Cooling and Refrigeration Solar Systems

Ali Ahmeed Ali Alrabee

College of Education, Abu-isa, Zawia University, Libya

a.alrabee@zu.edu.ly

Abstract

Photovoltaic (PV) Energy Systems and Thermal Energy Systems have been used for decades for the purposes of generating electricity and thermally needed processes. These systems are expanding more and more every year alongside the emerging new researches results aiming at the development of the different systems to provide the needs of cooling and refrigeration fields in general. This report will present the different available methods, materials and system's design of the cooling and refrigeration. Although in practice solar cooling and refrigeration are nearly the same process, but usually either the material, the methods or temperature ranges are different.

Keywords: *Solar Systems, Thermal Energy Systems, cooling and refrigeration*.

1. Introduction

cooling by solar energy can be accomplished by solar absorption refrigeration systems and adsorption refrigeration systems by using various working fluids and techniques. Flued Coefficient of Performance (FCP), specific cooling power, and cooling capacity, with minimum and maximum working temperature had made the possibility to study cooling efficiency studies and drive forward the use of hybrid cooling systems with many different techniques. Before going to the discussion of these systems, we have to present some facts and concepts of renewable and sustainable energy itself. Renewable energy refers to the energy which is produced from all natural sources that have the properties of sustainability over the time and renewability. These renewable energy sources include solar, wind, hydropower, geothermal, etc. this report is going to focus of the solar renewable energy and consider the new developments and application in this field that is related to the refrigerating and cooling [1].

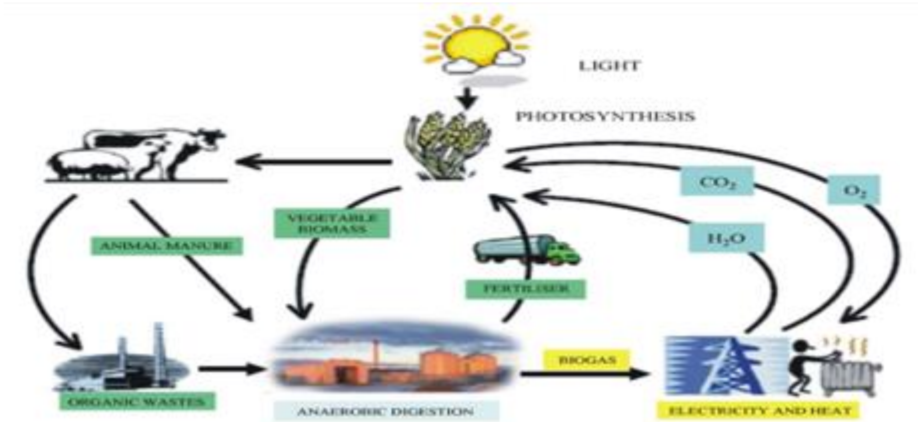

Fig.1a: sketch of the Sustainable cycle of the solar energy Source

1- Solar Energy:

Solar energy is an electromagnetic radiation reaches our planet Earth consisting of visible, infrared, and ultraviolet, and all of the other natural energy originating from the sun, (directly or in directly), these can be defined as the solar constant " SC". This is the radiation influx of solar energy, of the amount of 1368 w/m^2. Now if SC= 1368 w/m^2 and the global plane area is equal to $1.275x10^{14}$ m^2 with main radius of 6371 km = $6.371x10^6$ m, therefore the total transmitted radiation to the Earth is $1.74x10^{17}$ w. This amount off course could differ from place to place on the Earth's area. Many researches have calculated the irradiance of solar radiation for the entire year and calculated the maximum amount of radiation Fig.1b.

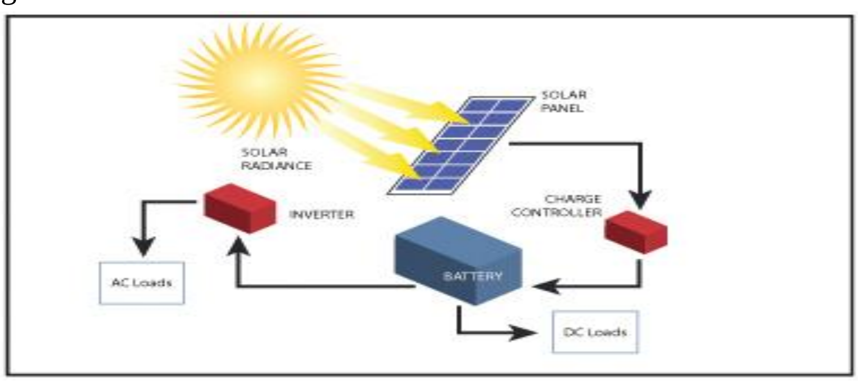

Fig.1b, The concept of solar PV-system

Solar energy can solve the problem of power shortage used for cooling and refrigerating in many countries of the world and in many rural, where grid power is not available for residential or commercial uses.

Solar energy is used to provide clean and low-cost energy for cooling and refrigeration applications all over the world. This application of solar energy can reduce the cost of energy by nearly 50%, many Mediterranean countries when used in cooling or refrigeration purposes. Solar refrigeration became attractive for cooling purposes by the use of desiccant gases such as Lithium Chloride (LiCl), and Lithium Bromide (LiBr), or by the use of water instead of the harmful gases.

Cooling is done by two methods; the first is the photovoltaic based solar energy system, method where solar energy is converted into electrical energy. The second method is using thermal refrigerating system in which a solar collector is used to directly heat the refrigerant through the collector tubes instead of using solar electric power. As it was mentioned before the report will focus on the solar thermal heating system, i.e. the second method of cooling and refrigeration system.

2. Solar Thermal Cooling System

Perforation of solar thermal cooling compared to PV-based cooling systems, come from the fact that thermal processes usually utilize more incident solar energy than PV-system (Fig.1,) where heating happens by infrared and orange light. this segment of the incident rays composes nearly 65% of the incident radiation energy, and only 35% can produce electricity by PV- system. For this reason, the thermal solar cooling is much more efficient than PV- cooling.

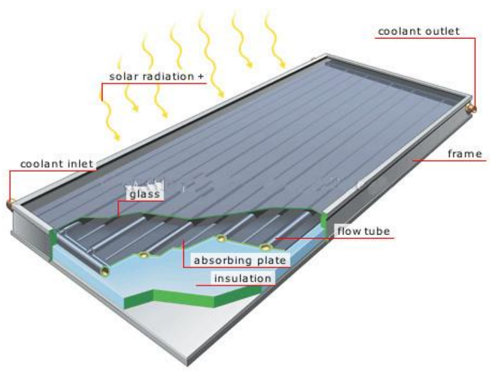

Fig.2 Solar collector for thermal conversion application

2.1-Solar Thermal Refrigerating System Components

Solar refrigerating system consists of four major parts:

- Solar collector array
- Tank for thermal storage.
- Thermal AC Unit.
- Heat exchange Tank.

Each of the above parts plays specific function in the cycle of the cooling as in the following;

A-The thermal collector, receives the solar energy and increases in temperature, as a result the refrigerant inside the collector become hot by heat convection process.

B- Thermal Storage Tanks used for storing hot refrigerant inside the collector's evacuated tubes.

C- The thermal AC unit is run by the hot refrigerant coming from storage tank , and refrigerant circulating through the entire system.

D- The heat exchange tank, it is responsible for transferring heat between hot and cold spaces, fig. (3,4,5)

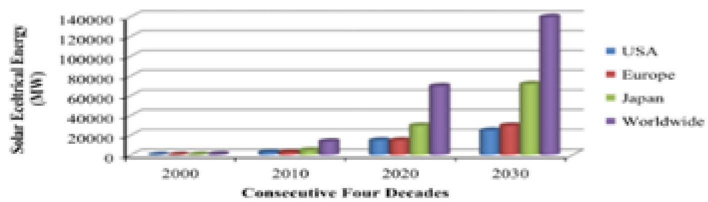

Fig. 2. Global PV-based solar electrical energy production over four decades [20].

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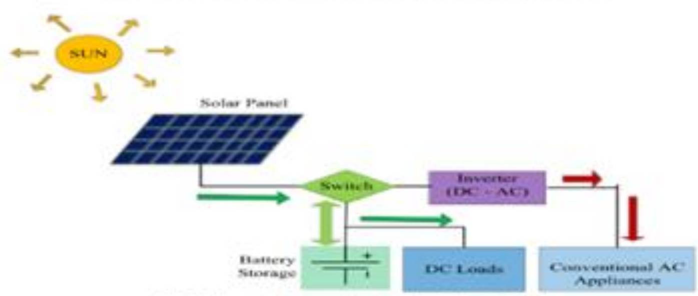


Fig. 3. Schematic diagram of a standalone PV system [21].

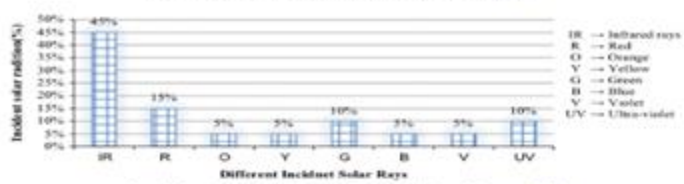


Fig. 4. Distribution of incident solar rays used in a PV system [21].

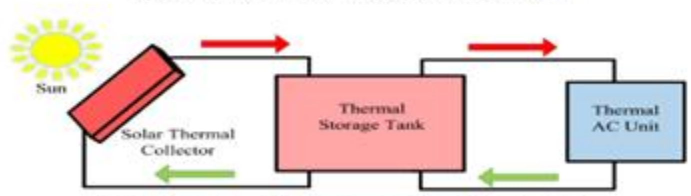


Fig. 5. Schematic diagram of potential solar thermal cooling system [22].

3 sorption Cooling technology

Sorption technology is the cooling effect obtained by the system from chemical or physical changes between the sorbent and refrigerant through closed sorption system or open sorption system. The closed sorption technique is divided into two basic methods, namely absorption refrigeration or adsorption refrigeration. This report will focus only on the closed sorption cooling system.

3.1- Absorption Cooling Working Pairs:

One of the advantages of solar energy sorption (SES) is its mobility, were, the system can be available where it is needed. The possibility of using Lithium Chloride (LiCl) and Lithium Bromide desiccant gases have made SES more attractive and easier to use anywhere. Other solutions like water can be used too for cooling cycles of the SES.
Cooling and refrigerating by SES could be achieved either by conversion of solar energy into electricity directly or via thermal solar energy conversion system. Thermal energy refrigeration cab be accomplished by sorption and adsorption refrigerating processes. These two processes are going to be discussed in more details.

3.2 - Absorption Cooling:

It is the process of absorption in which one substance transfer from one state into a different state. The two states create a strong bond for strong solution, or mixture accompanied with an increase of heat which generate the continuation of the process. Such as water and ammonia (NH_3) + H_2O), or water + Lithium Bromide of fluids for the chemical processes. The main advantages of an absorption system is its coefficient of performance (COP) which is considerably larger than other thermally operated techniques. The substances pairs play an important role in the absorption cooling system alongside with the chemical and physical properties of the fluid pair26/ the most important criteria of the solution pair is they must have a bound of miscibility between them at the same operational temperature in a liquid phase, in addition to the following conditions.

1- The pair must be pollution free, noncorrosive and cost effective, figs. (2,3,4).

2-The boiling points between the mixture and pure refrigerant should have a large differential under a constant pressure.

3- The stability of the circulation rate of refrigerant is related to. the high concentration the latent heat within the absorbent.

4- Thermal conductivity, viscosity and diffusion coefficient should be favourable.

5- The volatility of the refrigerant should be allowed to spread from the absorbent without filters.

6- The fluid should be chemically stable nontoxic, and nonexplosive.

There are many absorbents and refrigerants compounds. The most used pair is water + ammonia ($NH_3 + H_2O$,). Here NH_3 is the refrigerant, and water is the absorbent. They both have high latent heat of vaporization, and moderately low freezing temperatures (-77C^0, 0C$^{0)}$., therefore it can be used for low temperatures. The volatility of the thermodynamics of the system, it requires to separate water from ammonia for the stability of performance. It also characterized by low cost, and need to be used with coper and vessels. On the other hand, lithium bromide + water system technology is considered to be the second-best working pair of fluids. This system does not need to have filter for its stability and high latent heat of vaporization. The system need not be working below 0C^{0,} and need vacuum conditions, and high concentration leads to crystallization.

Both systems were been used widely in many parts of the world. New pairs were suggested by researchers among them the R21, and R22, which have greater solubility with an organic solvent. The most important solvents are Dimethyl-Formide (DMF), and Dimethyl Ether of the Tetra- Ethylene Glycol [DMETEG], there characteristics may be found in refs.

Fig 6 SEC.

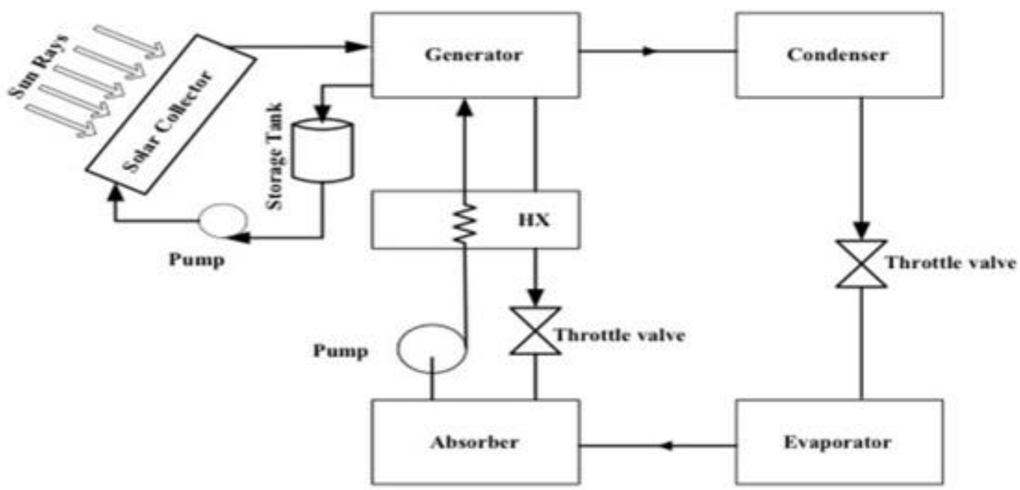
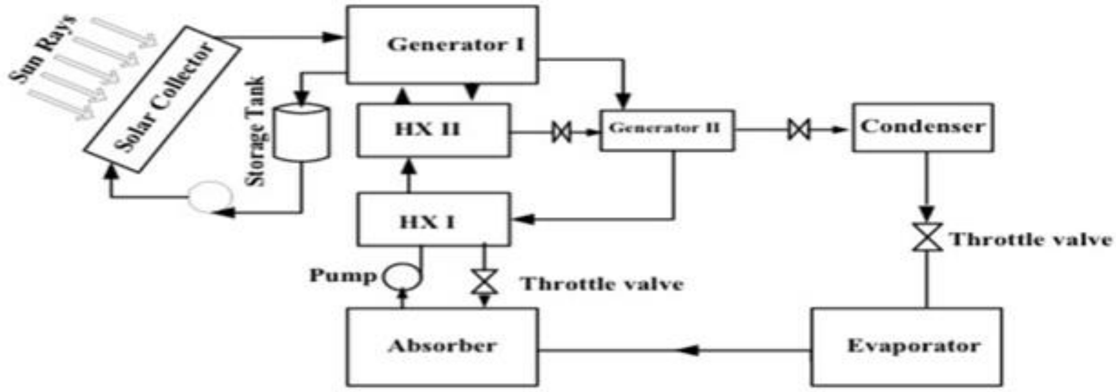


Fig. 6. A solar assisted single-effect LiBr–H_2O absorption cycle [44].



Fig,7 – the double effect LiBr / H_2O absorption system

3.3 -Solar absorption cooling systems:

In most refrigeration systems, there are generators, pumps, and absorbers,_and they are capable of compressing the refrigerant vapor. The evaporator then draws the vapor refrigerant, and the extra thermal energy separates this Vapor the solution. The condenser function is to condense the refrigerant vapor, and then the cooled refrigerant is expanded by the evaporator.

Mechanism of solar absorption Technology

In Solar thermal absorption refrigeration technology, heat from the tank is lead toward the chiller, which absorb this heat. The process then can be defined by the refrigeration of the solution and the thermal process cycle. Occasionally the absorption systems are classified into three categories:

A- Single effect solar absorption cycle.

B-Half effect solar absorption cycle.

C- double effect solar absorption cycle. Both single and half effect cycles chillers require low temperature in comparison to the double effect chillers. In addition to these systems there are two other absorption refrigeration systems namely, Diffusion absorption refrigeration (DAR), and hybrid absorption refrigeration (HAR), which can achieve better performance.

A-Single effect Solar Absorption Sycle:

Most absorption refrigeration system (ARS) are using single effect absorption technology with LiBr +H_2O Pair, via solar flat collector or evacuated tubular collector using hot water for the application of these systems fig.7,5 show LiBr- H_2O of single effect absorption refrigeration system. The single cycle effect starts at the absorber, which receives the vapor refrigerant from the refrigerator and provide the rich mixture. The pump then forwards this mixture to the generator or the high-pressure area (desorption). In the generator the refrigerant is then separated from the absorbent by heat received from the solar collector. The function of the pressure relieve valve is to lead the weak solution to the absorber again. The heat exchanger solution (SHX) is in place to recover the internal heat. The recovery of heat can improve the system efficiency and resisting the irreversibility of the cycle. A 60% higher COP can be achieved by using the solar heat exchange SHX. The refrigerant then continues the cycle through the condenser, expansion valve, and evaporator.

The solar absorption cooling system could work better when the solution mix is not volatile such as LiBr - H_2O, on the other hand if volatile pair is used then an extra rectifier should be used before the condenser to get pure refrigerant, this will also improve the efficiency. Some researchers, have observed that the energy demand for heating of approximately 8124kwh, compared to the cooling demand of approximately 13,255kwh throughout the year.

B-The half effect solar absorption cooling:

The main feature of the half effect absorption cycle is the running capability at lower temperatures compared to other cooling systems. The name itself "half effect" came from the COP, which is almost half of that for the SEC. Sarafanan R. et al, experimenting with the use of DMAC (absorbent) + R134a (refrigerant) pair. They were able to attain an evaporation temperature of – 7C^0 with the generator temperature varying from (55 – 75) C$^{0.\ with}$ COP of nearly 0.36. In another research activity, work was done using LiBr + water as a chiller system at low temperature for cooling extensively hot and dry regions. They used two stages system and found a cooling capacity of 100kw by integration with a solar refrigerating system. they concluded that the system had nearly the same COP as the conventional cooling system, but with almost 50% of cost reduction.

C- The double –effect solar absorption cooling systems:

Double-effect absorption cooling technology was started in the middle of the last century (1956) during the development of the system performance within a heat source at high temperature, see Fig. 7 The cycle begins with generator- I providing heat to the generator-II. The condenser rejects the heat and passes the working fluid towards the evaporator; within this step, the required refrigeration occurs. The fluid then passes through the heat – exchanger (HX-I and HX-II) e follow three different from the absorber to the generator-I via the pump during this process, HXII can pass the fluids to generator II which in turn passes it to HX-I. The complete cycle follows three different pressure levels (high, Medium and low25. It worth to mention that two single effect systems effectively form a double - effect absorption cooling system; therefore, the COP of a double-effect system equal nearly twice that of the single- effect absorption system (for example SEC which has COP =0.6 then the DEC will have COP nearly =0.96).

D-The Diffusion Absorption Solar Cooling System (Platen - Munters Cycle)

The DAR cycle system was introduced by von platen and munters , where they introduced hydrogen as auxiliary gas beside water (absorbent) and ammonia (refrigerant)pair . The important feature of this system that allows it to operate without the need to electrical or mechanical energy. In addition, it can operate in high temperature source (> 150C^0) and therefore can be installed anywhere. In fact, the DAR is self-circulating absorption system in which a bubble pump is maintaining the circulation of the fluids. The DAR system as mentioned before is free of any moving parts, no dynamic components, as the pump works with a single low pressure. The important function of the auxiliary fluid is to assist the main pair to keep the pressure stable for the expansion process the ammonia-water–hydrogen pair is the most widely used fluid far Dar system. Though the ammonia – water can utilize a heat source at more than 150 C^0 Lithium Bromide works at temperature below 100C$^{0.}$ Some research studies suggested the introduction of an extra bubble pump would increase the COP of the system by (14 – 20)0 % at temperature above 15C^0.

E- The Hybrid Solar Absorption Cooling Systems:

Hybrid Solar absorption cooling technology means the integration of three individual cooling technologies: Radiant cooling, desiccant cooling and absorption cooling. The entire system may be divided into four basic functions: absorption refrigeration, desiccant dehumidification, radiant cooling, and collecting solar energy. The first function utilizes an absorption chiller as the core apparatus. A water pump powers the chiller by providing hot water, while a desiccant wheel is the primary component for the desiccant dehumidification function. The third function utilizes active and passive beams and passive chilled beams specially designed for cooling and the final function utilizes a flat -plate collector capable of harvesting solar energy without freezing in winter., see table 1for the summary of the absorption cooling systems see table 1- Characteristics of some working fluids of absorption cooling technology

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Table 1
The characteristics of the working fluids found from various absorption cooling technologies.

Absorption cooling systems	Working-pairs	Features/results
Single-effect cooling	$LiBr-H_2O$, NH_3-H_2O	• Approximately 60% more COP can be achieved by using a SHX (solution heat-exchanger) [45] • A rectifier is needed to purify the refrigerant if the pair is volatile [24] • A system capacity of 70 kW can be achieved by using a vacuum tubular-collector (108 m^2) with flat-plate collectors (124 m^2) [47] • COP can be increased by 15% using a partitioned hot-water tank with a flat-plate collector (38 m^2) and chillers (4.7 kW) [50]
Half-effect cooling	$LiBr-H_2O$	• Within the optimum temperature range of 65–70 °C, the COP=0.36 and the evaporation temperature is -7 °C [53] • The pair is capable of providing the same COP as a conventional refrigeration system with reducing the cost by half. [57] • The system has 22% lower exergetic efficiency compared to the single-effect systems [58]
Double-effect cooling	$LiBr-H_2O$	• The system has almost double (0.96) the COP compared to the single-effect system [25] • The double-effect chillers with trough collectors show the maximum potential savings (86%) [61]
DAR	$NH_3/H_2O/H_2$, $LiBr-H_2O/H_2$, hydro-chlorofluorocarbon	• More than 150 °C of heat source can be utilized when the working pair is ammonia/water. Organic solvent can be used to run the system below 0 °C [64] • Approximately 50% of COP can be increased by using a coaxial heat-exchanger with a bubble pump [65] • The greater usage of bubble pumps in parallel indicates the better performance of cooling capacity [66]
Hybrid cooling	Combination of mentioned pairs	• These types of systems are widely implemented for the cooling of larger places, such as offices, markets or auditoriums [68]

4. Adsorption Cooling Technology:

The adsorption process differ from the absorption process in that absorption is volumetric phenomenon, whereas adsorption is surface phenomenon. The most important component of the adsorption system is a solid porous surface with a large surface area and large adsorptive capacity. This surface initially kept unsaturated. When a vapor molecule contacts the surface, an interaction occurs between the surface and the molecules and the molecules are adsorbed on the surface [2 The adsorption system is simpler to design and work than an absorption system. It can work in higher temperatures heat sources and not to worry about vibrations of moving parts. It also works without corrosion problems as in absorption systems.

4.1- Working principles of the solar adsorption cooling system.

Adsorption process is a process in which a molecule of a fluid is attached to a surface. The surface is composed of a solid material. The molecules do not engage in any chemical reaction, the phase change from fluid to adsorbate is exothermic, and the process is completely reversible. In the process some molecules adhere to the surface and become adsorbed, while some of them will rebound back.

The adsorption dynamic equilibrium will be reached when the rate of adsorption of molecules to the surface is equal to the rate of desorption of molecules from the surface. This equilibrium is depending on both the temperature and pressure of a fixed adsorbate-adsorbent system.

4.2- Adsorbents and working pairs:

In an adsorption refrigeration technique, the working pair plays a vital role for optimal performance of the system. In addition to some special properties of the refrigerant (high heat capacity, exact FP., saturation vapor pressure and good thermal stability), the performance is maximum if the adsorbent shows the following characteristics.

a-A large adsorption ability.

b- The ability to change capacity with temperature.

c- A flatter isotherm

d- Excellent compatibility with the refrigerant.

We can mention some of the working pairs that have closer properties.

(i) –silica gel /water, (ii) Activated-Carbon / Methanol,
(iii)Zeolite / water, (iv) Metal chloride / Ammonia,
(v) Composite adsorbent/Ammonia, (vi) Metal Oxides and Oxygen,
(vii) Activated carbon/ Ammonia, (viii) Metal hydrides and Hydrogen

According to most sorption techniques, all of these pairs lie in one of the two specific groups, chemisorption or physi-sorption. In Physi-sorption technology, the adsorbate molecule forms a van der Waals interaction with the surface molecules within the vacuum and clean environment rather than chemical bond. The adsorption pair remain unchanged in terms of their chemical composition The van der Waals bond require very low heat to brake. This technology is nonspecific and can be used in any adsorbent –adsorbate system. The most common working pairs used in adsorption technology are silica gel – water, Zeolite-water, activated carbon –(methanol/ammonia)

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Table 2
The properties of working pairs observed in different physisorption refrigeration systems.

Working fluids (Pairs)	Solutions		Features/results
	Refrigerants	Absorbents	
Silica gel	Water	Silica-gel	• The pair shows better performance up to 200 °C; hence, the COP decreases for overheating problems • Water shows better performance, as it has more latent heat than others, allows for running within very low temperatures
Zeolite-water	Water	Zeolite	• Because the water has an evaporation temperature of 0 °C; this pair is widely applicable for air conditioning purposes • It shows the better stability up to a temperature of 200 °C • By using specific materials, the SCP can be made higher (600 W/kg)
Activated carbon granular and fiber	Ammonia, methanol, ethanol	Activated carbon granular and fiber	• The carbon fiber is more preferable for its larger surface area, ensuring better performance in heat and mass transfer • Methanol is the widely used refrigerant with this pair because it has a low desorption temperature (100 °C) and large evaporation latent heat • The activated carbon fiber with ethanol chiller shows 10–12% more COP with 2–3 times increment of adsorption capacity
Activated carbon-methanol	Methanol	Activated carbon	• The pair exhibits the largest COP with methanol as the refrigerant • To avoid the decomposition of methanol, the pairs should be used with temperatures below 120 °C • It has lower thermal conductivity as an insulator
Activated carbon-ammonia	Ammonia	Activated carbon	• The pair has higher cooling capacity, accessibility of larger working temperature and better heat and mass transfer • Ammonia has 33% lower adsorption quantity (0.29 kg/kg) than methanol (0.45 kg/kg); the pair may struggle with problems of corrosion, leakage and toxicity

Table 2 shows properties of physi-adsorption systems and list of pairs. See table 2 for these physi-adsorption systems and list of pairs. Chemisorption is the process in which the adsorbate and the adsorbent atoms form a complex compound by sharing their electrons in a chemical reaction process. The bond here is stronger than the van der Waals bond, and the process is specific that is suitable for a fixed gas and a fixed solid adsorbent. Chemisorption has high COP compared with physi-sorption. See table 3 for the known chemical adsorption pairs.

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Table 3
Features of the working fluids used in chemisorption cooling systems.

Cooling systems	Working fluids (pairs)	Features/results	Sources
Chemisorption cooling system (single pairs)	Metal-chloride/ ammonia	• Lower boiling point, can be used for ice making, SCP=731 W/kg, COP=0.38. • A solution of 20% $CaSO_4$ can reduce the agglomeration problem by mixing it with the working fluids • Corrosion, decomposition, expansion and deterioration are the main problems	[110,111] [109] [93]
	Metal- hydrides/ hydrogen	• Can be widely used in condenser and evaporator because it has higher density (6.5–8 kg/L) and requires small spaces • There is no saturated refrigerant; hence the cycle follows the hysteresis phenomenon	[115] [114]
	Metal oxides/oxygen	• 1 MW energy can be achieved by using 2.85 m^3 of CaO within 1st hour at a temperature of 998 °C • The nanoparticles (10 nm) can be used to increase the system performance	[116,130,131] [117]
Hybrid chemisorption cooling systems (composite pairs)	Silica gel/chloride/ water	• Adsorption capacity is increased six times compared to standalone chloride/ water pair • Small pore of silica gel increases the adsorption performance and the rate of heat and mass transfer • The $CaCl_2$ of larger concentration shows the higher adsorption capacity	[112,124,132] [124] [125]
	Chlorides/porous media/ammonia	• The dimensional stability can be achieved by using the pairs with a density of 156 kg/m^3 • When the number of cycles increases, the COP decreases because $MnCl_2$ separates from the fibers	[127,133] [113,134]

Table 3 shows features of fluids used in chemisorption cooling systems.

5- Conclusion

Renewable energy sources, such as solar energy have been of considerable interest for its great advantages and its availability and sustainability. Solar thermal cooling and refrigeration systems technology are being used widely around the world. These systems are more suitable than conventional cooling and refrigeration systems for their pollution free working fluids. In this report, it was mentioned in summary different method and system of cooling and refrigeration technology. In addition, has shown some of the important features of these systems and the related cooling and refrigerating fluids. Comparison also presented between the COP of these systems indicating the limitations and advantages of these systems under various condition of temperatures, pressures etc.

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