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Subject

Techno-economic analysis of adsorption solar refrigeration systems: Application in Algeria

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With sincere appreciation,

Asmaa GOUACEM & HARUN Osman Maimuna .

Dedication

To our dearest family, friends, and ourselves,

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May this work contribute to the collective knowledge, and may it stand as a tribute to the bonds that sustain us.

With heartfelt appreciation,

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الملخص

يهدف هذا العمل إلى تقييم معامل أداء وتكلفة التبريد الناتج عن آلة التبريد بالامتزاز باستخدام معادلات دوبين-أستاخوف و برنامج **MATLAB**

تعرض هذه الأطروحة الوضع الحالي لفن نظام التبريد بالامتزاز الشمسي الذي يعمل بأزواج عمل امتزازيه مختلفة. ويرتبط تطبيق أزواج العمل المختلفة لأقصى قدر من الإشعاع الشمسي المختلف الذي تم الحصول عليه من برنامج **METEONORM**

بمعادلات نمذجة التوازن عند درجات حرارة وضغط مختلفين لحساب الحرارة المستقبلة والبرودة المنتجة وبالتالي معادلة **COP** والتكلفة. وبعد مراجعة شاملة للأدبيات، تم التوصل إلى أن هذه التقنية على الرغم من جاذبيتها إلا أن لها قيود، وهي انخفاض معدل الأداء في الأداء**(COP)** ، وأن زوج الكربون المنشط/الميثانول هو الأكثر كفاءة.

الكلمات الدالة: الطاقة الشمسية، امتزاز، التبريد، فحم منشط/ ميثانول، معامل اداء الحراري*

Abstract

This work aims to evaluate the performance coefficient and cost of the cold produced by adsorption refrigeration machine using the Dubinin-Astakhov (D-A) equations and the MATLAB software. This thesis presents the most recent development stage of solar adsorption refrigeration system working with different adsorption working pairs. The application of different working pairs for different maximum solar irradiation (obtained from Meteonorm software) is related to the equilibrium modeling equations at different temperature and pressure to calculate heat received and cold produced and thus, the COP and the cost. After a comprehensive literature review it was concluded that this technology as appealing as it is, has a low COP, and that also carbon/methanol that is activated is the most used and efficient pair.

Key words: Solar energy, Adsorption, Refrigeration, Activated carbon/methanol, thermal COP.

Résumé

Ce travail vise à évaluer le coefficient de performance et le coût du froid produit par une machine de réfrigération à adsorption en utilisant les équations de Dubinin-Astakhov (D-A) et le logiciel Matlab. Cette thèse présente l'étape de développement la plus recente des systèmes de réfrigération par adsorption solaire fonctionnant avec différentes paires de travail d'adsorption. L'application de différentes paires de travail pour différentes irradiations solaires maximales (obtenues à partir du logiciel Meteonorm) est liée aux équations de modélisation de l'équilibre à différentes températures et pressions pour calculer la chaleur reçue et le froid produit et donc, le COP et le coût. Après un examen approfondi de la littérature, il a été conclu que cette technologie, bien qu'attrayante, a des limites, à savoir un faible COP, et que le couple charbon actif/méthanol est également le plus efficace.

Mots clés : Énergie solaire, Adsorption, Réfrigération, Charbon actif/méthanol, COP thermique

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A	Solar collector surface, m^2
MAC	Mean adsorbent cost
AC	Activited carbon
COP	Performance coefficient
	specific heat , kj/kg.k
D	Parameters of equation D-A
I	Solar intensity /m^2
$I_{c.max}$	The maximum solar intensity, W/m^2
G	Global solar irradiation, W
L	Latente heat, kJ/kg
M_a	Mass of the adsorbate, kg
n	Exponential constant
P	Pressure, bar
P_s	Saturated pressure, bar
Q_f	The effect of the cold produced , W
Q_a	Adsobed/Absorbed heat
Q_g	Heat from the generator
Q_c	condensed heat
Q_e	Evaporated heat
T	Temperature,
t	Time, s
X	Concentration rate, $kg.kg^{-1}$

Clues

cd	Condensation
ev	Evaporation
max	Maximum
min	Minimum

Greek symbol

	Absorbness of the collector
	Reflectivity of the collector
	The effectivness of the solar collector

General Introduction

Today, the growing and expanding need of refrigeration and cooling systems have brought about the increased consumption of primary energy, negative environmental issues and electricity peak load. The primary energy, fossil fuels energy, refers to energy derived from the combustion of fossil fuels, such as coal, oil, and natural gas. These fuels are formed from the remains of ancient plants and animals that have been subjected to geological processes over millions of years. Fossil energy has been a primary source of energy for human civilization for centuries, powering industrial activities, transportation, and electricity generation. However, the reliance on fossil energy has significant environmental and societal implications. Burning fossil fuels emits carbon dioxide (CO2) and other greenhouse gases, leading to climate change and air pollution. Furthermore, the extraction, processing, and transport of these fuels can harm ecosystems, contaminate water sources, and adversely affect human health. As concerns about climate change and environmental degradation grow, there is increasing urgency to transition away from fossil energy towards cleaner and more sustainable alternatives, such as renewae energy sources like solar, wind, and hydroelectric power. Governments, businesses, and individuals around the world are investing in renewable energy technologies and implementing policies to reduce dependence on fossil fuels and mitigate the impacts of climate change. This transition represents a fundamental shift in the global energy landscape and presents both challenges and opportunities for achieving a more sustainable and equitable future. Fossil fuels are the largest source of energy for electricity generation which is used in vapor compressed systems to provide refrigeration hence the increased electricity peak load. Traditional refrigeration systems which heavily rely on fossil fuels contribute significantly to global warming and climate change so in attempting to reduce the negative environmental impacts of fossil fuels while addressing the growing energy demand for cooling applications, solar refrigeration technologies have gained attention as sustainable alternatives utilizing solar energy for cooling purposes.

Solar cooling, a rapidly advancing field within the realm of renewable energy technologies, offers a sustainable and environmentally friendly approach to meeting the cooling needs of diverse applications ranging from residential and commercial buildings to industrial processes. Harnessing the abundant energy from the sun, solar cooling systems utilize various technologies to provide cooling without relying on traditional fossil fuel-based energy sources, thereby reducing greenhouse gas emissions and mitigating the impact of climate change. It offers a wide range of

cooling techniques powered by photovoltaic-based electrical and solar collector-based thermally driven cycles cooling systems. Solar cooling can be achieved by four basic methods: PV cooling, thermo-electrical, thermo-mechanical and thermos-cooling, and as the name suggests in the first one solar energy is converted into electrical energy, the second uses thermoelectric process, the third one converts the thermal energy to mechanical energy to produce refrigeration effect and the fourth one uses thermal refrigeration systems in which the refrigerant is directly heated through solar collector tubes hence the sorption systems. The execution of the framework is decided by calculating the performance coefficient . We dive into the essentials of sun based cooling innovation especially the sorption innovations investigating its standards, components, applications, benefits, and challenges.

Solar sorption refrigeration systems operate based on the principle of absorption and adsorption, adsorption is the adhesion of gas/liquid molecules to a solid surface while solar absorption refrigeration system utilizes the absorption process which involves the dissolution of a refrigerant into an absorbent material. The use of solar energy in these systems reduces the dependence on fossil fuels thereby contributing to a more sustainable energy future, has lower operating cost compared to traditional refrigeration systems and lower maintenance requirements. Despite their potential benefits, the efficiency of these systems is lower compared to conventional refrigeration systems due to the lower temperature difference between the refrigerant and the heat source resulting in reduced cooling capacity and although solar energy is essentially free the initial investment cost can be higher due to the cost of collectors, heat exchangers and storage systems.

The research aims to evaluate the adsorption refrigeration system considering the coefficient of performance (cop) and the cost of the cooling produced in dinars (dza/Kw of adsorption) by providing a comprehensive analysis of the Techno-economic aspects of solar adsorption refrigeration system by evaluating technical performance and efficiency, economic viability and cost-effectiveness, identifying barriers and challenges and explore potential applications and market opportunities. We will evaluate the technical performance and efficiency and the cost by using the available solar energy and the cold it will produce to calculate the coefficient of performance of a Dubinin-Astakhov solar adsorption model and by analyzing the cost of the components and the working adsorption pairs respectively.

We are going to cover the generalities of solar energy, its potential in Algeria and general cooling technologies in chapter one, our particular adsorption theme in chapter two, the methodology in chapter three and lastly our results and interpretation in the last chapter.

Chapter one

Bibliographic Research

Chapter one : Bibliographic Research

1.1 Introduction

In the current world, applying solar energy is considered an important innovation. On the agenda of science and technology, solar power offers the development of renewable and sustainable energy, considering the price fluctuations and shortages in conventional energy sources. Recognizing the positive impact of these concerns, Algeria, within its geographic location and its significant solar energy potential, offers a great opportunity to meet the increasing demand for cooling and refrigeration solutions while contributing to energy security, environmental sustainability, and socio-economic development. Leveraging the abundant solar resources and adopting innovative solutions gives the country the potential to be a leader in solar-powered refrigeration and pave the way for a sustainable future. A refrigeration system needs mechanical energy from conventional fuel sources, making it a significant source of carbon emissions and other greenhouse gases like HFCs and CFCs that play a significant role in ozone depletion. Based on this context, the solar refrigeration systems have gained immense attention because of their ecological benefits and energy savings.

1.2 Solar energy

Solar energy is the energy emitted by the Sun's rays. This radiation, which includes radio waves, gamma rays, and visible light, consists of photons, the basic units of light and carriers of so

lar energy. Solar energy originates from the nuclear fusion reactions powering the Sun. The Sun's radiation can produce heat, trigger chemical reactions, or generate electricity.[1]. To express in thermal units the solar energy reaching the earth's atmosphere in one year, if we adopt the unit Q, used in global energy studies (Q=1018BTU British Thermal Unit) and corresponding to 40 billion tonnes of normal coal, we find that this annual solar energy represents 5,000 Q units. We see how fantastic this energy is, if we compare it with the energy used by mankind , which in 1972 was equal to 0.2 Q, and secondly to the solar energy used by photosynthesis on our planet in one year, also equal to 0.2 Q.[2]

1.2.2 **Electrical energy**

Solar radiation can be directly converted into electricity using solar cells, also known as photovoltaic cells. These cells produce a little electric voltage when light hits the intersection between a metal and a semiconductor (such as silicon) or between two distinctive semiconductors. A single photovoltaic cell typically produces about two watts of power. However, by connecting many cells together in solar-panel arrays, it is possible to generate hundreds or even thousands of kilowatts of electricity, either in a solar power plant or a large household array. The energy efficiency of most current photovoltaic cells is about 15 to 20 percent. Because solar radiation intensity is relatively low, large and expensive assemblies of

cells are needed to produce even moderate amounts of power.[3]

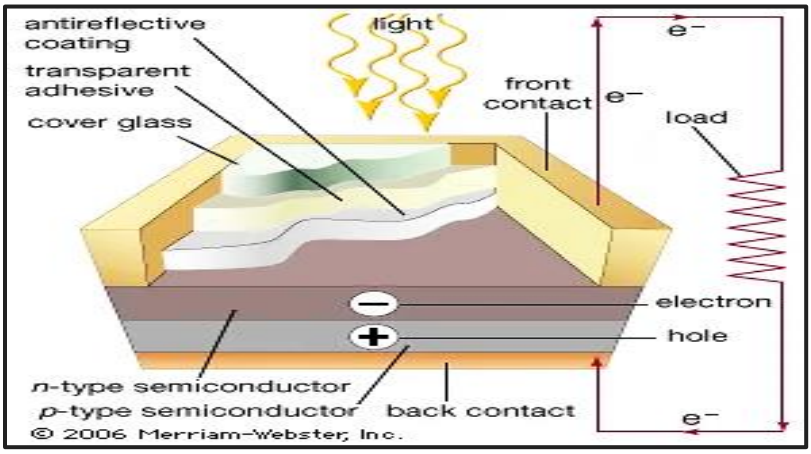

Figure1-.1solar cell

1.2.3 **Definitons**

Severel definitions will be useful in understanding the balance of this chapter.

Beam Radiation: Solar radiation received directly from the sun without atmospheric scattering. It's also known as direct solar radiation, avoiding confusion with diffuse radiation.

Diffuse Radiation: Solar radiation received after scattering by the atmosphere changes its direction. It's sometimes termed sky radiation or solar sky radiation in meteorological literature, distinguishing it from infrared radiation emitted by the atmosphere.

Total Solar Radiation: The combined sum of beam and diffuse solar radiation received on a surface.

Irradiation or Radiant Exposure (J/m^2): The incident energy per unit area on a surface, calculated by integrating irradiance over a specified time, often an hour or a day.

Insolation: A term specifically denoting solar energy irradiation, typically represented by the symbol H. Subscripts such as T and n indicate radiation on tilted or normal planes to the direction of propagation. If neither T nor n is present, radiation is assumed to be on a horizontal plane.

Radiosity or Radiant Exitance (W/m^2): The rate at which radiant energy leaves a surface per unit area, considering combined emission, reflection, and transmission.

1.3 Solar potential –The case of Algeria

The potential of solar refrigeration in Algeria is mainly because of the abundant solar resources and a growing demand for refrigeration and cooling solutions. [7] evidenced that Algeria receives high levels of solar irradiance throughout the year because of its geographical location in the Sahara Desert and Saharan regions. The country experiences clear skies and minimal cloud cover, resulting in optimal conditions for solar energy generation. For example, solar irradiance levels typically range from 1,800 to 2,300 kWh per square meter annually in most parts of the country, with some areas experiencing even higher levels of up to 2,700 kWh/m^2 [7]; [8]. Algeria can leverage its geographical potential because its land area and favorable geographic conditions provide ample opportunities for harnessing solar energy. The expansive desert regions offer vast

stretches of uninhabited land with minimal shading, ideal for large-scale solar projects such as solar farms and concentrated solar power (CSP) plants [9]. The flat terrain and low humidity also contribute to efficient solar energy capture and conversion.

1.3.1 Solar Radiation Data in Algeria

1.3.1.1 Definitions

There are basically two types of equipment for measuring solar radiation.

A **pyrheliometer** is an instrument that uses a parallel detector to measure solar radiation (i.e., normal incidence A) from the Sun and a small portion of the sky around the Sun.

Pyranometer is an instrument for measuring the total solar energy (beam and diffuse light) in a hemisphere, usually on a horizontal plane, in the shadow of the beam radiation. a pyranometer measures diffuse radiation.

The Algerian Climatology Centre comes under the supervision of the National Meteorological Agency. Measurements of solar radiation in Algeria are carried out through the network of the National Meteorological Office (ONM), which comprises 81 weather stations measuring the duration of solar radiation. fig1-3 shows the geographical distribution of these stations, where only seven stations are equipped with pyranometers and are used to measure the diffuse and global components received on the horizontal plane, while only two stations are equipped with pyrheliometers measuring direct radiation, plus a few global radiation measurements carried out by universities and research centers. In addition, these series of measurements contain missing data, which can be attributed to downtime.

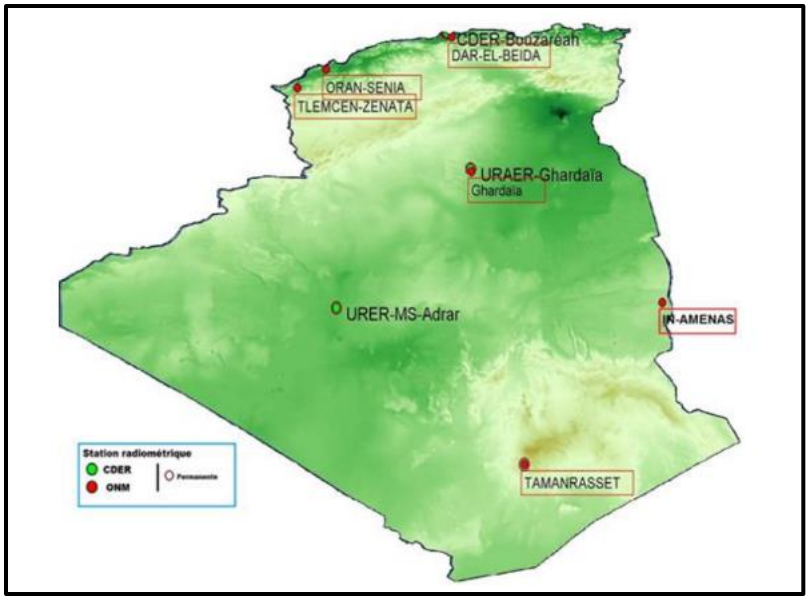

Figure1-2Pyranometric network (ONM)

1.3.1.2 Climatic characteristics in Algeria

Algeria has enormous potential for solar energy, due to the vastness of its area on the one hand, and its geographical location on the other hand, it's one of the richest solar fields in the world, considering the amount of energy received per square meter of 5 kWh, on most parts of the national territory, and sometimes up to 7 kWh, this allows an annual radiation exceeding 3000 kWh per square meter per year over an area of 2,381,745 km².[10] The average annual radiation in Algeria exceeds 2000 hours to reach 3,500 hours of sunlight in the desert, which constitutes 4/5 of its land area , thus it was concluded by the German Aerospace Center (DLR) that Algeria has the biggest sun powered potential within the Mediterranean bowl [11] where this solar capacity represents [12]

- 169,440 terawatt-hours per year,
- 5000 times consumption of Algerian electricity,
- 60 times consumption of Europe's electricity ,
- 04 times consumption of global electricity

The following table shows the capacity of solar energy capacity in Algeria in different regions. [13]

Solar energy capacity by region in Algeria.

Table 1Solar energy capacity by region in Algeria.

Regions	**Coastal areas**	**High plateaus**	**Sahara**
Area %			
sunshine duration (hours / year)			
Rated power (kWh/m²/ year)			

Algeria, through its geographical location, enjoys large amounts of solar brightness. This makes it an important solar mine.

The South, in particular the southeastern and southwestern, have the largest potential of the entire Algerian territory as shown in fig 1-4.

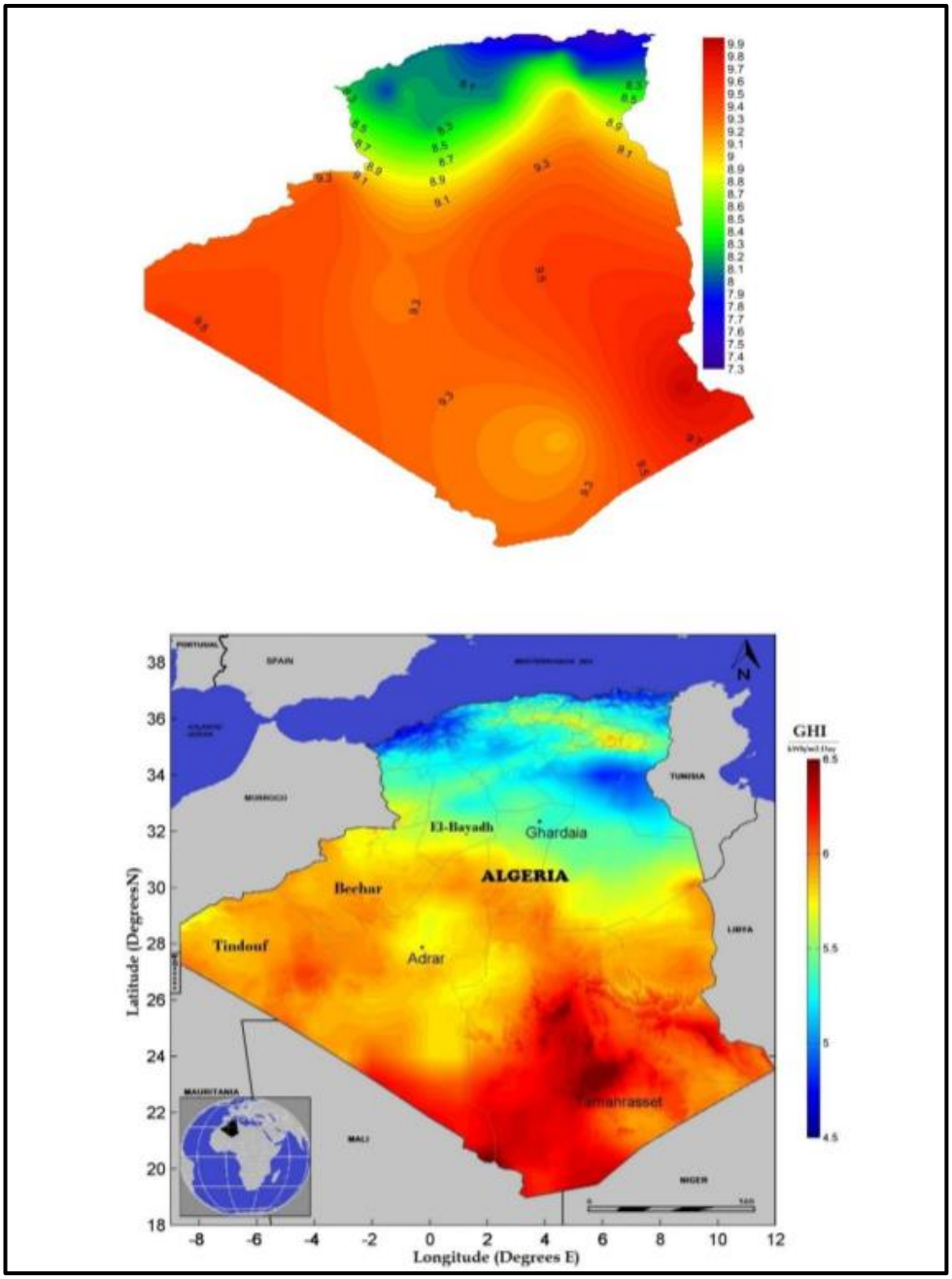

Figure1-.3Map of the average annual sunshine duration in hours (1983-2012)

The following figure shows the monthly average of the insolation duration of the year (1983-2012) and the year of potential insolation (the maximum duration of insolation) , we see that the best and the long duration of insolation is by the months of Jully and august .

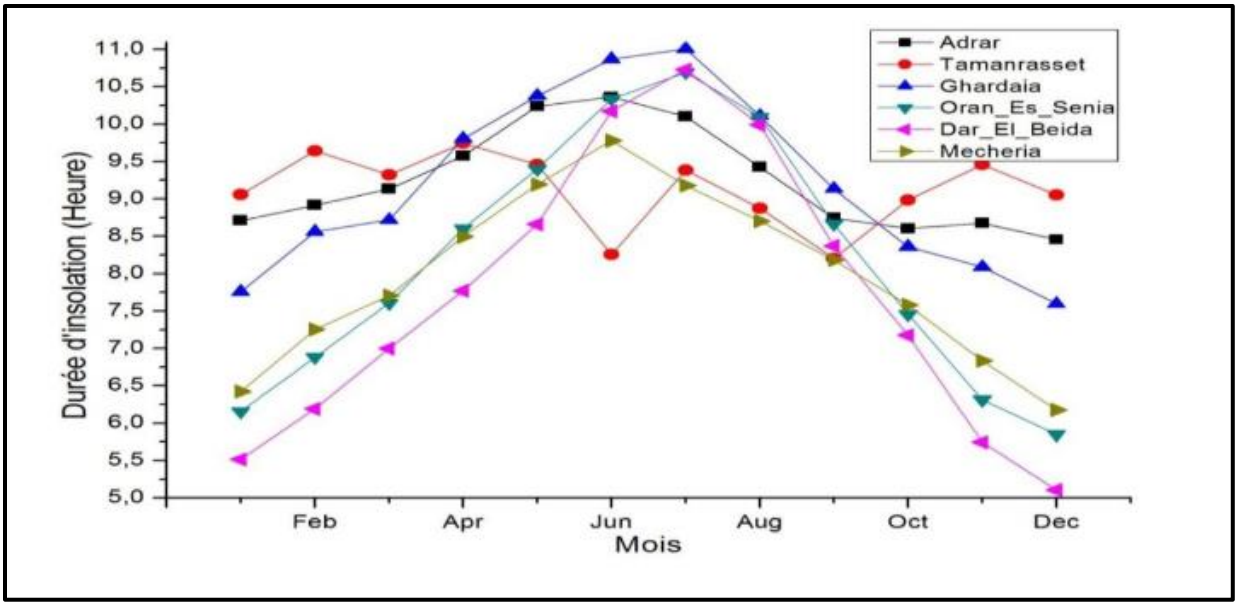

Figure1-4The change in the monthly average of the daily insolation durations of six region

1.4 Solar Cooling Technology

Two approaches can be used to leverage solar energy in solar cooling systems.

1.4.1 Solar photovoltaic (PV)

It allows for the direct conversion of sunlight into electricity, which powers the components necessary for cooling through either absorption or adsorption cooling cycles [15]. Solar PV panels will be used to generate the electricity that will be used to drive the electric prime mover of the conventional cooling machine or create the cooling effect in the thermoelectric element [16]. The photovoltaic cells are the heart of the system. They are made of semiconductor materials, like silicon, which can convert sunlight directly into electricity through the photovoltaic effect [17]. When sunlight strikes these cells, it excites electrons within the material, generating an electric current. The photovoltaic cells are arranged in solar panels, typically installed on rooftops or in areas with ample sunlight [18]. These panels capture sunlight and convert it into direct current (DC) electricity. The DC electricity produced by the solar panels needs to be converted into alternating current (AC) electricity to power standard household or industrial appliances. An inverter does this conversion [19]. The electricity generated by the PV panels is used to power the cooling system components. This might include the compressor, fans, and pumps necessary for the cooling cycle to operate [17]. The biggest advantage of using solar panels for refrigeration is the simple construction and high overall efficiency when combined with a conventional vapor compression system.

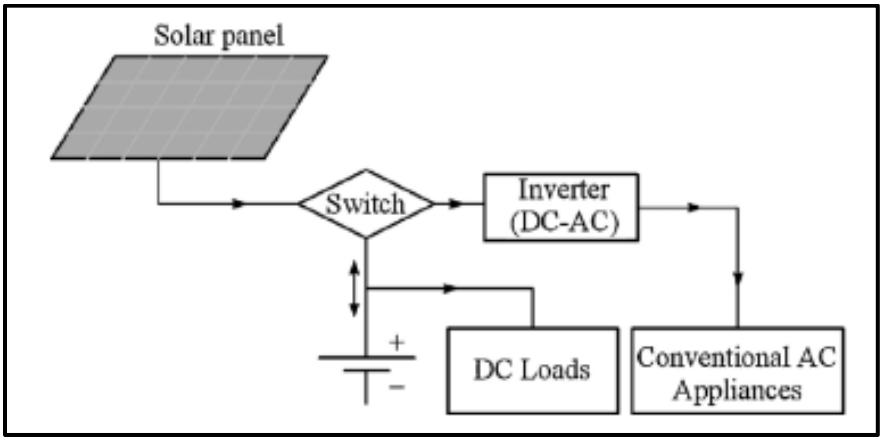

Figure 1-5Schematic of a stand-alone PV system.

Besides vapor compression cooling, some other types of electric refrigeration technologies can be used in combination with solar panels, these are thermoelectric, stirling, thermo-acoustic and magnetic refrigeration which have different COPs and varying cost.[4].

1.4.2 **Solar thermal energy**

1.4.2.1 Thermo-mechanical

The system shown in fig1-7 includes equipment like concentrating sun-based collectors or evacuated tube collectors [21]. These collectors generate steam, which is processed in the thermodynamic cycle to create a cooling effect like in ejector systems[22]. The thermo-mechanical cooling utilizes solar energy to drive a mechanical cooling cycle, typically based on the principles of thermodynamics. The process starts with a solar collector. It absorbs sunlight and converts it into thermal energy [21]. The collector may consist of mirrors or other concentrating devices to focus sunlight onto a heat-absorbing medium, such as a heat transfer fluid or a solid material [21]. The collected thermal energy is transferred to a working fluid, such as a refrigerant or a heat transfer fluid circulated through the system. This heat transfer raises the temperature of the working fluid. The working fluid undergoes thermal expansion, typically in a heat exchanger or an expansion valve [4]. The expansion increases the pressure and volume of the fluid while reducing its temperature. As the working fluid undergoes the mechanical cooling cycle, it absorbs heat from the environment, such as a refrigerated space, causing a cooling effect [22]. This heat absorption lowers the temperature of the conditioned space, providing the desired cooling. After absorbing heat from the environment, the working fluid releases this heat in a heat rejection process [22]. This heat is typically expelled to the surroundings, allowing the working fluid to return to its original state and complete the cycle. This technology can be beneficial in off-grid or remote locations where access to electricity is limited, offering a sustainable and environmentally friendly cooling solution [23].

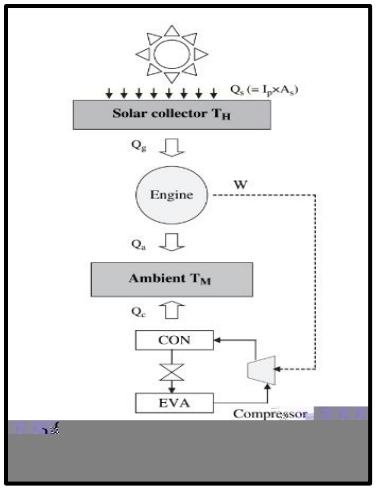

Figure 1-6Solar thermo-mechanical refrigeration system.

1.4.2.2 Thermal sorption system

It has several subsystems that work together to generate the cooling effect. These systems typically involve sorbent materials that can adsorb and desorb refrigerant vapors, allowing for the transfer of heat and the generation of cooling effects[22]. The system has solar collectors, energy auxiliary units, a heat rejection module, and a sorption system. Solar collectors absorb the thermal solar energy and send it to the sorption machine at a particular temperature [7]. An effective solar collector depends on the type of sorption machine and needs a specific temperature level. Evacuated tube collectors and concentrators usually produce thermal energy at high temperatures, effective for double or triple absorption systems [22]. The non-concentrating collectors produce thermal energy that delivers water at low or medium temperatures, making it suitable in some sorption systems. A heat rejection module is necessary in the thermal solar cooling system to remove excess and unrequired heat created during the thermodynamic cycle [22]. The cooling towers and complementary heat pumps are the conventional modules to facilitate heat rejection. The energy auxiliary units ensure increased effectiveness and reliability because of their actions when there is no solar energy or insufficient solar irradiation for operating the system under the required conditions. The auxiliary units include heat exchangers, energy storage elements, and auxiliary heaters [22]. However, places like Algeria, which receives sufficient solar energy generation, will not need energy auxiliary units [9].

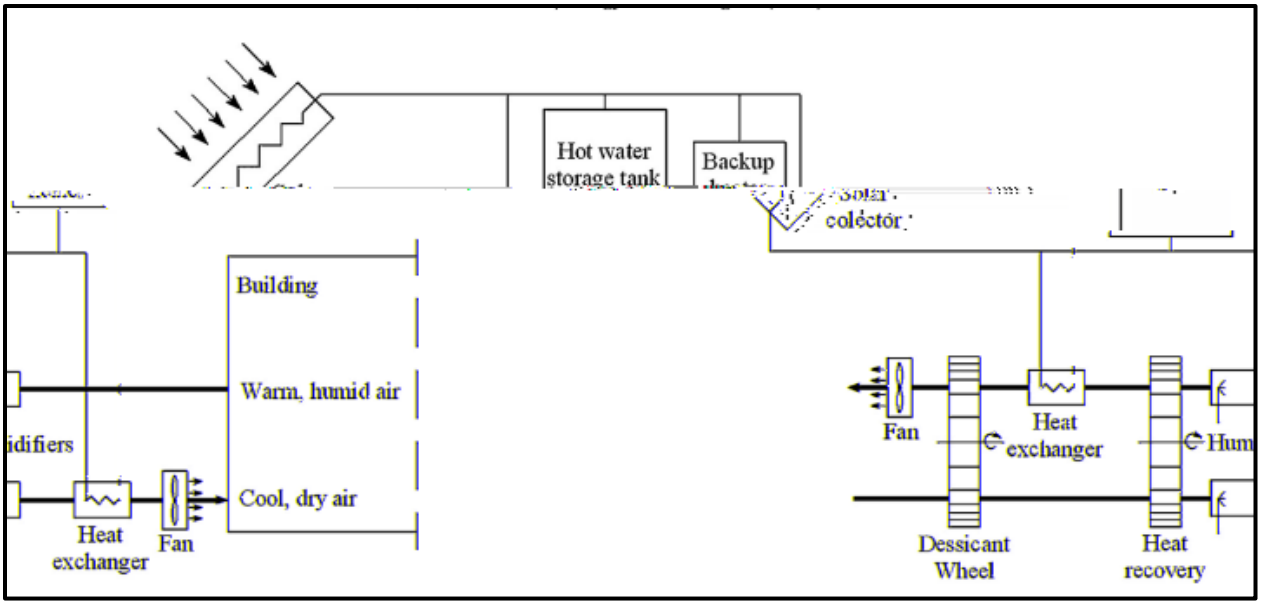

Figure1-7Schematic of desiccant solar cooling system.

The sorption machines rely on absorption, adsorption, and dissociative evaporative cooling (DEC) technologies. The adsorption and absorption systems use a closed cycle, while DEC uses an open cycle. Nevertheless, absorption technology has the highest thermal-driven cooling system globally, dominating the solar sorption cooling technology with about 82%-84% share [22]. Adsorption and DEC systems have 9%-11% and 7% shares, respectively [22]. The primary distinction between adsorption and absorption technologies is their respective technology in the sorption approach [23]. For example, the technology in absorption entails the sorption process being done by an absorbent material as the volumetric phenomenon. However, the technology behind the sorption process is conducted by a solid adsorbent material as the surface phenomenon [22]. The approach in DEC systems can be adsorption or absorption. The frequently used absorbents include water, silica gel, LiCl, and LiBr [22]. The right technology is chosen for different cooling applications, such as refrigeration and air conditioning, depending on the availability of absorbent, the needed refrigerant conditions, peak load time, available technology or capacity, control system strategy, and equipment required [23]. When [22] compared solar-powered cooling systems with conventional ones, they highlighted various optimization approaches that can be used to leverage the efficiency of these systems. Solar sorption systems are viable when a suitable combination of system components is used.

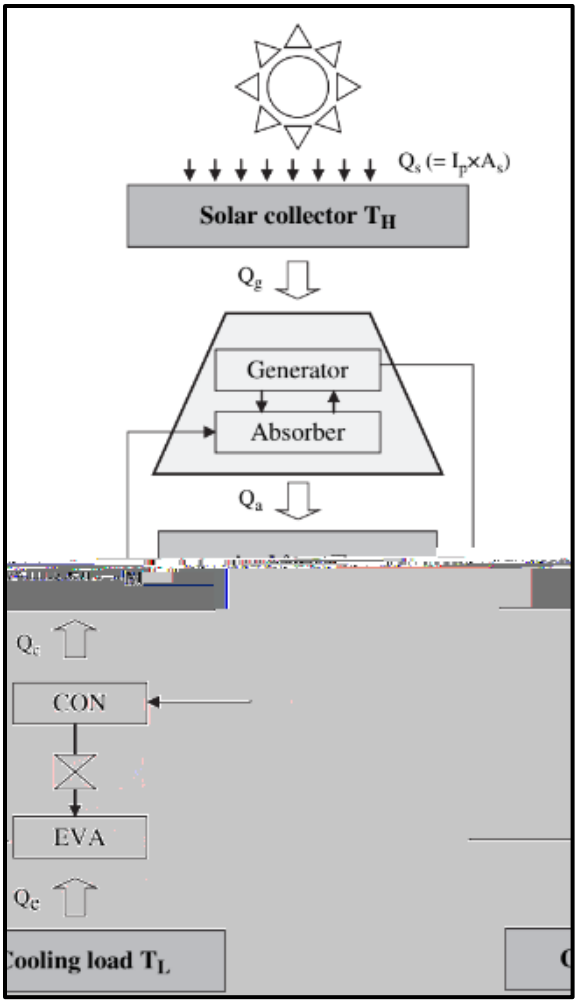

Figure1-8Solar sorption refrigeration system

1.4.3 **Coefficient of Performance (COP) of Solar Cooling Technology**

The Coefficient of Execution (COP) could be a key metric utilized to survey the proficiency of cooling frameworks, counting those fueled by sun oriented vitality (Duffie & Beckman, 2013). In the context of solar cooling technology, the COP indicates the ratio of cooling output, in terms of thermal energy removed from the conditioned space, to the input energy, typically electrical energy required to achieve that cooling (Duffie & Beckman, 2013). The performance of this refrigeration s energy indicators. Therefore, the COP can be calculated as:

— (1)

In this equation

E_u is the cooling output,

whereas E_c is the electrical input [15].

In solar cooling technology, the electrical input comes from the electricity generated by the photovoltaic (PV) panels, which convert sunlight into electricity. This electrical energy powers the cooling system's components, such as compressors, fans, and pumps. The cooling output is the amount of heat removed from the conditioned space, which provides the desired cooling effect (Duffie & Beckman, 2013). This is typically measured in units of power, such as kilowatts (kW) or British thermal units per hour (BTU/h)[20]. A higher COP value indicates greater efficiency, which means more cooling output is achieved per unit of electrical input[4]. Therefore, maximizing the COP is crucial for optimizing energy efficiency and reducing operating costs in solar cooling systems. The COP of a solar cooling system can vary depending on factors such as the system's design, the efficiency of the components, the climatic conditions, and the cooling load requirements of the conditioned space[22]. Additionally, different types of solar cooling technologies, such as absorption or adsorption, may have different COP values. The COP helps to evaluate its effectiveness in utilizing solar energy for cooling purposes [24].

1.4.4 **Economic Aspect of Solar Cooling Technology**

[25] asserted that using solar energy for refrigeration offers economic prospects because the

cooling from the sun is an attractive opportunity for people. Therefore, leveraging the abundant solar resources and adopting innovative solutions gives the country the potential to be a leader in solar-powered refrigeration and pave the way for a sustainable future. The economic assessment conducted by [25] aimed to provide stakeholders with valuable information and insights to support decision-making regarding the adoption of solar cooling systems. By quantifying the costs, benefits, and financial implications associated with this renewable energy technology, the research contributed to. understanding its economic potential role by mitigating climate change, reducing energy consumption, and achieving sustainable development goals.

Research studies like [25] and [4] provided a comprehensive assessment that helped to determine the costs and financial impact of using solar cooling technology vis-à-vis conventional cooling

systems. The main factor in this assessment was the cost analysis through the required initial investment. Usually, a user wanting solar cooling technology is supposed to pay upfront the lifetime system costs. For example, the researchers determined the costs incurred when installing the solar cooling systems such as the cost of solar collectors, absorption chillers, storage tanks, and other necessary components. The study also evaluated the operational and maintenance costs, which are low compared to the initial costs (Otanicar et al., 2012). The cost analysis deduced that solar cooling technology has a high initial cost, impeding the extensive commercialization of this technology. This assessment helped to conceptualize financial modeling that helped to compute the return on investment (ROI) and payback period for solar cooling systems.

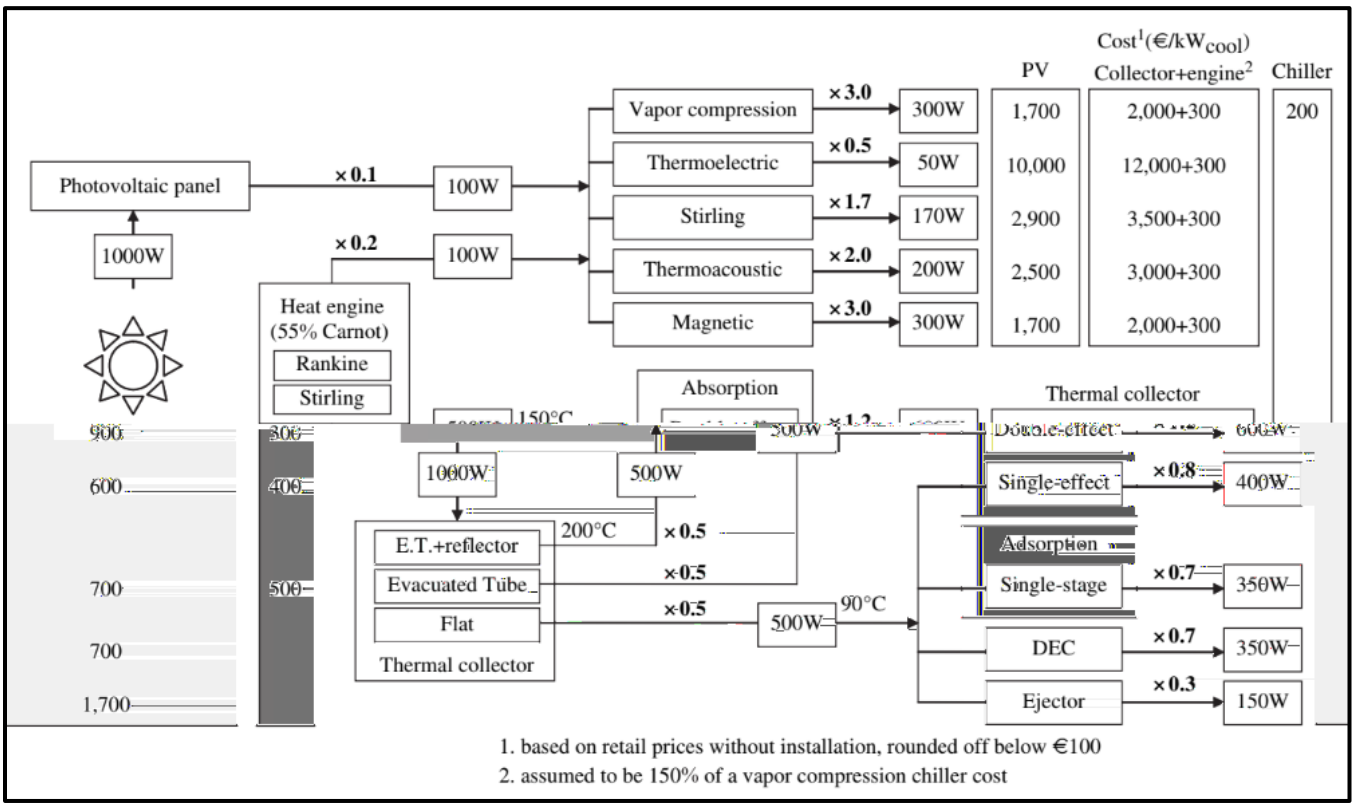

Figure1-9COP and cost of various solar refrigeration systems.

1.5 Conclusion

Chapter Two

Thermodynamics of adsorption

2 Chapter Two :Thermodynamics of adsorption

2.1 Introduction

2.2 Principle of Adsorption

The principle of adsorption revolves around the reversible process wherein molecules in a refrigerant adhere to the surface of a solid adsorbent materials. This adherence occurs because of the weak intermolecular forces including Van der Waals forces between the adsorbate and the adsorbent material. In the context of adsorption refrigeration, solar heat is used to induce the sorption of of the refrigerant molecules from the adsorbent material. To enumerate, the heart of an adsorption refrigeration system lies in its working pair, which comprises of combination of materials including silica gel/water, activated carbon/methanol, activated carbon/ammonia, zeolite/water, or activated carbon granules and fiber adsorbents. The adsorption cycle typically involves two sorption chambers, an evaporator, and a condenser. Water vapor is first vaporized under low pressure and low temperature in the evaporator. Nevertheless, the vapor goes to the sorption chamber where solid sorbent such as silica gel, adsorbs the water vapor [25]. In another sorption chamber, the water vapor is released by regenerating the solid sorbent through the application of heat. The condensed water vapor returns to liquid form through cooling water supplied from a cooling tower. Through alternating the functions of the two sorption chambers, chilling water is continuously obtained.

2.3 History of adsorption

Adsorption technology is rooted to have started in the 19th century. Since then, this technology has seen significant evolution and application. The early developments in adsorption were majorly focused on comprehending the fundamental principles of this phenomenon. However, it was not until the early 1990s that the adsorption technology found practical application in refrigeration and heat pumps, marking a new era in its uses[27]. Historically, the earliest mention of adsorption phenomena for refrigeration dates back to 1848, when Faraday discovered that silver chloride could produce cooling by adsorbing ammonia. Compression refrigeration systems emerged in the 1930s following the development of Freon. During the 1970s energy crisis and over the past four decades, the environmental impacts of traditional refrigeration systems have been globally acknowledged, providing a significant opportunity for the advancement of adsorption refrigeration systems (ARSs) [28]. This shift towards adsorption technologies underscores the growing recognition of their potential to offer efficient and environmentally friendly solutions for refrigeration and cooling needs. All in all, the history of adsorption technology reflects a journey from fundamental scientific exploration to practical applications in refrigeration and heat pump systems. [20]. With ongoing advancements and the integration of renewable energy sources, adsorption-based refrigeration systems are dignified to play a significant role in addressing the challenges of sustainable cooling in the future.

2.4 Definition

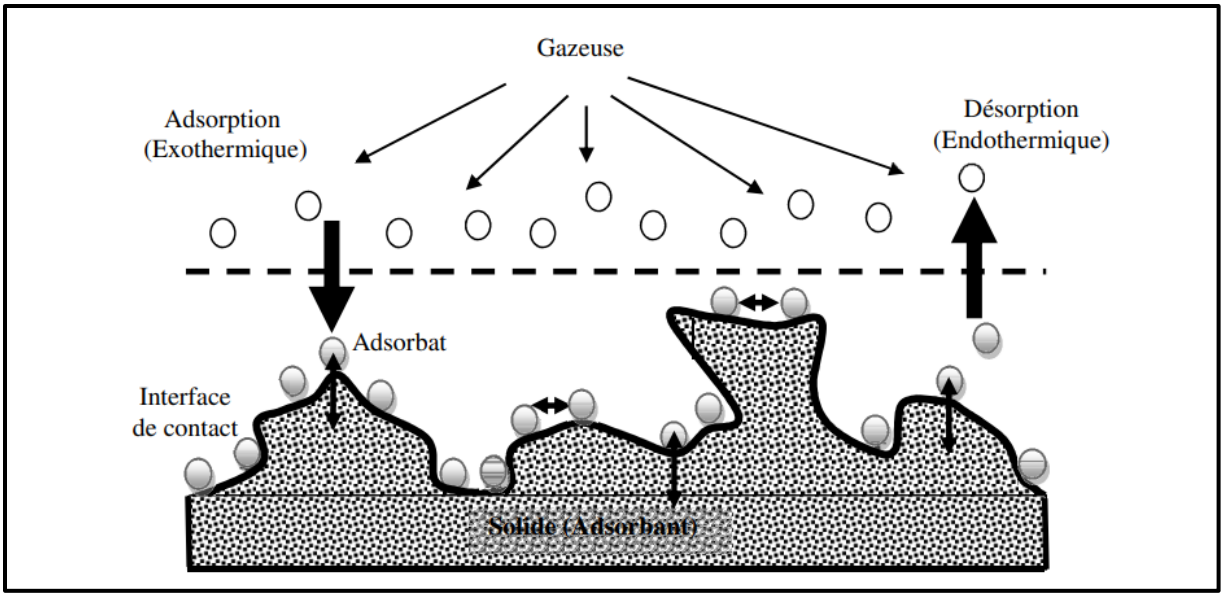

Figure 2-1Adsorption phenomenon

2.5 Types of adsorption

2.5.1 Chemical adsorption

In chemical adsorption, the process occurs due to a chemical reaction that forms chemical bonds between the adsorbate molecules (refrigerant) and the adsorbent's (solid) surface. This strong bond has a fairly high binding energy of the order of 50 to 400 kJ/mol making it harder to reverse contrasted to physical adsorption. [31]. It is an irreversible phenomenon favoured by high temperature. Under the right conditions, chemical adsorption can often be superimposed on physical adsorption. (N). In chemical adsorbents, the uptake is not restricted by the material's surface area, typically resulting in higher mass transfer kinetics compared to physical adsorbents. Metal chlorides are often used as chemical adsorbents due to their high adsorption capacity. Examples include calcium chloride (CaCl2), strontium chloride (SrCl2), magnesium chloride (MgCl2), barium chloride (BaCl2), manganese chloride (MnCl2), and cobalt chloride (CoCl2), among others. Calcium chloride (CaCl2) is a common chemical adsorbent in solar cooling applications. It adsorbs ammonia to produce particular chemical compounds like CaCl2$8NH3 and CaCl2$6H2O. Physical adsorbents like silicates and chemical adsorption have been combined to improve refrigeration performance. Chemical adsorption, in which hydrogen is used as the refrigerant, is another method that is utilized in metal hydride refrigeration systems [33]. Reversible reactions take place during heating and cooling cycles in these systems, which make

use of beds filled with both high-temperature and low-temperature hydrides. Chemical adsorption technologies continue to be investigated for further advancements in refrigeration and heat pump systems, despite trials involving low cooling power density. They offer a unique advantage in particular applications.

2.5.2 **Physical adsorption**

2.6 Adsorption mechanism

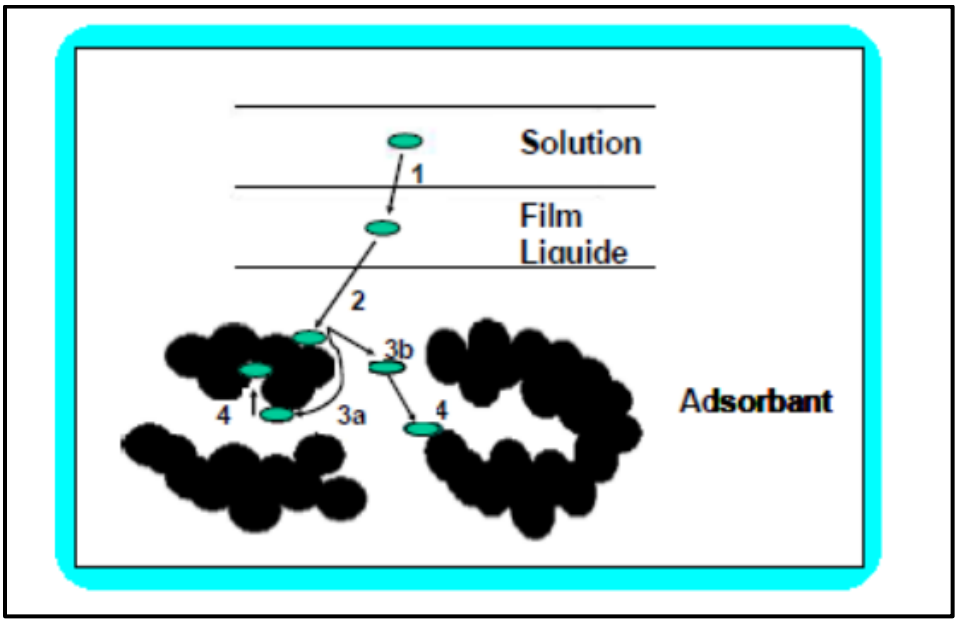

Figure 2-1adsorption mechanism

2.7 Adsorption isotherms and classifications

The thermodynamic state of a couple (adsorbent-adsorbate) is characterized by a relationship between three quantities: mass (x), pressure (P) and temperature (T). The determination of the form of this relationship is reported in the literature dealing with the thermodynamics of adsorption. It can be seen that the equilibrium can be described in three ways:

The adsorption isotherm x=f(P)T

Adsorption isobar x=f(T)P

Adsorption isostere P=f(T)x

The adsorption isotherms shown have variable shapes and can be grouped into five types into five types according to their overall appearance based on the classification of Brunauer, Emmet and Teller[41], shown in Figure2.3

Type I: Langmuir isotherm representing cases of mono-molecular adsorption

(monolayer) adsorption.

Type II: This is the most frequently encountered isotherm, when adsorption occurs on surfaces that are not microporous or have macrospores, it is characteristic of a superiority of the attraction by the adsorbent compared to the intermolecular attractions of the

the adsorbate.

Type III: This type represents the adsorption phenomenon in which the interaction between the adsorbent and the adsorbed molecules is weak compared to the adsorbate-adsorbate interactions, but sufficient to increase the tendency of the molecules to accumulate on the surface of the adsorbent.

Generally, isotherms I, II and III are reversible where desorption follows the same curve as adsorption.

Type IV, V: These types are characterized by the presence of micropores and macropores in the adsorbent , the parts corresponding to low relative pressures are similar to those of type II isotherms.

those of type II and III isotherms, for the same reason. But the parts of the isotherms corresponding to higher relative pressures could be expressed by the filling of capillaries ending at a pressure lower than the saturation pressure due to highly developed because of the highly developed interaction forces prevailing in these capillaries, causing rapid condensation of the adsorbate.[42]

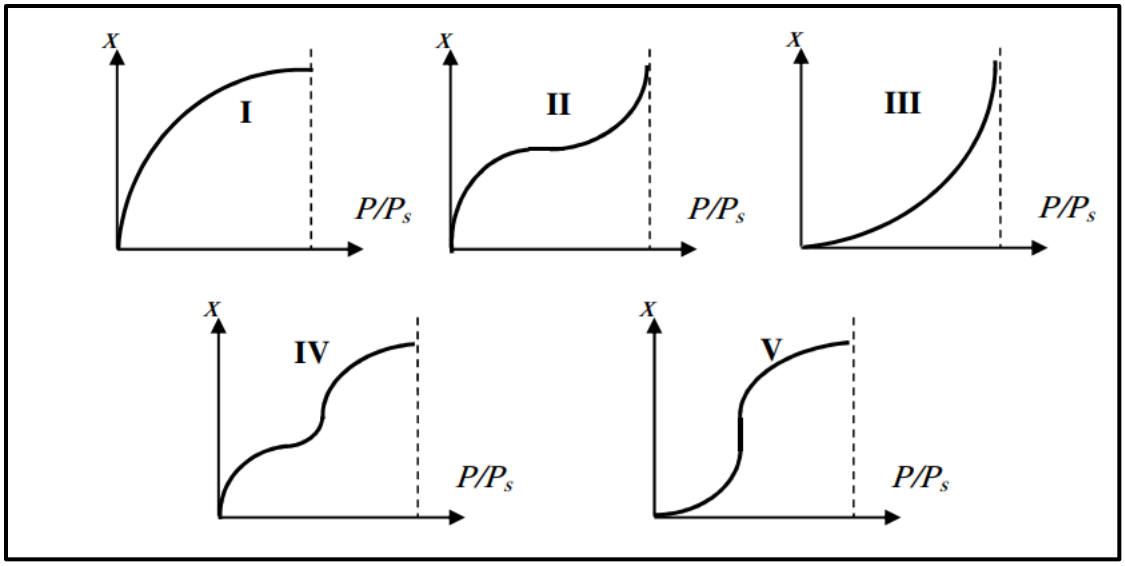

Figure 1-3Different types of adsorption isotherms

2.8 Factors influencing adsorption parameters

Adsorption depends on many factors, the main ones being[35]:

*Adsorbent characteristics: polarity, pore volume, specific surface area and Surface functions

*Adsorbate characteristics: polarity, solubility and molecular weight.

*physio-chemical parameters of the medium: temperature and pH.

2.9 Adsorbent and refrigerants

Based on the parameters mentioned above there are different physical and chemical adsorbent and adsorbate.

2.9.1 Chemical adsorbents and refrigerants

Chemical adsorbents mainly include metal chlorides, metal hydrides and metal oxides , but they are not suitable in adsorption because of the swelling and agglomeration that occurs during adsorption which influence the mass and heat transfer.[43]

Hydrogen and oxygen are examples of chemical refrigerants that can be adopted in adsorption refrigeration systems, but are inflammable, explosive and require extreme precaution to be handled.

2.9.2 **Physical adsorbents and refrigerants**

Activated carbon and activated carbon fiber: The microcrystal for the activated carbon produced from bone is a six element carbo-atomic ring [44], and the adsorption performance is influenced by the functional groups that is connected to the carbo-atomic ring. Activated carbon has a specific surface area ranging from 500 to 1500 m^2/g. Its pore network consists of irregular channels, with larger pores on the grain surface and narrower pores within the grain [45]. Unlike other adsorbents, activated carbon's surface is unique; it is coated with an oxide matrix and some inorganic materials, making it non-polar or only weakly polar. The specific surface area of activated carbon fibers is larger than that of activated carbon, the pores of activated carbon fiber are more uniform than that of activated carbon, and the heat tranabon, theance d

Separation and purification processes for liquid and gas mixtures, chemicals, isomers, and air involve various techniques. Here are some examples:

- Gas Masks: Gas masks, which protect against toxic gases like methane (CH_4), chlorine (Cl), and sulfur dioxide (SO_2), use specific adsorbents that preferentially adsorb these harmful gases to purify the air. Typically, they contain a layer of activated carbon for this purpose.

- Dyeing Applications: In dyeing, garments are first soaked in a mordant, such as alum, and then in the dye solution. The mordant is adsorbed onto the fabric, followed by the dye, resulting in better adhesion to the fibers.

- Hard Water Softening: Hard water, containing dissolved calcium and magnesium salts, is softened using ion exchange resins. These resins work on the principle of selective adsorption, removing ions that cause hardness. Zeolites in the permuting process adsorb calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, softening the water.

- Pharmaceutical Industry Applications: Some drugs can adsorb and neutralize pathogens, protecting against diseases. Activated carbon, magnesium oxide, and tannic acid are used to adsorb toxic substances. Adsorption is also essential in the preparation of vitamin B1, bacterial filtration, and other pharmaceutical processes.

- Sugar Clarification: Sugar is decolorized by treating its solution with charcoal powder, which adsorbs the unwanted colorants.

- Separation of Noble Gases: Noble gas mixtures are typically separated by adsorbing them on activated carbon, leveraging the different adsorption degrees of each gas.

Chromatographic Analysis: In chromatographic analysis, selective adsorption by a specific solid adsorbent is used to separate components of a mixture. For instance, in column chromatography, a vertical tube filled with an adsorbent allows the mixture solution to pass through, separating components as they are collected sequentially from the bottom.

Elimination of impurities from liquid and gaseous media. We cite the following examples in this case:

- Paint Industry: paint manufacturing, dissolved gases are removed using suitable adsorbents because these gases do not adhere well to surfaces and reduce the paint's covering power. Wetting agents are employed

to eliminate gaseous, liquid, or solid films from the paint's surface. Alcohol is often used as a wetting agent in furniture polishing.

- Removal of Coloring Materials: Adsorption is commonly used to eliminate unwanted coloring materials from raw sugar solutions, juices, vegetable oils, and petroleum. Adsorbents such as animal carbon, activated carbon, and fuller's earth are utilized for this purpose.

- Creating a Partial Vacuum: Adsorption of gases on solids, especially at low temperatures, is employed to create a partial vacuum. A container needing evacuation is connected to a vessel containing activated carbon immersed in liquid nitrogen. The adsorption capacity of gases on the solid increases significantly at low temperatures, allowing the gases to be adsorbed by the activated carbon, thereby creating a partial vacuum.

Recovery of chemicals from waste. Such as:

Application of Adsorption in Froth Flotation Process: The froth flotation process, commonly employed to concentrate sulfide ores, relies on adsorption. When sulfide ore is agitated with pine oil and water, the ore particles adhere to the froth that rises to the surface, while gangue particles like silica and earthy materials settle in the reservoir. The resultant froth contains the concentrated sulfide ore.

Industrial Waste Recovery: The separation of components in a mixture can be achieved by leveraging the different adsorption capacities of the mixture's components. Adsorption principles are utilized to recover valuable materials from industrial waste.

Drying Gases and Liquids: A well-known application of this process is dehumidification Certain substances have a solid partiality for water and can be utilized to diminish or dispose of dampness from the air. Silica gel is widely used for dehumidifying, particularly in protecting electronic equipment by absorbing moisture from the air.

Environmental applications

The main application concerned is water treatment, through the elimination of synthetic organic chemical pollutants contained in drinking water such as pesticides, herbicides, detergents, polycyclic aromatic hydrocarbons, and heavy metals like Cd, Cr, Hg , Cu, Fe, V, Zn. The procedure consists of using activated carbon or granular activated carbon to adsorb these constituents improving the taste and odor of the water.

Heat and cold pump adsorption applications

For energy reasons, ecological, the field of heating and air conditioning mainly aims to find alternative solutions to vapor compression machines because of the high consumption of electrical energy and the use of polluting refrigerants. Thanks to its characteristics given in the field of cold production, new research has proposed the technology of adsorption machines as an alternative solution to vapor compression systems.

The production of cold by adsorption can be powered by cogeneration installations by exploiting waste heat to produce cold, as can be powered by solar energy. This last application is the objective of the work proposed in this study and will be detailed in the next chapter.

2.11 Conclusion

This chapter provided an in-depth analysis of adsorption phenomena, examining its definition, history, working principle and its applications within the broader context of solar adsorption refrigeration. Through a comprehensive review of relevant literature and data we have identified adsorption continues to gain attraction and has the potential to fill gaps and create opportunities to reduce our carbon footprint.

As we transition into the methodology chapter, it is crucial to build upon these insights. The forthcoming chapter will delineate the research design and methods employed to investigate the efficiency and cost of adsorption. By employing the D-A equilibrium model equations we aim to systematically explore the roles played by solar irradiance and adsorbent-adsorbate concentration.

Chapter Three

Modeling of adsorption refrigeration machine

3 Chapter Three: Modeling of adsorption refrigeration machine

3.1 Introduction

From a thermodynamics perspective, an adsorption refrigeration cycle can be viewed as two distinct cycles: a heat engine and a refrigerator (or heat pump). These cycles operate across three temperature levels, with the work generated by the heat engine powering the refrigerator. Just as the vapor compression refrigeration system would, it has different components with specific roles. The adsorbed content of refrigerant varies cyclically, depending on the adsorbent temperature and system pressure which vary between maximum condensation pressure and minimum evaporation pressure. There are different working pairs of adsorbate-adsorbent used based on different working temperatures and the rate of heat transfer. The chapter aims to provide a thorough overview of the components of an adsorption refrigeration machine, the thermodynamic cycle, the working pairs and mathematical equations to determine the COP.

3.2 Basic cycle of an adsorption refrigeration machine

Realization of the ideal cycle of an adsorption refrigeration machine is based on the principle of the reversibility of physical adsorption: the molecules of the refrigerant vapor are fixed on the adsorbent when cooled and released from it when heated. The system is therefore bivariant, this means that only two independent variables completely describe the system and that the thermodynamic equilibrium is controlled by these two variables. So the mass of adsorbed the pressure P:

$x = f(T, P)$

We can see that balance can be described in three ways:[48]

- ✓ Isobars giving the mass adsorbed as a function of temperature x=f(T)
- ✓ Isotherms giving, the adsorbed mass as a function of the pressure x=f(P)
- ✓ Isosteres giving, the pressure as a function of the temperature P=f(T)

Generally, the isosteres are represented in a practical way in the diagram of Clapeyron (lnP, -1/T), in more detail. The operating principle of the thermodynamic cycle of the machine is represented on the Clapeyron diagram (lnP, -1/T), in Figure

This so-called ideal cycle represents the evolution of the state of the adsorbent/refrigerant mixture contained in the adsorber. The thermodynamic path is made up of two main phases: one heating phase of the mixture (adsorbent/refrigerant) and another of cooling of the same mixture. The modeling of the basic cycle of the adsorption refrigeration machine was the subject of numerous studies, both theoretical and experimental, it should be noted in particular the work by: [49],[50],[51],[52],[53].

3.3 Description of adsorption refrigeration machine

These are the different components of an adsorption refrigeration machine:

- An adsorber, also known as a generator or reactor, is in direct contact with a heat source. It contains highly porous materials called adsorbents, like silica gel, activated carbon, or zeolite, with a large internal surface area. These adsorbents have a strong ability to attract specific gases known as adsorbate or refrigerant, such as water, ammonia, or methanol. Typically, these adsorbents are arranged on a metal surface to facilitate heat transfer to or from a heat transfer fluid (HTF), often water, flowing through the bed. The adsorbent bed functions as a thermally driven compressor, cycling the refrigerant in an adsorption process by periodically alternating between heating and cooling the HTFs. [54]
- A condenser, in contact with an intermediate source in which the refrigerant (adsorbate) condenses at the condensation pressure
- A tank for storing liquid refrigerant.
- An evaporator, in contact with the cold source, in which the refrigerant vaporizes to the evaporation pressure thus producing the cold sought in the cold room.
- An expansion and check valves

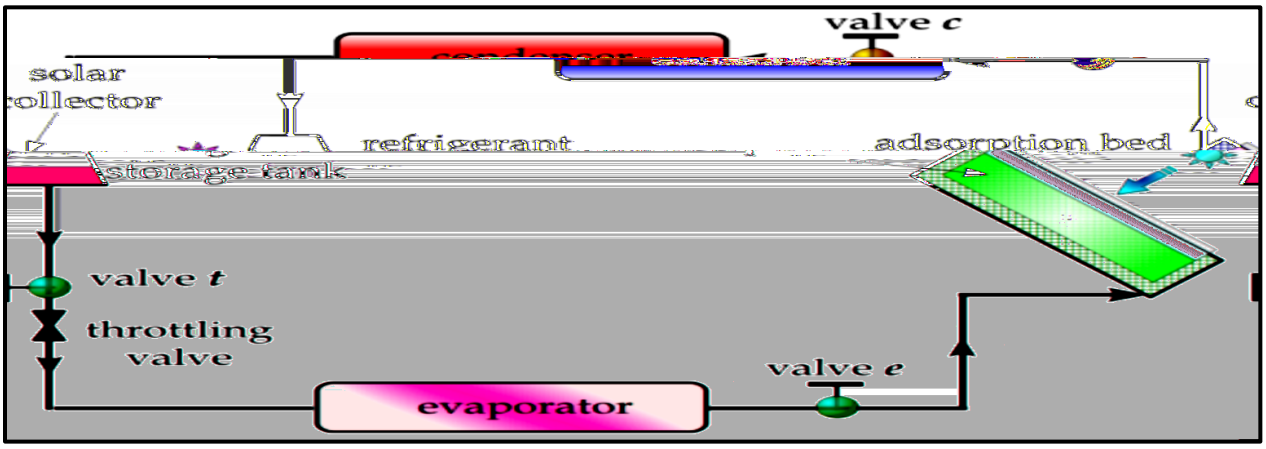

Figure 3-1schematic diagram of adsorption cooling

3.4 Ideal thermodynamic cycle of adsorption refrigeration machine

A basic adsorption refrigerator creates cooling by undergoing four consecutive stages: pre-heating, desorption, pre-cooling, and adsorption. A Clapeyron diagram (LnP vs. -1/T) is commonly employed to depict the four ideal thermodynamic processes of an adsorbent bed in relation to the isosteres of the adsorbent-adsorbate pair. This diagram helps in calculating the theoretical COP (Coefficient of Performance) of the cycle. In this ideal cycle, the adsorber (or adsorbent bed) functions between two constant pressures: the condenser and evaporator pressures, and the two levels of adsorbate concentration (minimum and maximum). [48]

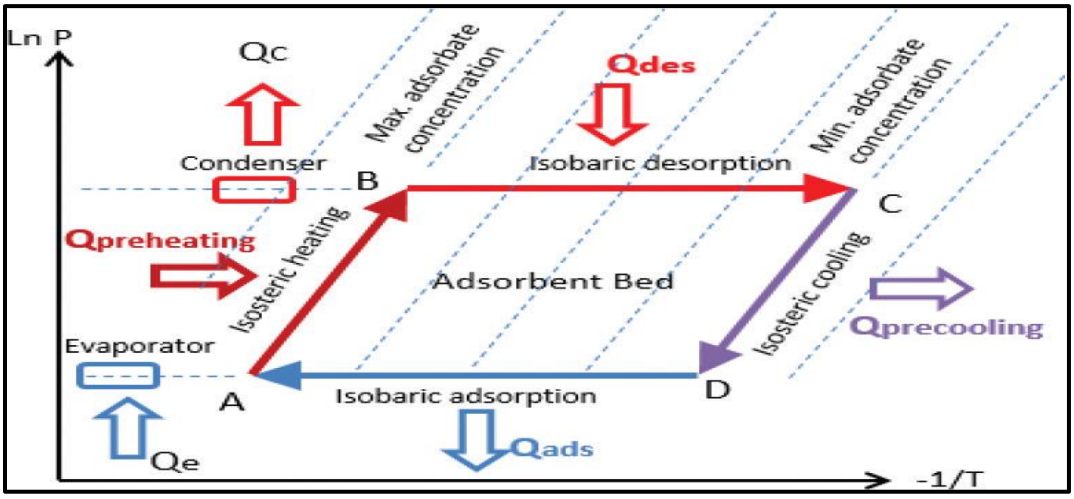

Figure 3-2Ideal Clapeyron diagram of an adsorption refrigeration cycle.

Based on the thermodynamic path of a refrigeration cycle as shown in the above figure each phase of the system cycle is analyzed assuming that:[48]

The refrigerant behaves like an ideal gas;

The sensible heat effects of the vapor phase are negligible;

n micropores, macropores and in interstitial spaces is negligible;

he adsorbed or desorbed refrigerant is considered to be liquid phase;

During the desorption-condensation and evaporation-adsorption phases, the pressure equals the saturation pressure and the condensation temperature equals the evaporation temperature, respectively;

or/adsorber during the phase of heating.

Pre-heating process (A−B): During this heating and pressurization phase, the valves connecting the adsorbent bed to both the condenser and evaporator are shut. The adsorbent bed functions as a closed system, being heated by a high-temperature heat transfer fluid (HTF) at temperature TH (High Temperature). As a result, the temperature of the bed rises, leading to an increase in vapor pressure inside. However, the total amount of refrigerant in the adsorbed phase remains constant at its maximum concentration. This phase continues until the vapor pressure matches the condenser pressure at point B.[32]

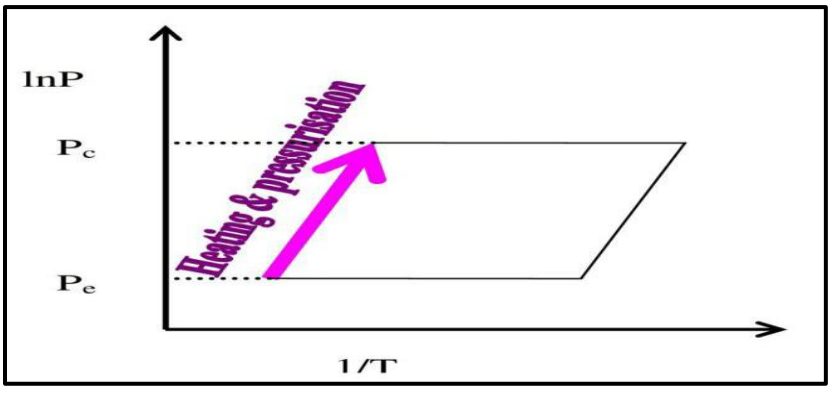

Figure 3-3heating and pressurization process

Desorption process (B−C): Following the initial phase, heating of the adsorbent bed persists as the valve connecting the bed to the condenser is opened. The temperature of the bed gradually rises, causing a portion of the refrigerant in the adsorbed phase to transition from the solid adsorbent surface to a vapor phase, known as 'desorption process'. This vapor then moves into the condenser where it condenses. Throughout this period, the vapor pressure in the bed matches the condenser pressure, and the process concludes once the adsorbed amount reaches the minimum concentration level. [32]

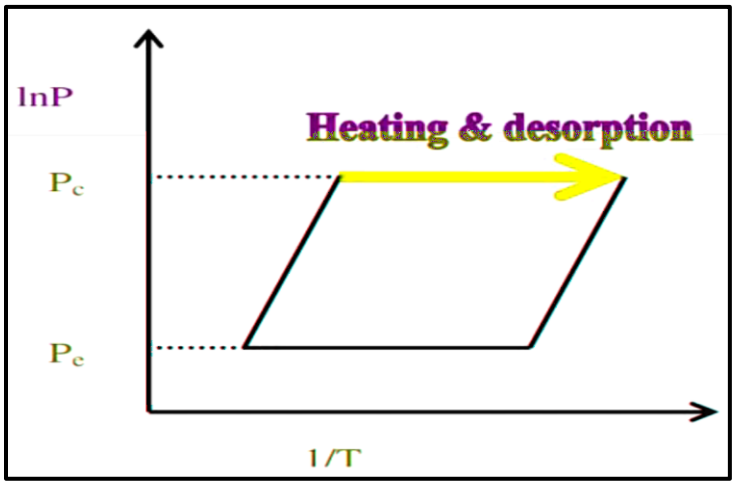

Figure 3-4heating and desorption process

Pre-cooling process (C−D): Following the bed reaching its peak temperature in the cycle at point C, the cooling and depressurization phase for the bed commences, during which both valves are closed. Subsequently, the temperature decreases, causing the pressure inside the adsorber to gradually decrease to match the pressure level of the evaporator by the end of this phase. [32]

- Evaporation temperature below 0 1C (for refrigeration purposes; it can be higher in the case of air-conditioning applications).
- Small molecular size so as to facilitate the adsorption effect; High latent heat of vaporization and low specific volume when in the liquid state.
- High thermal conductivity.
- Low viscosity.
- Thermally stable with the adsorbent in the operating temperature range.
- Chemically stable in the operating temperature range.
- Non-toxic, non-corrosive and non-flammable.
- Low saturation pressures (slightly above atmospheric pressure) at normal operating temperature.
- Absence of ecological issues, unlike common refrigerants.

:

This combination is ideal for solar energy applications due to its low regeneration temperature, which requires low-grade heat sources, typically below 85°C. Additionally, water has a higher latent heat compared to other conventional refrigerants, making it suitable for air-conditioning applications with high chilled water flows and high evaporation temperatures, and it is widely used in adsorption chillers. However, this pair has low adsorption capacity and low vapor pressure, which can impede mass transfer. Moreover, the system needs to operate under vacuum conditions, as any non-condensable gas can significantly reduce its performance [27], [59], [60], [61].

:

Activated carbon paired with methanol is widely used in adsorption refrigeration systems. It operates efficiently at low regeneration temperatures, although temperatures exceeding 120°C can lead to methanol decomposition. While this pair offers advantages such as high cyclic adsorption capacity, low adsorption heat, and high evaporation latent heat of methanol, activated carbon's low thermal conductivity acts as a thermal insulator, decreasing the system's COP. Similar to the silica-gel-water pair, activated carbon-methanol also requires vacuum conditions for operation. Additionally, caution is necessary when handling methanol due to its high toxicity and flammability [62], [60], [63].

: it necessitates regeneration temperatures that may surpass 150°C. While its adsorption heat resembles that of the activated carbon-methanol pair, it requires elevated operating pressures, thereby improving heat and mass transfer efficiency, reducing cycle duration, and preventing air infiltration into the system. These factors collectively enhance the system's specific cooling capacity. Additionally, this pair's compatibility with high-temperature energy sources and the high cooling potential of ammonia render it particularly appealing to researchers. Nonetheless, activated carbon exhibits a lower adsorption capacity with ammonia compared to methanol, and caution is warranted due to ammonia's toxicity, pungent odor (even at low concentrations), and corrosive properties. [27], [60].

:

it exhibits regeneration temperatures that can exceed 200°C, with an adsorption-evaporation temperature lift of up to 70°C or more. This pairing demonstrates stability at elevated temperatures, and water's latent heat surpasses that of traditional refrigerants like methanol. However, systems utilizing the zeolite-water pair are better suited for air-conditioning applications due to water's solidification temperature, which prevents freezing. Additionally, it boasts significant adsorption heat, surpassing that of the silica gel-water pair. Moreover, the low-pressure evaporation of water slows the adsorption stage, while high desorption temperatures increase the adsorber's sensible heat, resulting in relatively lower specific cooling capacities for these systems. Furthermore, the low working pressures can impede mass transfer [27], [62], [60].

3.6 Mathematical modelling

This section concerns the thermodynamic analysis of an adsorption refrigerating machine. Starting from fundamental data relating to temperat

cycle analysis associated with this machine, makes it possible to highlight the influence of the different parameters on the criteria of machine performance. For this, we established a numerical model derived from the equilibrium state equation (Dubinin-Astakhov) and the characteristics of

the working pair chosen. The calculation code developed allows the study of the influence of parameters on the quantity of cold produced at the evaporator (Qev), the quantity of heat absorbed (Qs) by the adsorber during the (heating/desorption) phase and the coefficient of thermal performance (COPth). Modeling the basic cycle of a machine has been the subject of numerous studies both theoretical as well as experimental [13, 21, 22, 27, 30, 34].

3.6.1 **Equilibrium models for chemiosorption**

The equilibrium adsorption model for chemical adsorption is

$$x = x_n$$

where n is the mole number of refrigerant adsorbed by the adsorbent.[43].

In chemical adsorption, the variation in adsorption quantity occurs incrementally, adhering to specific equilibrium parameters. Each reaction, characterized by defined stoichiometric coefficients, corresponds to an equilibrium condition, limiting the maximum adsorption capacity to the stoichiometric value. Consequently, once the system attains equilibrium at a particular temperature, increasing pressure does not enhance refrigerant adsorption unless it triggers equilibrium for another reaction with distinct stoichiometric coefficients.[43]

3.6.2 **Equilibrium models for physiosorption**

Equilibrium models pertaining to physical adsorption are dependent on both the temperature and pressure of the adsorbent, typically expressed in a generalized format as

Models with different fixed parameters are as follows:

isothermal

isobaric

isosteric

Adsorption isotherm models are primarily employed to analyze data from micro-adsorption quantity measurements since achieving isothermal conditions becomes challenging with larger adsorption quantities, leading to increased heat production from the adsorption reaction. On the other hand, adsorption isobar models are better suited for designing adsorption refrigeration

systems as they facilitate easy calculation of the desorbed and adsorbed amounts during a cycle. Meanwhile, adsorption isosteric models are advantageous for calculating adsorption heat and are commonly utilized in the selection of working pairs.

3.7 Coefficient of performance

The performance of the adsorption refrigeration machine given in this study is characterized by the coefficient of performance COP. [47]

In the rest of our study, the coefficient of performance and the heat quantities do not take into account the metal parts of the various components of the machine such as the adsorber, condenser, etc. It is expressed by thermodynamic relations and does not take into account the mass and heat transfers of the system.

In this case, the coefficient of performance is given by the following relationship:

— (1)

With 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]:

(2)

Where,

Dubinin-Astakhov D-A equation [7]. It can be defined as:

(3)

—— (4)

With is the maximum absorption capacity, D and n are the parameters of the D-A equation, is the saturated pressure of the adsorbate.

. Solar intensity and ambient temperature

The evolution of transient solar irradiance is given by the following equation :

(5)

With:

I_(c.max): The maximum total solar irradiance composed of direct, diffuse and reflected irradiance from the ground (reflected irradiance is assumed to be negligible compared to the other two components). This is expressed by the following equation :

s (6)

The total irradiance received by any surface of the solar collector is given by:

(7)

With:

efficiency of the solar collector.

Equation (4.32) is used to estimate the ambient temperature [113].

(8)

With:

and are the maximum and minimum ambient temperatures.

3.8 Conclusion

In this chapter, we have outlined the research methodology adopted to investigate the coefficient of performance. The approach was designed to ensure a rigorous and systematic examination of adsorption, leveraging Meteonorm to gather and analyze data. The development of adsorption system for refrigeration is promising. An overall thermodynamic based comparison of adsorption system shows that the performance of system depends highly on both the adsorption pairs and processes. The technology continues to develop and the cost of producing power with solar adsorption refrigeration is falling.

As we move forward to the analysis and results chapter, the foundation laid out in this methodology chapter will guide the interpretation of the collected data. The insights gleaned from the D-A model will be critical in addressing the research questions and contributing to the broader understanding of adsorption refrigeration.

Chapter four

Results and discussion

4 Chapter Three : Results and discussion

4.1 Introduction

This chapter presents the results of the COP and cost analysis conducted for the proposed project. It includes a detailed examination of the energy used, cold produced and costs incurred, and an interpretation of the findings. The objective is to determine the COP, cost-effectiveness and financial feasibility of the project.

4.2 Determination of COP

4.2.1 Solar Irradiation

The total solar irradiation (TSI) is the energy that determines our climate. TSI data is available from various sources, including satellite measurements and composite databases but in our study we used METEONORM and we calculated the rest of the equations using MATLAB.

This graphs represent the hourly evolution of the solar irradiation in different regions in Algeria

(Tlemcen, Adrar, Ghardaïa and Algiers) , in the month of April where the horizontal axis represents time of day, ranging from 6:00 AM (morning) to 6:00 PM (evening) and the vertical axis represents solar irradiance, measured in Watts per square meter (W/m^2).

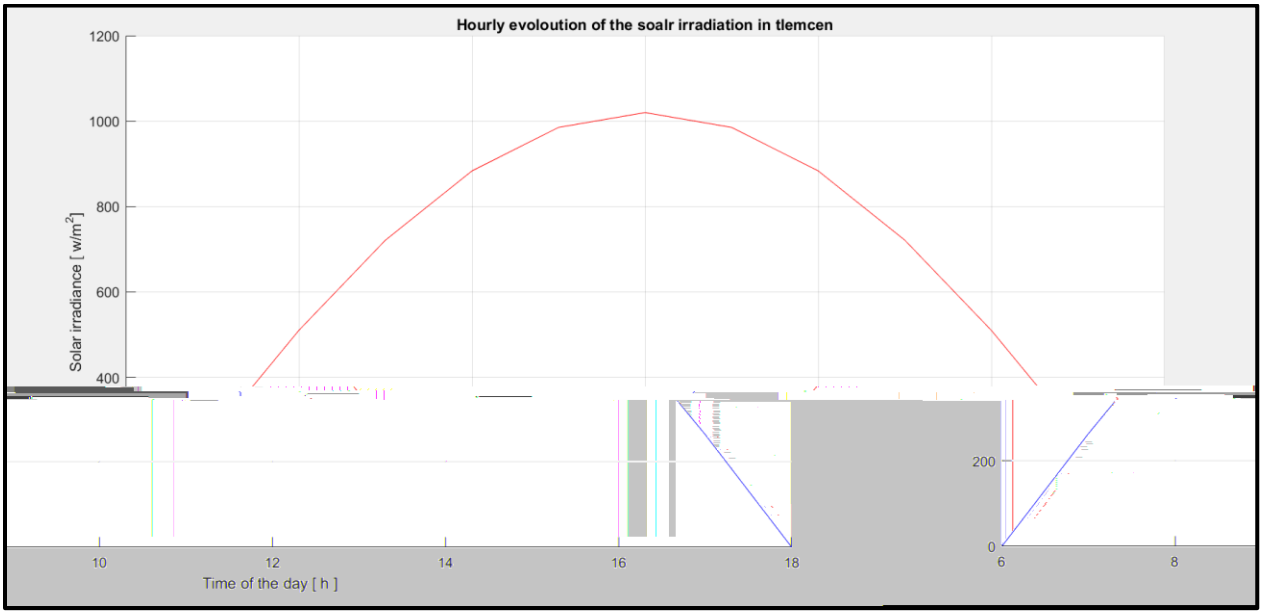

Figure 4-1Total solar irradiation in Tlemcen

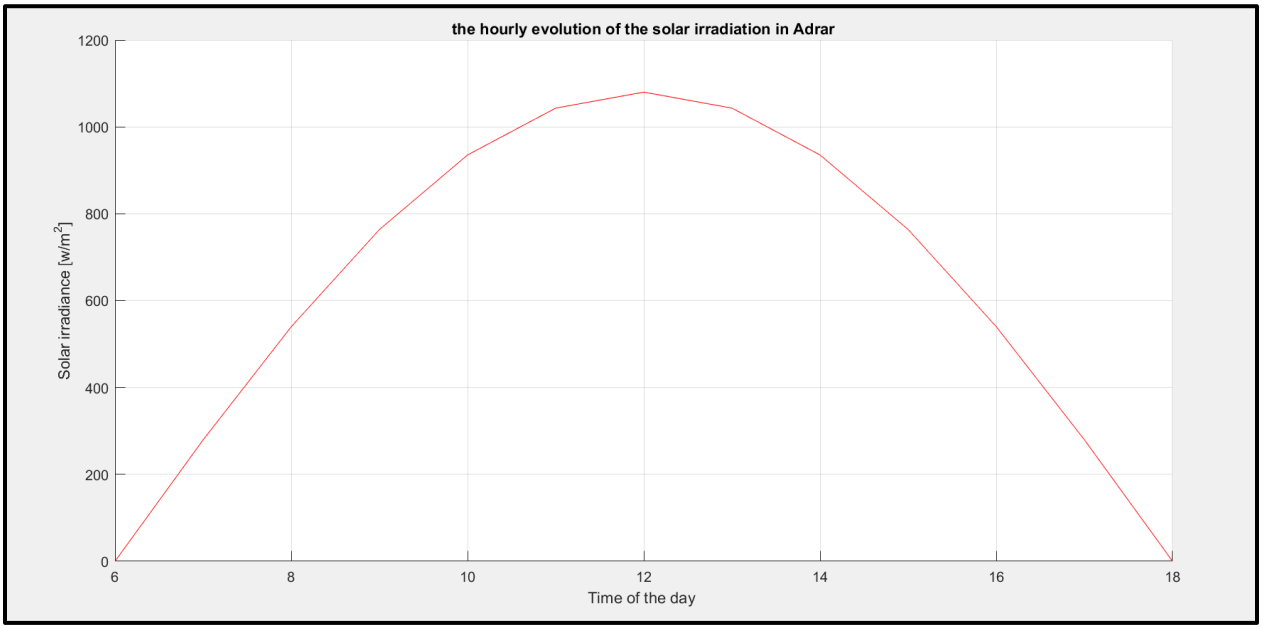

Figure 4-2Total solar irradiation in Adrar

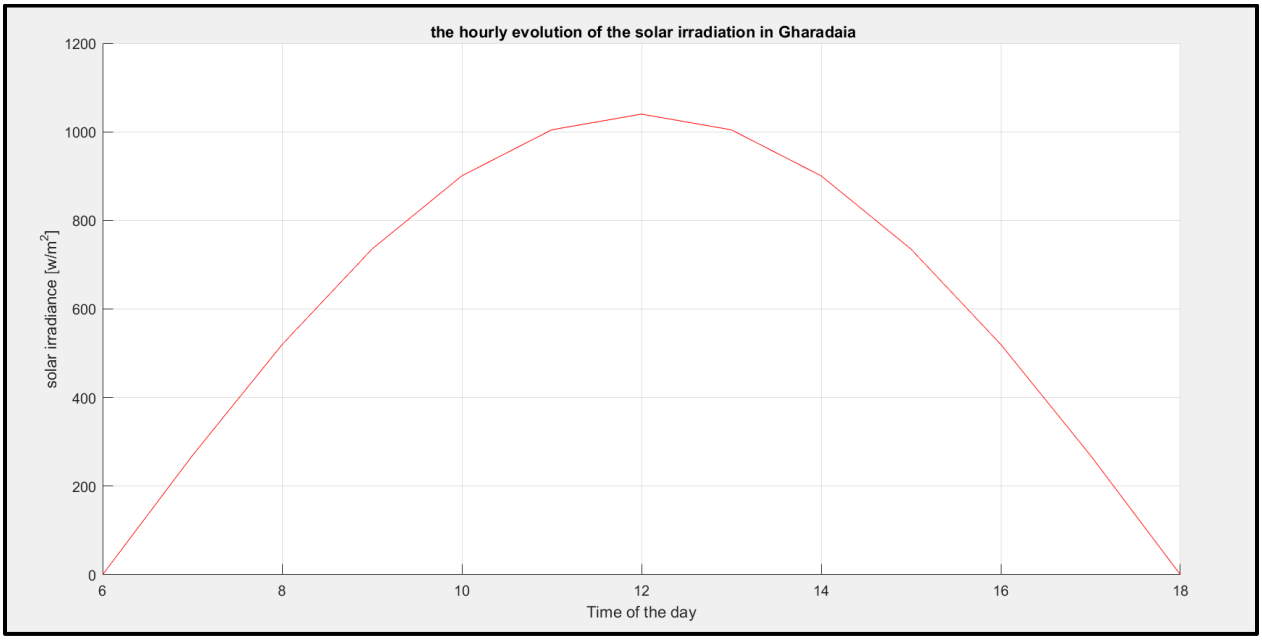

Figure 4-3Total solar irradiation in Ghardaïa

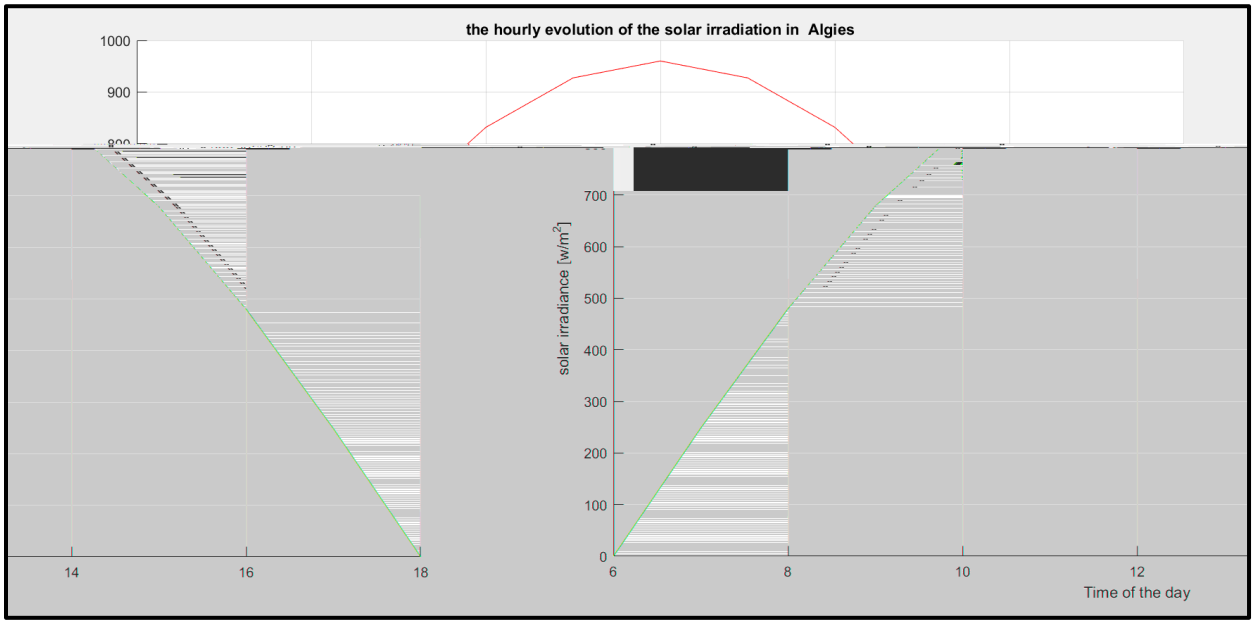

Figure 4-4total solar irradiation in Algiers

In this study we used the maximum total solar irradiance and the time of sun availability in the day to determine energy received by the solar sensor G(t). Using MATLAB, we calculate it by

incorporating the influence of the rays absorbed, reflected and diffused and the surface area of the panel: Alpha, Gamma, Eta ,A respectively.

2

Table 3 maximum irradiance

4.2.2 **The adsorption concentration of the working pairs**

In this tables we present the results of maximum and minimum adsorption concentration obtained from MATLAB using D-A model and the constants.

The coefficients of the D A equation of the working pairs are:

Table 4coefficients of the D–A equation of the working pairs

	D	**N**	**X_0**
AC /Methanol			
Zeolite / water			
Silica gel /water			

Table 5Change in concentration of the working pairs

	Xmin [kg/kg]	Xmax [kg/kg]
AC/Methanol		
Zeolite / water		
Silica gel /water		

It is interesting to note that the change in the adsorption concentration is used to determine the value of cold produced Q_f.

The graphs below show the adsorption concentration of each working pairs at different temperatures

Activated Carbon /Methanol

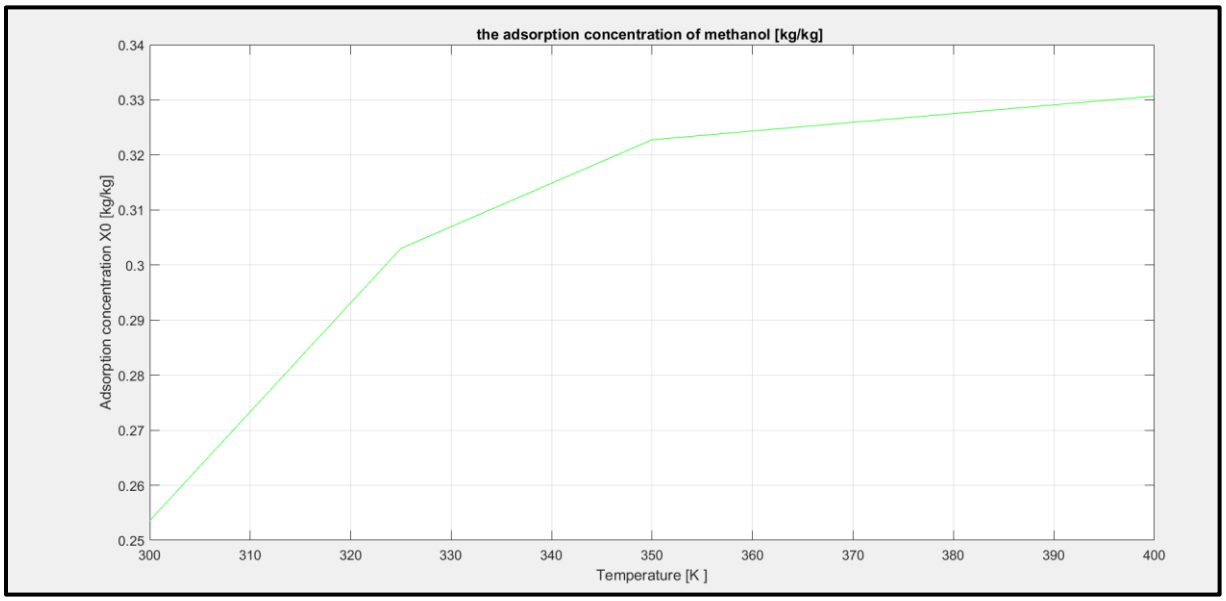

Figure 4-5the adsorption concentration of Ac/methanol

Silica gel /Water

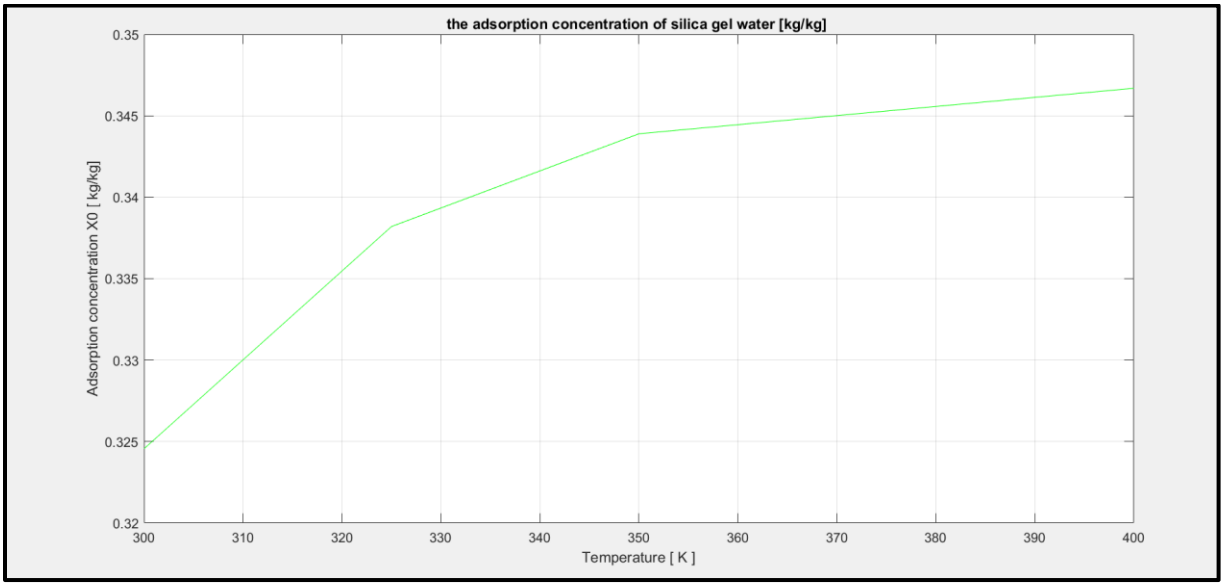

Figure 4-6the adsorption concentration of silica gel/Water

Zeolite /Water

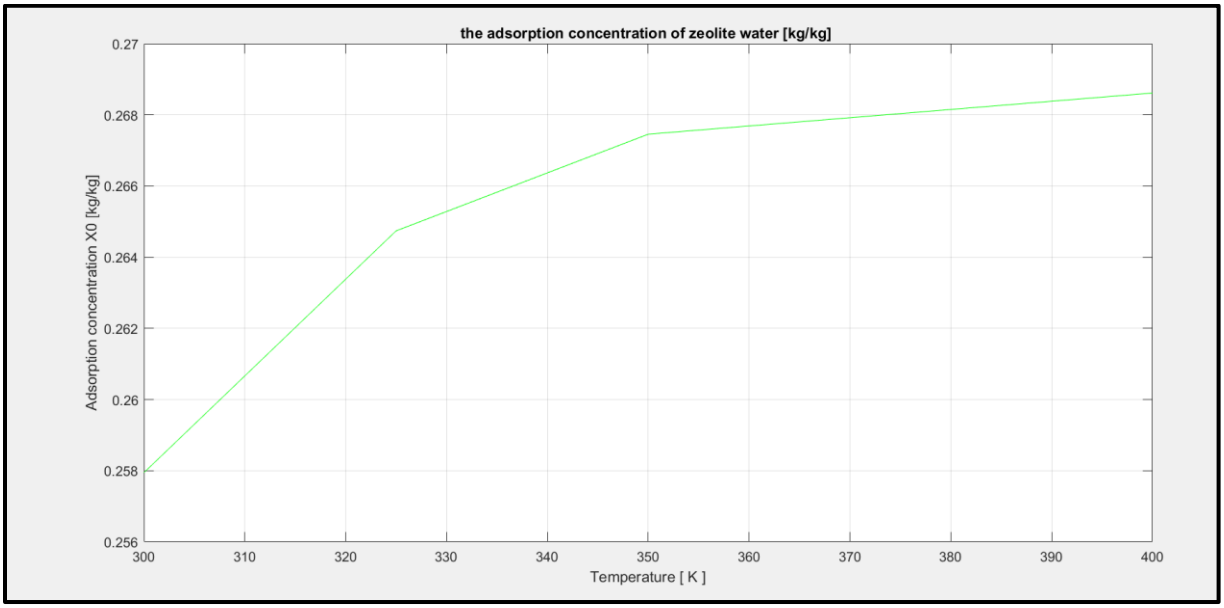

Figure 4-7the adsorption concentration of zeolite/water

Coefficient of performance

The table below represents the coefficient of performance (COP) calculated using MATLAB for adsorption machine with different working pairs in various regions. It is determined from energy received and cold produced.

The table shows several working pairs used in adsorption machines. These pairs consist of an adsorbent material and a working fluid. The working pairs mentioned in the table are: AC/Methanol, Zeolite/water, Silica gel /Water.

The COP is a measure of the efficiency of an adsorption machine. It indicates how much cooling or heating effect the machine produces per unit of energy input. Higher COP values indicate better performance. The working pair with the highest COP is AC/Methanol (0.2378), followed by Silica gel/water (0.1458), and then Zeolite/water (0.0702). Generally, higher COP values are desirable because they indicate better energy efficiency.

Table 6 COP of the diffrent working pairs in the different regions

We represented the table as a bar-graph

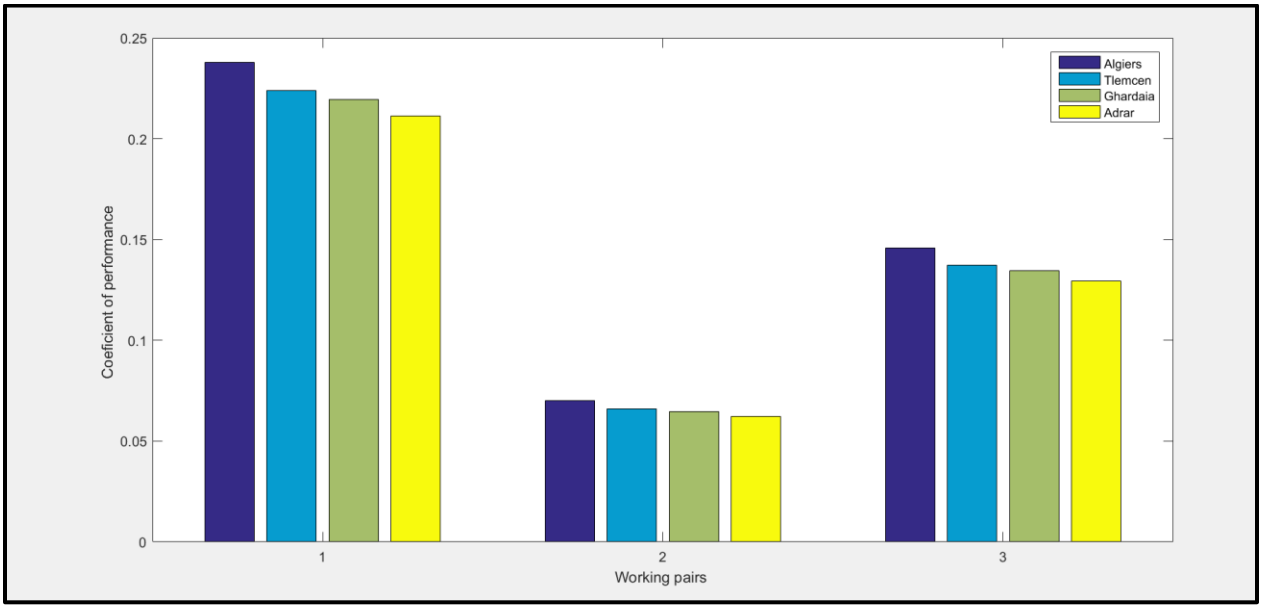

Figure 4-8 Coefecient of performance of the diffrent working pairs in the diffrents regions

Where:

1:AC/methanol, 2: Zeolite/Water, 3: silica gel/water

In summary when choosing working pairs for adsorption machines, consider both COP and (the effective temperature lift is the difference in temperature between the heat source and the heat sink) but in our case we are concentrating on the COP.

4.3 Cost analysis

The total cost of the project is divided into several categories: initial cost, operational costs, and maintenance costs. The initial investment includes the cost of equipment and installation. The largest component of this cost is the purchase of the solar collector and its components. The operational and maintenance cost are pretty much minimal because of the less upkeep and repairs needed.

4.4 Mean Adsorbent Cost

As part of the initial cost we can determine the mean cost of the adsorbents per kilowatt (kW) of adsorption used in our refrigeration system by:

(9)

Table 7Mean price of adsorbents

Table 8cooling effect of adsorbents

Table 9Mean Adsorbent Cost

This bar graph compares the cost of the three adsorbents

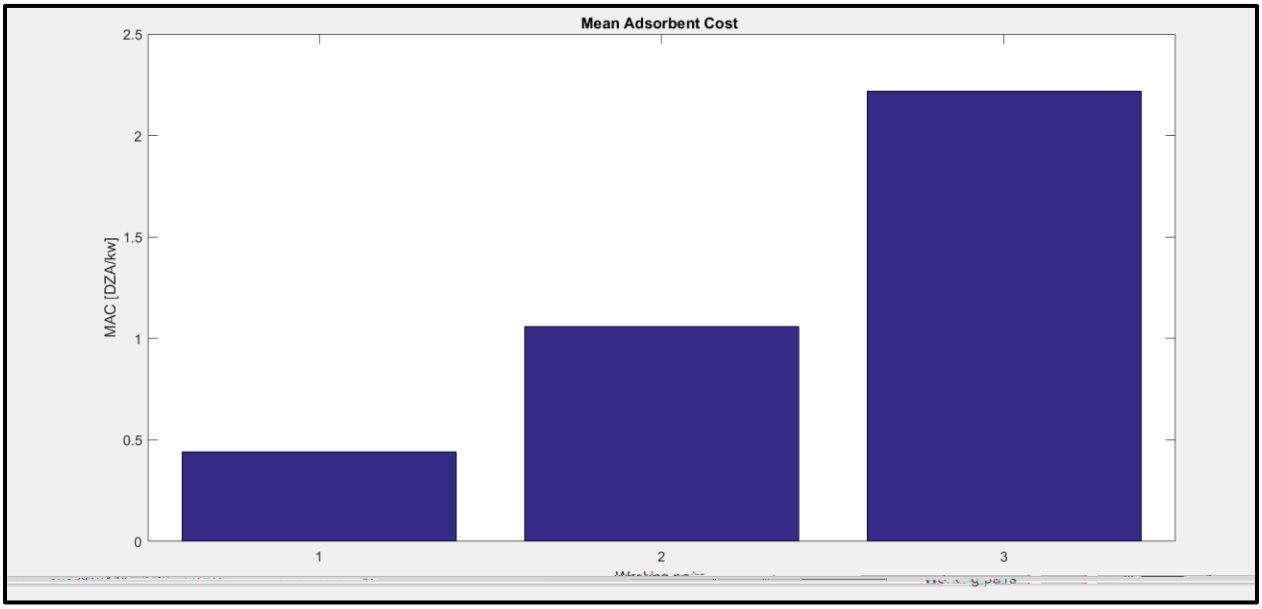

Figure *Mean cost of adsorbent in DZ*

4.5 CONCLUSION

General conclusion

The aim of this thesis was to the study the coefficient of performance and the cost of a refrigeration machine operating with adsorption phenomena which uses solar energy as a source for the production of cold in the Algerian region. This machine makes it possible to cover refrigeration needs over a wide range of temperature. Studies in the literature indicate that solar-driven adsorption refrigeration systems have the capability to provide a good alternative to contribute mainly in a considerable number of areas of human life (making ice, air conditioning, conservation of food and vaccine storage), particularly in isolated rural areas. In addition, this machine, compared to conventional vapor compression systems, is simple, inexpensive, and can be operated without moving parts. The machine is free from toxic substances which are harmful to the environment (natural refrigerants such as water, ammonia and methanol are used). It is also seen that the adsorption systems with flat plate solar collectors are simpler (and cheaper) than other types and the most commonly used working pairs is activated carbon and methanol. Nevertheless, the purpose and the conditions dictate the configuration (type of collector), working pair and therefore the performance of each system. But compared to compression systems, it suffers from low energy performance.

This Dubinin-Astakhov (D-A static model) established is based on the thermodynamics of equilibrium states allowing the calculation of adsorbed mass and desorption as a function of temperature and pressure. In this context and in light of the results available in literature, we have estimated instantaneous solar radiation received by an inclined surface in the four regions using data provided by Meteonorm software, mathematical modeling constant and concentration of each working pair and the application of this modeling to investigate the performance and benefits of the machine such as economic profit and environmental impact based on the working parameters and certain thermodynamics considerations.

With the current technology the theoretical and experimental COP is still considerably low (between 6% and 25% depending on the working pair) and seemingly unlikely to increase further despite the efforts made and the numerous conducted studies.

The majority of current applications are in the demonstration and prototyping phase hence low commercial success and unpredictable conditions so a lot of research still needs to be done to further enhance the efficiency and practicability of the basic intermittent cycle. In this study the room of improvement exists in the potential from the adsorption thermal storage system due to its capacity to store thermal energy for long periods of time without losses which allows major energy savings. These extends the area of applications of adsorption technologies making them more attractive and cost effective. Recently, many researchers are focused on the development of combined systems of solar adsorption cooling with other refrigeration cycles and heating to improve the overall system performance by recovering the condensation heat and/or the heat of adsorption to produce hot water.

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Solar sorption, **2**, **15**, **16**

surface area, **4**, **23**, **27**, **28**, **48**

sustainable, **1**, **2**, **3**, **13**, **17**, **21**

T

thermal conductivity, **38**, **39**, **40**

Thermal sorption, **14**

thermodynamics, **13**, **26**, **32**, **52**

thermo-electrical, **1**

thermo-mechanical, **viii**, **1**, **13**

Tlemcen, **45**, **48**, **51**

toxic, **29**, **30**, **38**, **39**, **52**

W

Water, **20**, **28**, **29**, **51**, **54**, **57**

Working pairs, **38**

Z

Zeolite, **28**, **48**, **50**, **51**, **57**

الملخص

يهدف هذا العمل إلى تقييم معامل أداء وتكلفة التبريد الناتج عن آلة التبريد بالامتزاز باستخدام معادلات دوبين-أستاخوف وبرنامج **MATLAB**

تعرض هذه الأطروحة الوضع الحالي لفن نظام التبريد بالامتزاز الشمسي الذي يعمل بأزواج عمل امتزازيه مختلفة. ويرتبط تطبيق أزواج العمل المختلفة لأقصى قدر من الإشعاع الشمسي المختلف الذي تم الحصول عليه من برنامج **METEONORM**

بمعادلات نمذجة التوازن عند درجات حرارة وضغط مختلفين لحساب الحرارة المستقبلة والبرودة المنتجة وبالتالي معادلة **COP** والتكلفة. وبعد مراجعة شاملة للأدبيات، تم التوصل إلى أن هذه التقنية على الرغم من جاذبيتها إلا أن لها قيود، وهي انخفاض معدل الأداء في الأداء**(COP)** ، وأن زوج الكربون المنشط/الميثانول هو الأكثر كفاءة.

الكلمات الدالة: الطاقة الشمسية، امتزاز، التبريد، فحم منشط/ ميثانول، معامل اداء الحراري

Abstract

This work aims to evaluate the coefficient of performance and cost of the cold produced by adsorption refrigeration machine using the Dubinin-Astakhov (D-A) equations and the MATLAB software. This thesis presents the most recent development stage of solar adsorption refrigeration system operating with different adsorption working pairs. The application of different working pairs for different maximum solar irradiation (obtained from Meteonorm software) is related to the equilibrium modeling equations at different temperature and pressure to calculate heat received and cold produced and thus, the COP and the cost. After a comprehensive literature review it was concluded that this technology as appealing as it is, has a low COP, and that also activated carbon/methanol is the most used and most efficient pair.

Key words: Solar energy, Adsorption, Refrigeration, Activated carbon/methanol, thermal COP.

Résumé

Ce travail vise à évaluer le coefficient de performance et le coût du froid produit par une machine de réfrigération à adsorption en utilisant les équations de Dubinin-Astakhov (D-A) et le logiciel Matlab. Cette thèse présente l'étape de développement la plus recente des systèmes de réfrigération par adsorption solaire fonctionnant avec différentes paires de travail d'adsorption. L'application de différentes paires de travail pour différentes irradiations solaires maximales (obtenues à partir du logiciel Meteonorm) est liée aux équations de modélisation de l'équilibre à différentes températures et pressions pour calculer la chaleur reçue et le froid produit et donc, le COP et le coût. Après un examen approfondi de la littérature, il a été conclu que cette technologie, bien qu'attrayante, a des limites, à savoir un faible COP, et que le couple charbon actif/méthanol est également le plus efficace.

Mots clés: Énergie solaire, Adsorption, Réfrigération, Charbon actif/méthanol, COP thermique