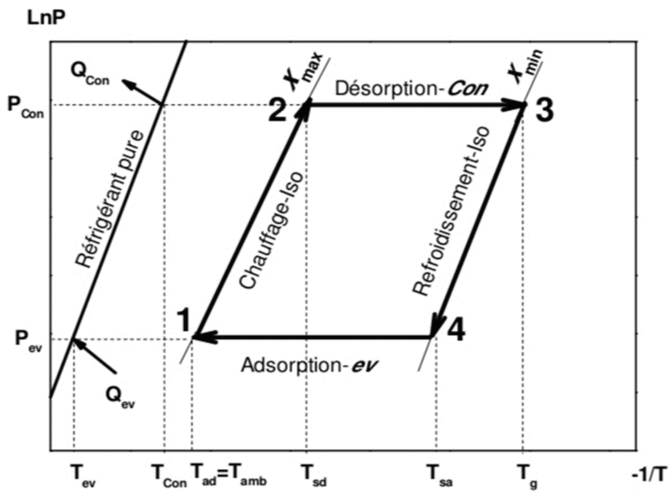

Fig. 3. Ideal thermodynamic cycle of the machine in a Clausius diagram Clapeyron [35]

V. THERMODYNAMIC CYCLE

As part of the optimization of adsorption solar coolers, a thermodynamic study of the basic cycles associated with this machine is necessary. Fig. 3 shows the installation of the main components of the solar adsorption machine and its ideal basic thermodynamic cycle in the Clapeyron diagram (LnP, -1/T). As shown in the figure, the two stages (1-2) and (2-3) correspond to the first stage (heating/desorption), and the other two stages (3-4) and (4-1) correspond to the cycle (cooling/adsorption). Furthermore, the entire thermodynamic cycle is defined by four operating temperatures [35].

- Adsorption temperature (Tad=Tamb): the minimum temperature reached by the mixture.
- Regeneration temperature Tg: the maximum temperature reached by the mixture.
- Condensation temperature T (con).
- Evaporation temperature T (ev).

The thermodynamic cycle of a machine is complete when the two critical points (thresholds) of this cycle are determined and defined. The desorption threshold temperature Tsd is defined as the beginning of the desorption phenomenon, corresponding to the appearance of the first liquid drop in the condenser. The adsorption threshold temperature Tsa is defined as the temperature at which the adsorption phenomenon begins, corresponding to the evaporation of the first liquid drop in the evaporator. However, when calculating the coefficient of thermal performance (COPth), we only need the threshold temperature Tsd desorbed and Tsa adsorbed [37].

VI. RESULTS AND DISCUSSION

It is important to test the system under real-world conditions to validate the modeling and optimization results. Experiments can be used to refine the mathematical model and improve the system design.

Matlab is a development and programming environment that allows you to analyze data, model complex systems, and develop algorithms for a variety of applications. Some of Matlab's most common applications include data analysis, mathematical modeling, simulation, signal and image processing, and control system design.

A. Metrological Data

The daily variation of solar irradiance and ambient air temperature in a representative day of April from 6:00 to 18:00 for five chosen cities are shown in Fig. 4 and Fig. 5, respectively. Solar and ambient conditions for April are given in Table I.

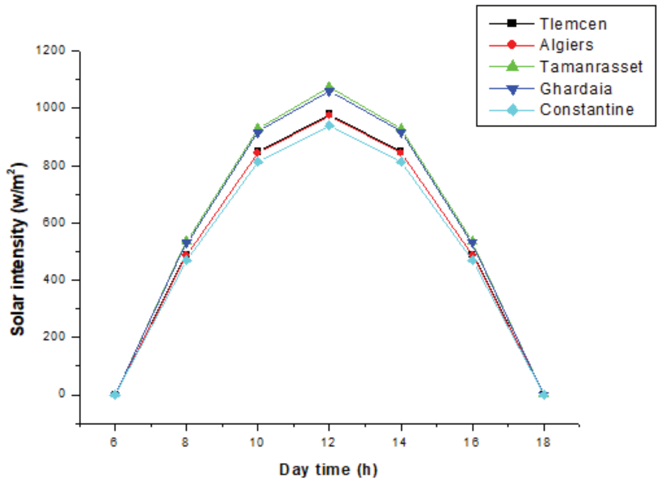

Fig. 4. Hourly evolution of the solar intensity during one day

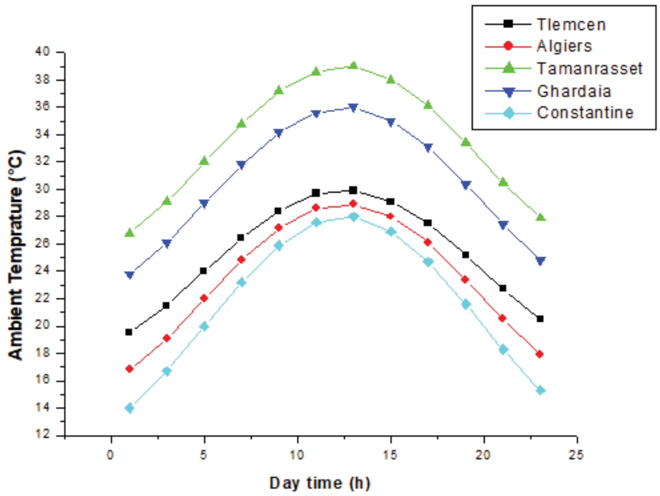

Fig. 5. Hourly evolution of the ambient temperature during one day

During the day, the ambient temperature always kept rapidly rising due to the solar radiation, which in turn kept rising also before 12:00, then both the ambient temperatures and received solar irradiation reached the maximum values and would start to drop till the end of the calculation at 18:00. Similar results were seen for all the five locations of the solar collector. The total solar irradiance received on the solar collector during the considered day for the five chosen sites: Tlemcen, Algiers, Tamanrasset, Ghardaia, and Constantine was respectively 7494,7455,8213,8105 and 7188 W/m^2.

B. *Adsorption Capacity*

The adsorption capacity of different working pairs at six different temperatures are shown in Fig. 6. the working pairs chosen for this study are AC/methanol, Zeolite/water and composite/ethanol. The D-A parameters used in this study for the chosen working pairs are given in Table II.

As can be seen from Fig. 6, the adsorption capacity for the working pairs was kept increasing against the increasing in temperatures for a given pressure of adsorption of 2 bar. The adsorption capacity then reached the maximum values and remained almost unchanged till the end of the calculation at T=400 K which are the maximum adsorption capacities.

The results shows that the maximum adsorption capacity differs from each working pair to another, the composite/ethanol working pair has reached a higher adsorption capacity then the AC/methanol and the zeolite/water which is the lower among them.

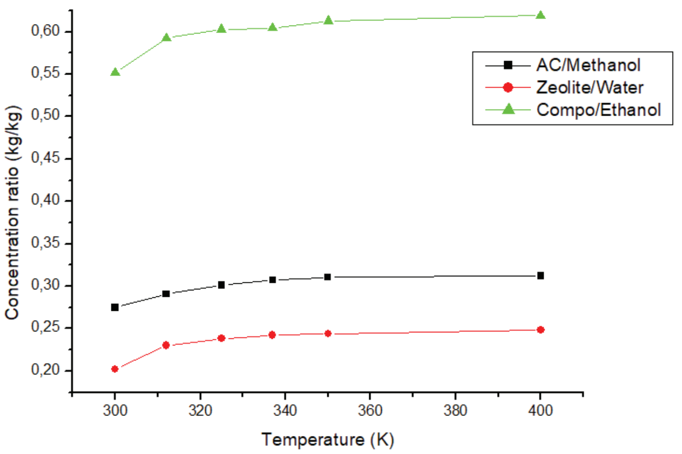

Fig. 6. Adsorption capacity evolution during the adsorption process

C. *Coefficient of Performance*

The effect of the various working pairs used for a solar adsorption refrigeration system in a basic cycle option at different solar collector locations on the coefficient of performance in Algeria is shown in Fig. 8.as can be seen from Fig. 7 that the COP changes and varies with the change of the working pair and even the solar collector site. The composite/ethanol working pair has shown a better performance than the AC/methanol, while the zeolite/water working pair has the lower one. Similar results were seen with the variation of the studied sites, which led to the change in solar radiation and then the COP difference. The city of Tamanrasset and Ghardaia has the best performance for the composite/ethanol working pair with a COP of respectively, while the sites of Algiers and Constantine present the lower performance for the zeolite/water working pair with a performance of respectively.

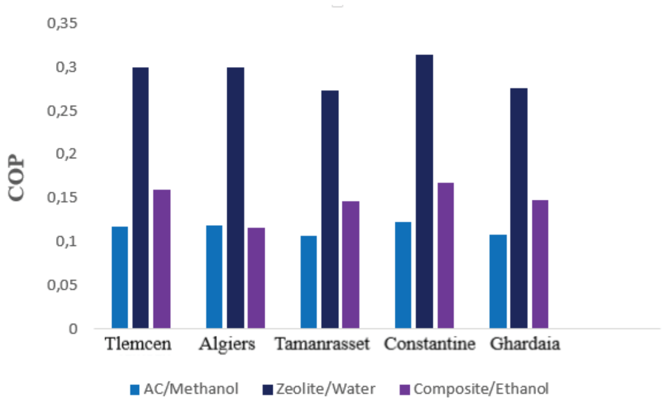

Fig. 7. COP variation with a working pair type for different solar collector locations in Algeria

D. *System Optimization*

In this work, the objective of optimization is to find the best possible performance of a selected working pair. The study consists of varying the operating parameters, including the condensing and evaporating temperatures, as well as the solar collector area for the Composite/Ethanol working pair for best configurations and operating parameters affecting the system performance.

1. Effect of solar collector area

Fig.8 represents the effect of the solar collector area on the performance of the solar adsorption refrigeration system for the composite/ethanol working pair at the Tlemcen site. As can be seen from the figure, the COP decreases with the increase in the solar collector area for both types of pairs. This is due to the fact that increasing the solar collector area will increase the daily total solar irradiance G(t) while the cooling production during the day is the same. Consequently, the variation of the cooling production is too much lower than the variation of the solar irradiance due to the increase in the solar collector area, which causes the decrease in the COP.

 Volume 11, Issue 1, June 2025 - ISSN 2356-8569
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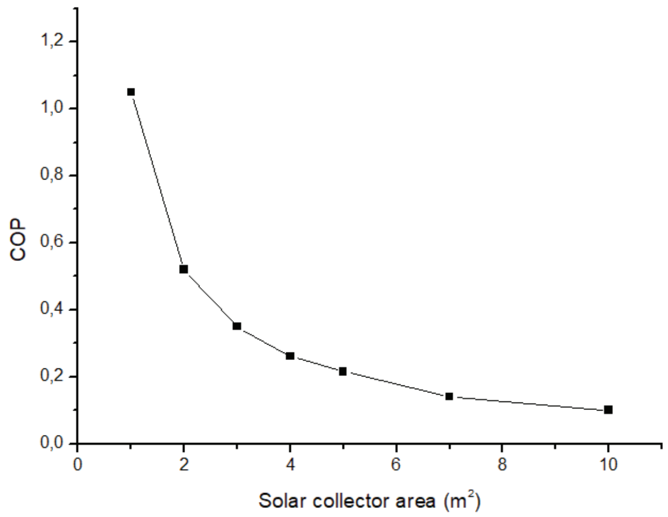

Fig. 8. Effect of solar collector area on system performance

2. Effect of condensing temperature

The effect of condensing temperature on the system performance for the composite/ethanol working pair at the Tlemcen site is shown in Fig. 9 for a fixed evaporating temperature of 5 °C. The figure shows that the increase in condensing temperatures leads to a slight decrease in COP. This is due to the fact that the increase in condensing temperature causes an increase in the sensible heat of condensation, but in a slight manner. So, the enhancement in the sensible heat of condensation leads to a decrease in the difference between the latent heat of evaporation and the sensible heat of condensation, which leads to a decrease in cooling production and COP. For good system performance, the condensing temperature should be kept lower in the range of twenties, and in order to keep it lower, especially in summer, it is better to adopt a cooling system for the condenser with water instead of the natural convection of the air.

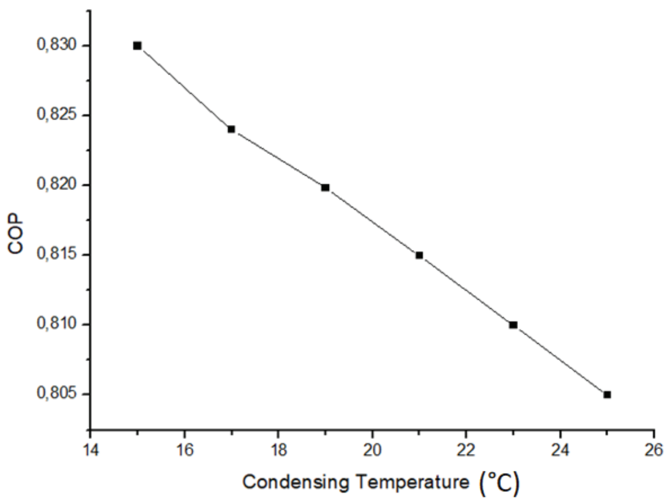

Fig. 9. Effect of condensing temperature on system performance

3. Effect of evaporating temperature

The effect of evaporating temperature on the system performance for the composite/ethanol working pair at the Tlemcen site is shown in Fig. 10. As can be seen from the figure, the performance of the system given by the COP increases as the evaporating temperature increases for a condensing temperature of 25 °C. This is because the enhancement in evaporating temperature leads to the increase in the adsorbate latent heat of evaporation $l(T_e)$ .The sensible heat of evaporation rests much lower than the latent heat, which is why it has a neglected effect on performance. So, the evaporating temperature positively affects cooling production and the COP of the system. In general, the evaporating temperature depends on the type of cooling, i.e., for ice making, it is better to limit it between -5 °C and -10 °C and for air conditioning and the cold rooms, the evaporating temperature can be fixed between 5°C and 10°C respectively.

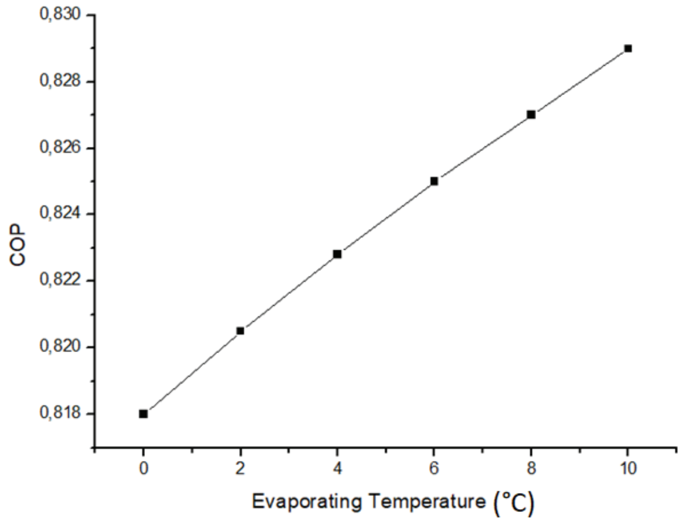

Fig. 10. Effect of evaporating temperature on system performance

VII. CONCLUSION

A comparative study based on a thermodynamic model of a solar adsorption cooling system was carried out. The adsorption capacity (X) of a three chosen working pairs for adsorption process has been theoretically studied basing on the Dubinin-Astakhov (D-A) model. The study was conducted over a temperature range from 27°C to 127°C and pressure of 2 bars.

A comparative study was conducted on the effect of the various working pairs on the coefficient of performance of a solar adsorption refrigeration system in a basic cycle option at different solar collector locations. The chosen working pairs were AC/methanol, Zeolite/water, and composite/ethanol, while the studied sites were Tlemcen, Algiers, Tamanrasset, Ghardaia, and Constantine in Algeria. The effect of the solar collector area, the condensing and evaporating temperatures, and the coefficient of performance for the composite/ethanol working pair at Tlemcen City were discussed.

The results show that the maximum adsorption capacity was found to be 0.31, 0.25, and 0.62 kg of adsorbate/kg of adsorbent, respectively, for the selected working pairs AC/methanol, Zeolite/water, and composite/ethanol. Results show that the maximum COP of 0.314 was achieved with Zeolite/water for the solar collector location of Constantine City, while the minimum COP of o.107 was achieved with the AC/Methanol working pair for the Tamanrasset city location. In addition, the optimization results show that the system performance strongly varied with the solar collector area and was sensitive to the operating temperatures.

The system costs of the cooling effect are set to be very high in comparison with other technologies like the vapor compression cycles, which are the widest used in the world. Thus, the low performance of the adsorption systems and the high cost of the adsorption cooling effect are the main factors that prevent the significant market extent of this technology.

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