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Review of Solar Cooling Technologies

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Abstract

Solar cooling is a clean and cost-effective technology, solar cooling offer environmental benefits including reducing main grid demand and shift the load during peak usage and reduced greenhouse gas emissions.

The main objective of this paper is to review and analyze different solar cooling technologies that can be used to provide the required cooling and refrigeration effect from solar energy. This paper is covering a wide range of solar cooling technologies including solar electrical refrigeration system, thermo-mechanical combined power and cooling systems and advanced triple effect refrigeration cycles.

This paper includes comparisons of different technologies highlighting the advantages and disadvantages. This comparison would assist the decision makers to select the proper solar cooling technology for specific application.

Keywords: Solar cooling; Refrigeration; Air Conditioning; Solar Energy

Introduction

Throughout the history of the human race, major advances in civilization have been measured by the increase in the rate of energy consumption. Today, energy consumption appears to be related to the life standard of the population and the degree of industrialization of the countries. However, the world today faces unfavorable condition of atmospheric pollution on a scale that has not been faced earlier in human history because of huge revolution in human use of fossil fuel in all activities, it is also Global warning for further temperature increase by 1.4-4.5 K up to 2100 [1].

In order to avoid these unfavorable impact, we need to reduce the harmful emission resulting from burning fossil fuel as a source of energy. This can be achieved either by increasing energy conversion efficiency of the fossil fuel based system or using renewable source of green energy. Among these sources, solar energy is the most important and attractive source; because of the solar energy universal abundance and unlimited nature unlike many other renewable energy sources [2]. The attractive characteristic of solar energy is continuous source being unending even it is intermittent source during the day and night. In addition, solar energy does not cause air pollution or affect the earth's surface as fossil fuel. Solar energy is easy to collect unlike the extraction of fossil fuel.

In the field of solar thermal system, solar cooling has huge potential, because the cooling demand reach its peak coincides with peak solar energy availability.

Solar Cooling Technologies Classification

Solar Cooling technologies can be classified in three main categories: solar electrical, thermal and combined power/cooling cycles as illustrated in Figure 1.

Solar Cooling System and Application Temperature Ranges

The solar cooling system can be divided into three major components; solar energy collecting element, refrigeration cycles, and the application at different temperature ranges.

The proper cycle for each application mainly can be selected based on cooling demand and required temperature ranges. Figure 2 shows different solar cooling technologies that could produce refrigeration effect at different temperature ranges.

Some applications require different range of cooling which cannot be achieved by any single refrigeration cycle.

The Multi-effect system is the best way to achieve different magnitude of refrigeration effect and temperature ranges by using solar energy that helps in eliminating problems affecting the environment.

Solar Electrical Cooling

A solar electrical cooling system consists of photovoltaic panel and electrical refrigeration device. Photovoltaic cells transform light into electricity through photoelectric effect. Many of solar electrical refrigeration system are made for independent operation [1].

PV cells made of semiconductor materials, single crystalline thin films, poly-crystalline and silicon-wafers represent the solar panel materials, and the silicon is major component of PV cell in the market.

The efficiency of polycrystalline thin films is higher than that of silicon wafer, the efficiency of polycrystalline thin films in range of 10 to 17% [2], single crystalline thin file efficiency can reach 15 to 20% by using multi-junction cell structure, while as silicon wafer performance is low and its cost are high compare the thin film technologies.

The produced power by solar photovoltaic cells is supplied either to the thermo-electrical system, Stirling cycle or normal vapor compression systems.

Thermo-electric Cooling (Peltier Cooling System)

Thermo-electric device utilizes the Peltier effect to make a

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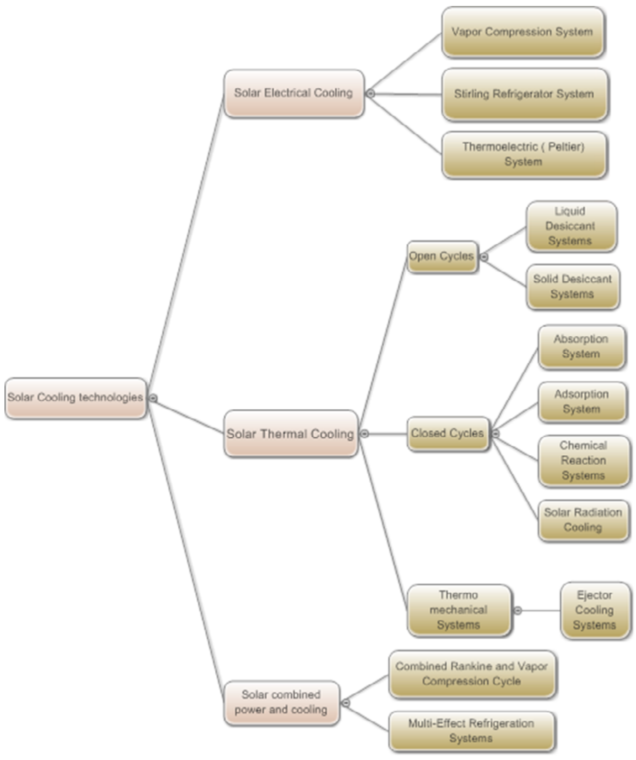

Figure 1: Solar Cooling Technology.

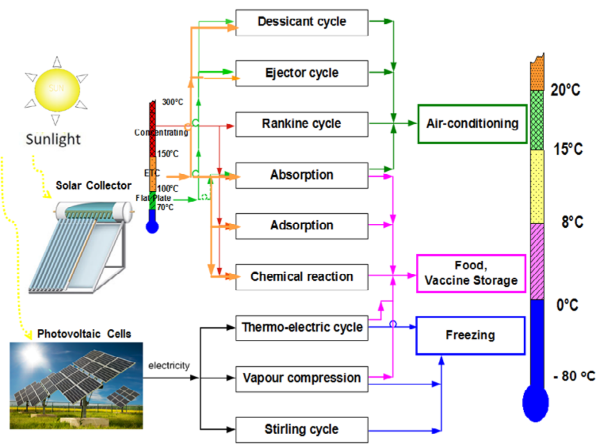

Figure 2: Solar Cooling System and Application Temperature Ranges.

temperature gradient of two types of semiconductors materials. Peltier effect can be defined as presence of heating or cooling at junction of two different conductors due to electricity flow [3].

When a DC current is passed through one (or more pairs) of n and p-type semiconductor materials, the temperature of one conductor decreases and absorb the heat from its surrounding space. The absorbed heat from the space occurs when electrons pass from a p-type material to the n-type material (from low energy level to high energy level) (Figure 3) [3].

When a temperature gradient is achieved between the hot and cold ends of the conductor, adverse voltage is created [4].

The heat is transferred through n and p-type semiconductor from cold side to the hot side then the heat is rejected to outside. If the direction of the current is reversed, the direction of the heat flow is reversed also, and air conditioning system operates in the heating mode [5].

Usage of thermo-electric cooling is less compare to vapor compression cycle in the market.

The Lack of moving parts is the major feature of a Peltier cooler compared to other refrigeration cycles. In addition, the lack of circulating liquid, near-infinite life, very low potential leaks, and its small size are unique features of peltier cooler (Figure 4). Thermoelectric devices contain no chlorofluorocarbons, so it is environment friendly and it is fully reversible cycles, precise temperature control, and work efficiently in sensitive application.

High cost and low efficiency is the main disadvantages. Many researchers are working now to develop peltier cooler with low cost and high efficiency.

Thermoelectric can be used for cooling electronic devices, refrigerator and air conditioners. Thermoelectric equipment can be used for particular applications in military, aerospace, instruments, medicine and industrial.

Riffat et al. [3] explained thermoelectric working principle and materials used for thermoelectric and its application. They also discussed thermoelectric devices application in refrigeration and power generation, and as sensor in thermal energy, they discussed the

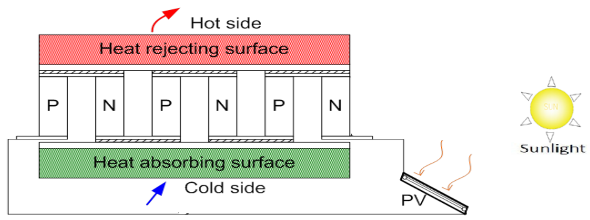

Figure 3: Peltier Cooling System.

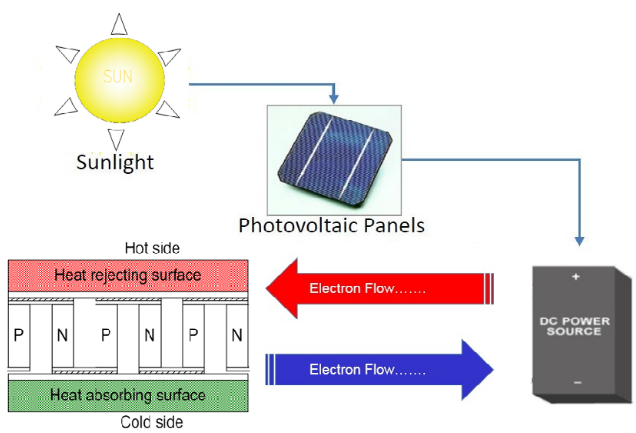

Figure 4: Thermoelectric Refrigeration System.

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development of new materials that could improve the thermoelectric devices for many applications.

The main disadvantage of thermo-electric is low COP but it does have high potential in specific application, such as cooling electronic devices, where thermo-electric is preferred due to small size and consume very less electricity [5].

Solar Powered Vapor Compression Cooling System

PV panel converts solar radiation to DC power which is supplied to a conventional vapor compression system. The Coefficient of performance of the system depend on the efficiency of the PV panel.

The solar radiation is intermittent source, and the solar radiation will not be available all times therefore an alternative source of power to run the system is required when the solar radiation becomes low or unavailable (Figure 5).

The cost of electricity supplied from photovoltaic is equal to or cheaper than grid power, is easily achieved in sunny areas and high costs for grid electricity such as in United States and Japan [Going for grid parity 2005 article].

Klein and Reindl [6] investigated the electrical characteristics that produced from Photovoltaics cells and compare it with required characteristics of compressor motor.

The most important characteristic is the voltage that should be close to voltage producing the maximum possible power in order to run the system at highest efficiency.

This can be done by many ways to track the highest power then select electric motor with current and voltage producing maximum power of the system.

Stirling Refrigeration System

The Stirling Cycle engine was invented by the Reverend Robert Stirling of Kilmarnock in 1812.

A Stirling system is suitable for specific applications requiring low temperatures, Stirling refrigerator can be used for cooling at very low temperatures of about 3 K.

The stirling refrigerator has been used in the application that require low temperature on a relatively small scale such as producing liquid nitrogen and liquid oxygen from atmospheric air.

Most often gas used in a stirling refrigerator is hydrogen due to low molecular weight while as nitrogen is used in commercial and standard units as it is very cheap and safe.

Stirling refrigeration cycle principle is based on volume changes

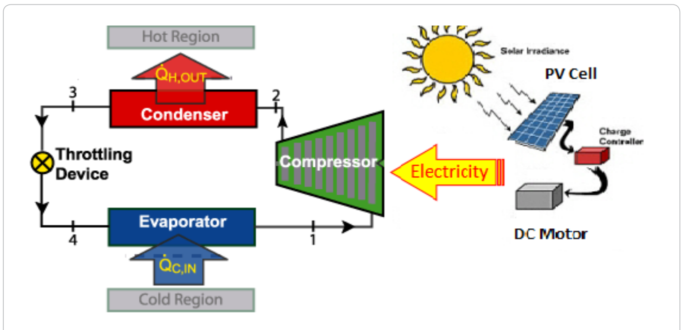

Figure 5: Solar Powered Vapor Compression cycle.

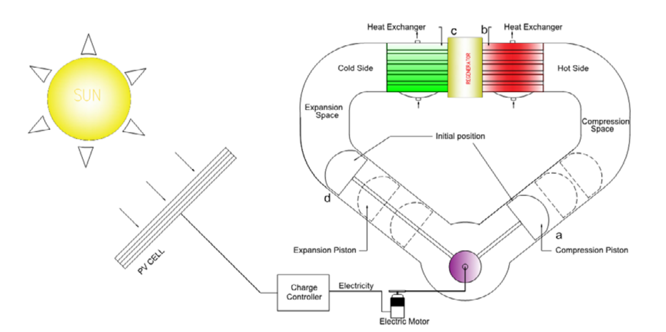

Figure 6: Solar Assisted Stirling Refrigerator Schematic.

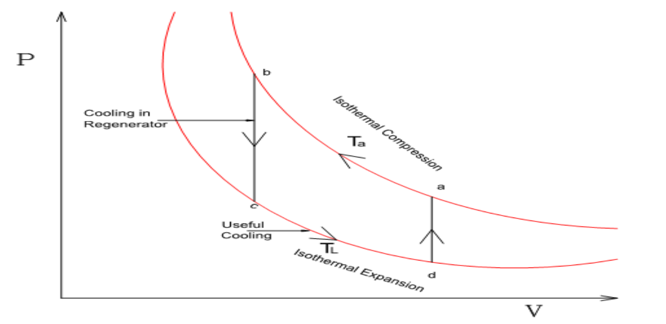

Figure 7: P-V Diagram for Stirling Refrigerator.

caused by pistons, thus inducing changes in pressure and temperature of a gas (no phase change). On the other hand, it yields very good performance at large temperature increases [7].

The Main Concept of Stirling refrigerator is to convert mechanical energy to thermal energy (Useful Cooling).

The cooling cycle is split in four processes as shown in Figure 6, the cycle starts by isothermal compression process; compression of a gas at ambient temperature, the motive force for the compression process is provided by outside source such as electric motor that takes power either from main grid electricity or solar energy through photovoltaic cells.

The cycle starts when the compression and expansion piston at the left position. The compression piston moves to the right while the expansion piston is fixed, the compression at the hot and compression space is isothermal.

The gas moves through hot side heat exchanger due to increase in pressure and the heat dissipated to outside at ambient temperature Ta.

The hot gas enters regenerator as two piston moves to the right, the gas cool in the regenerator to the temperature of cold side heat exchanger, the gas give off heat to the regenerator material. This process take place at constant volume between two pistons (Figure 7).

The compression piston moves to the right while the expansion piston is fixed, the gas expansion take place in the expansion space(isothermal expansion) and the heat is taken up in the cold heat exchanger, and becomes cooler, it represent useful cooling.

The cold gas absorbs heat from conditioned space or machine, the gas absorb the heat and return to environment temperature.

The two pistons move to the left while the total volume remains constant. The gas moves back to compression space at the end of expansion, during this step the low temperature gas passes the regenerator so the regenerator material is taken up the heat and the gas leaves it with high temperature.

Table 1 summarizes the piston movement during the operation of stirling cycle. This cycle is reversible so the COP (the cooling power to the input power) is equal to the Carnot COP that equal to TL/ (Ta-TL), where TL is low temperature and Ta is high temperature.

Ewert et al. [8] discussed the test result of 100 watts Stirling refrigerator that showed decreasing of COP from 1.5 to 0.8 for temperature variation 13-33 K with outdoor temperature from 23-28°C.

Berchovitz et al. [9] discussed the test result of similar machine of Ewert et.al. 1998 with 40 Watts capacity, the results showed COP decreasing from 1.65 to 1.17 with variation temperature of cold side from -1.4 to -19.1°C and temperature of hot side from 28.4 to 30.3°C.

Raine et al. [10] reported test result from the Heat pump stirling cycle development programmed which showed high performance at specific condition compared to conventional vapor compression cycle. This is associated with changes of the hot/cold HEX varied from their design temperatures with a lower performance drop. Further the results obtained showed the heating COP of the Stirling-system machine at 6°C outdoor temperature is only very slightly less than that of a conventional vapor compression system. However, at 0°C outdoor temperature the vapor compression machine has considerable less COP than the Stirling system, even the Stirling cycle machine is operating at an even lower outdoor temperature of -5°C.

There is many challenges in designing efficient Stirling refrigerator as low COP due to poor heat transfer between working fluid and ambient air [11].

Process	Piston Movement	
	Compression Piston	Expansion Piston
a-b	Toward Right	Fixed
b-c	Toward Right	Toward Right
c-d	Fixed	Toward Right
d-a	Toward Left	Toward Left

Table 1: Piston movement of the Stirling cycle.

Riffat et al. [4] conducted a comparative study of the performance between vapor compression cycle, the absorption cycle and the thermoelectric refrigerator. The comparison showed that vapor compression have high COP and low cost. However, some of refrigerant used vapor compression system will be phase out due to their effect on depletion of the ozone layer like system used R-12 or R-22.

Absorption cycle generally require large space and high initial cost but consume very less electricity to run the pumps and fan as it depends on waste energy source or solar energy to provide the required thermal energy to generator, so the operational cost is very low, while as low noise or almost very less vibration due to no moving parts, small size and light weight are unique features of thermo-electric. Thermo-electric does not require refrigerant so no effect on the environment (Table 2).

Solar Thermal Cooling

Solar energy conversion systems can be used to transform solar thermal energy to cooling or heating through chemical or physical Processes.

Open Sorption Cycle Solar Cooling

It represents desiccant systems that are used in air conditioning applications for humidification or dehumidification basically transfer moisture from one air stream to another one. These cycles cab be used as pre-cooling of other system and can be used to provide cooling for specific application with special requirement (Figure 8).

The main operation concept of open sorption cycle is to absorb and release the moisture in three processes as follow:

Description of Open Sorption Cycle Solar Cooling shown in Figure 9.

Liquid Desiccant System

The system consists of a conditioner and regenerator, the principle operation of the system as follow:

Conditioner

System	Vapor Compression	Thermoelectric (Peltier)	Stirling Refrigerator
Power of 1 W of refrigeration effect (Watts)	12-50	A few W	3 - 17
COP	2-4	~0.5	~3
Working Fluid	R-134A, R407C & R410A etc.	-	He, H_2 and Air
Application	Refrigeration, Freezing, food storage & vaccine storage	Refrigeration, large LCD screen, Military communication, etc.	Cryogenic applications including: IR – Infra Red imagers.
Noise (dB)	35~48 indoor	NA	~35
Size	Medium	small	small
Life expectancy, year	10-15	~23	~15
Advantages	-High COP. -Widely Commercial Available. -Long Term Experience.	- No moving parts. - No working fluid. - Quiet. - Small Size. - Light Weight. - Near-Infinite Life. - Invulnerability to potential leaks.	- High COP for high temperature difference. - Mechanically more simple than other application for low temperature operation. - Environmentally friendly working fluid. - Mobility and Light weight.
Disadvantages	- Installation Cost is high. - PV cells cost is high. - Requires Battery for energy Backup. -Requires more space for PV cells.	- Low COP. - High Cost. - Difficult to achieve low ref. temperature. - Low Reliability.	- High Production Cost. - Complexity in Design.

Table 2: Comparison between solar electrical cooling systems.

Figure 8: Process of Moisture Transfer by Desiccant.

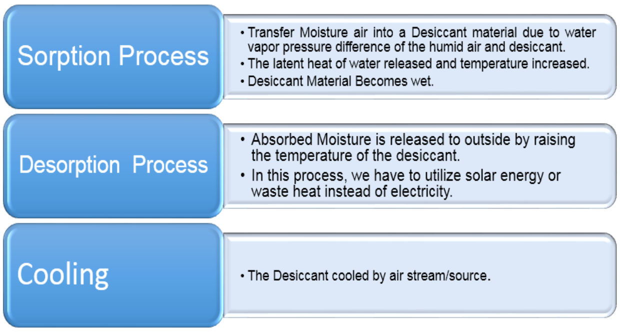

Figure 9: Description of Open Sorption Cycle Solar Cooling.

The liquid desiccant is pumped and passes through nozzle that will spray the desiccant in the air to absorb the moisture from air due to difference in surface vapor pressure of the desiccant and air.

The liquid desiccant falls to the basin of conditioner and spray back in air, the desiccant temperature and pressure has increased

The water content increased due to absorption of moisture and in order to increase the concentration of desiccant small amount of the mixture of water and liquid desiccant is pumped from conditioner basin to regenerator basin.

Regenerator

The desiccant is sprayed in the air and the desiccant heated before spraying so its partial pressure increased, therefore the moisture had absorbed by regenerator's air and leave it in hot and humid condition.

The concentration of liquid desiccant increased in the basin of regenerator and its temperature and pressure increased as well.

Small amount of desiccant return to conditioner to spray again. Finally before spraying the liquid desiccant, it must be cooled by cold water from chiller or other cooling sources.

Lithium chloride, calcium chloride, and lithium bromide are main materials used in liquid desiccant systems [12].

The advantage of liquid desiccant cycle that the desiccant can be regenerated by using low grade energy source shown in Figure 10.

Gommed and Grossman [13] investigated solar assisted liquid desiccant cooling system using Lithium chloride and water as working fluid, outside temperature was the influencing factor that is having high effect on the dehumidification process (Figure 10).

The result showed that the system supplied 16 kW of dehumidification capacity with 0.8 coefficient of performance.

Davies [14] developed the liquid desiccant system based on Abu Dhabi data weather with the solar collector for regenerative heating coil and the adiabatic cooler to reduce inside condition in greenhouses. The result revealed clearly the possibility of lower outside temperature by 5°C as cooling effect.

Solid Desiccant System

The solid desiccant system used to provide air conditioned air through basic process as shown in the below Figures 11 and 12 shows Dry bulb temperature.

Working Principle of Solid Desiccant Wheel

(1-2) Dehumidification process by adsorpting the water in the desiccant wheel, the air enter the wheel is Warm and humid, so the humidity ratio decreases and dry bulb temperature increase.

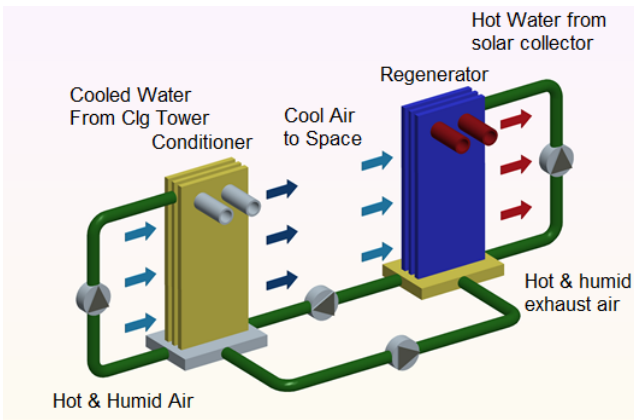

Figure 10: Schematic of Liquid Desiccant System.

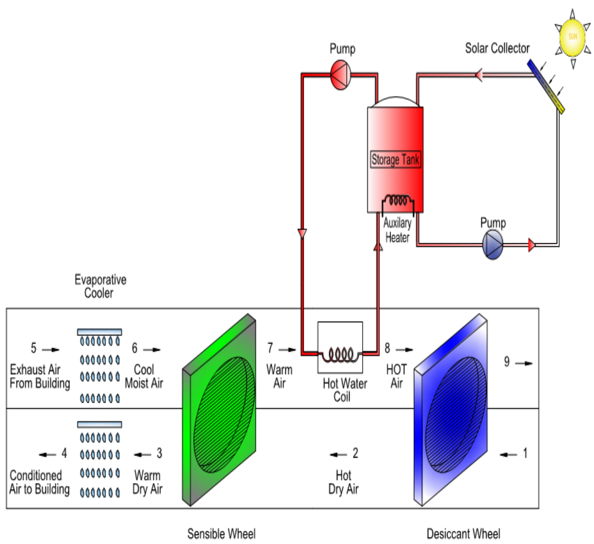

Figure 11: Schematic of a Solid Desiccant Cooling System.

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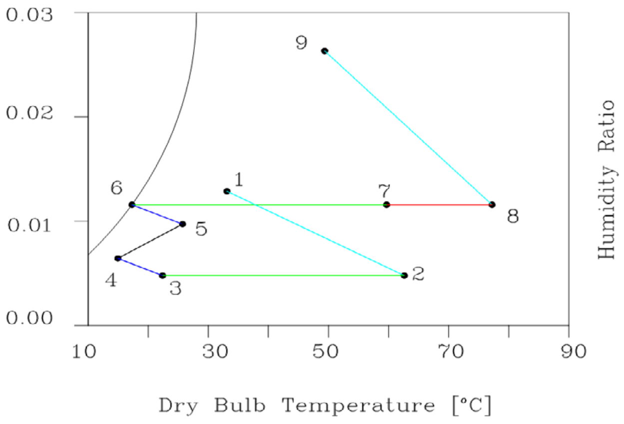

Figure 12: Psychometric Chart of a Solid Desiccant System Process.

(2-3) Sensible cooling of the supply air in sensible wheel.

(3-4) the air is humidified and further cooled by evaporative cooler, the required room temperature and humidity can be set by using controller on supply air stream.

(5-6) the exhaust air stream from the air conditioned space is humidified by evaporative cooling to achieve the full cooling potential needed in sensible wheel

(6-7) the exhaust air is heated up in sensible wheel, the cold side of the wheel moved to supply air side to achieve the required cooling. (7-8) the air pass through the regenerative heat coil and air temperature increased. The hot water received from dedicated solar collector in a comparatively low temperature around 70°C.

(8-9) the desiccant wheel has to be regenerated to keep the system operate continuously for dehumidification process, so the humidity ratio increased and dry bulb temperature decreases of the exhausted air.

The solar system consists of solar collectors and hot water storage to maximize the utilization of the solar system. Auxiliary water heater is needed to maintain continuous operation during the night and when the solar source is not available or enough.

Standard desiccant wheel might not be efficient in coastal areas where the outdoor air is very hot and humid as the system will not be able to reduce the humidity to level which evaporative cooling can work efficiently. Therefore, more complex design can be implemented to overcome this problem.

Henning [15], Simulated a solar assisted solid desiccant system with solar collector (20 m^2 Area) and storage tank (2 m^3 volume). The results showed that a 54% collector efficiency, 0.6 COP and 76% solar fraction (auxiliary energy supplied).

Henning [16] Investigated a solid desiccant cooling system, the result showed that the maximum COP was about 0.7.

Closed Solar Cooling Sorption Cycle

Closed cycles are divided in two categories based on the sorption material as follow:

Figure 13 describes Closed Solar Cooling Sorption Cycle.

Solar Cooling Absorption systems

Absorption refrigeration cycles require hot water from waste heat source, solar collector or boiler to separate a water refrigerant from a mixture of LiBr/Water in the generator (Figure 14).

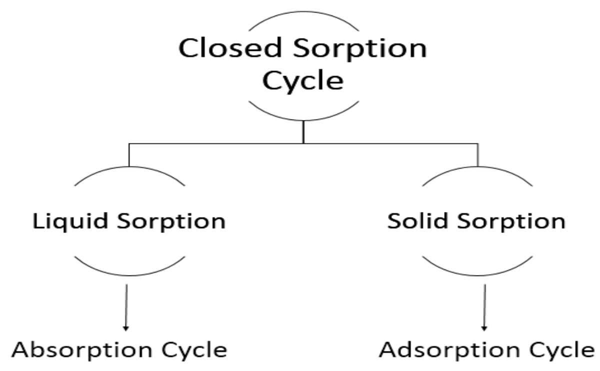

Figure 13: Describes Closed Solar Cooling Sorption Cycle.

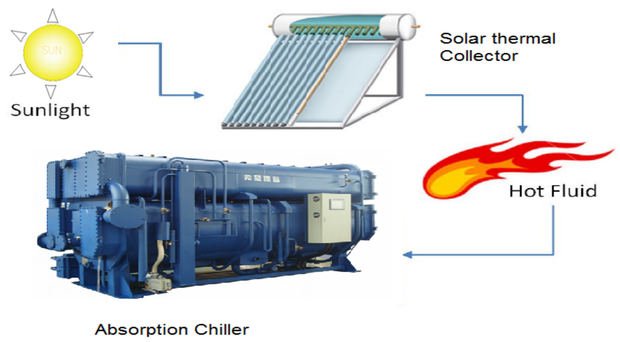

Figure 14: Thermal Solar Cooling Absorption System.

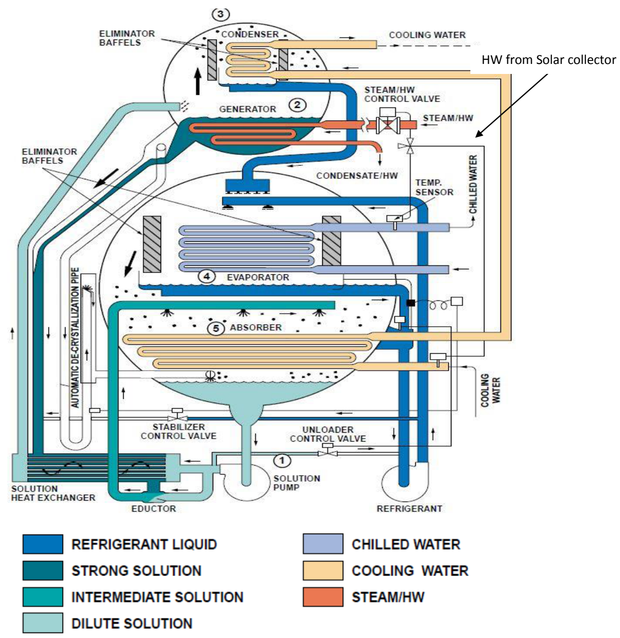

Figure 15: Schematic of a solar absorption system.

The history of an absorption cycle started in the 1700's. It was used to produce ice by an evaporation of pure water from a vessel placed within an evacuated container with sulfuric acid [17-19].

Ferdinand Carre developed machine using water/ammonia as the working Fluid in 1859 while as system using $LiBr/H_2O$ as the working fluid was developed in 1950 shown in Figure 15.

The working principle of a solar assisted absorption refrigeration System as follow:

Solar Energy Conversion System

The solar collector converts the solar energy from sunlight to thermal energy, The Thermal energy is then passed through high temperature energy storage tank then to the absorption system.

Evaporator

The building load is taken in the evaporator, as the water evaporate and the water vapor will pass to absorber. Inside the evaporator, relatively warm return water from the chilled-water system flows through the tubes. An evaporator pump draws the liquid refrigerant from the bottom of the evaporator and continuously circulates it to be sprayed over the tube surfaces. This maximizes heat transfer.

As heat transfers from the water to the cooler liquid refrigerant, the refrigerant boils (vaporizes) and the resulting refrigerant vapor is drawn into the lower pressure absorber. Physically, the evaporator and absorber are contained inside the same shell.

The vacuum is created by hygroscopic action due to the strong affinity lithium bromide has for water makes the refrigerant to move to absorber.

Absorber

The Lithium bromide absorbs the water and form weak solution then it is passed to the generator through intermediate heat exchanger.

Absorber types used for Lithium bromide-water system is absorption of vapor refrigerant into a falling film of solution over cooled horizontal tubes [20-27].

Generator

The hot water used to separate the weak solution form water vapor and form strong lithium bromide solution, then the water vapor is passed to the condenser.

The hot water provided from Low-grade heat source can be upgraded by using solar energy [28], power plant waste heat or other industrial application [29,30]. The absorption heat source performance with various working fluids has been investigated; LiBr/water [31], Dimethyl Formamide (DMF)/R21 [32-34].

Heat exchanger

The strong solution of lithium bromide is passed to the absorber through heat exchanger after the separation in the generator. The weak solution from the absorber is pumped through the same heat exchanger to the generator, so the temperature of weak solution increased while as the strong solution temperature decreased.

Condenser

The cold water from cooling tower used to remove the heat and condensate the water vapor, then the liquid water will enter the expansion valve.

Cooling water from cooling tower

Cold water supplied from cooling tower used to remove the heat from condenser and absorber then the heat is dissipated in the cooling tower to outside.

Auxiliary heat source

The auxiliary heat source is needed when sun is not shining or solar energy source is not enough to main continuous operation.

Performance of absorption solar cooling system

$$COP = \frac{\text{Cooling Capacity at evaporator}}{\text{Heat Input at Generator} + \text{Pump Required Power}}$$

The performance of Absorption solar cooling system depends mainly on thermodynamic properties of the working fluid [35].

Working Fluid in Absorption Solar Cooling System

The most common working Fluid are $LiBr/H_2O$ where Water is the refrigerant and LiBr is the absorbent and H_2O/ammonia are widely used in absorption systems where ammonia (NH_3) is refrigerant and Water is the absorbent.

Marcriss discussed all possible working fluids that can be used in absorption solar cooling systems, he found that there are 40 refrigerant compounds and 200 absorbent compounds available to be used in absorption refrigeration systems [36].

H_2O / NH_3 thermodynamic properties can be obtained from [37-41].

$LiBr/H_2O$ thermodynamic properties can be obtained from [42-46]. A corrosion inhibitor may be added to $LiBr/H_2O$ as [47-50] or to enhance heat and mass transfer performance [51-55].

Many research has been carried out to investigate the thermodynamic properties of new working fluid like fluorocarbon refrigerant with number of organic solvents, Research on these kinds of working fluids may be obtained from the literature [56-61].

Ghaddar [62] investigated a solar assisted absorption system located in Beirut. The results showed a minimum collector Area for each ton refrigeration is 23.3 m^2 and with best water storage tank size varied from 1,000 to 1,500 L for seven hour of operation on solar energy.

Hammed and Zurigat [63] Studied the performance of solar assisted absorption system with 1.5 ton cooling capacity, 14 m^2 solar collector and Shell and tube heat exchangers. The test carried on April and May in Jordan and the test result showed actual COP around 0.55.

Florides [64], designed a solar cooling system to handle the house load for whole year, the system consist of a solar collector storage tank, an auxiliary water heater and a LiBr/water absorption system. Selection of solar collector area can be decided through economic analysis without compromising of the system performance.

Hammad and Audi [65] simulated the performance of a non-storage solar assisted absorption system without storage tank. The results showed a maximum ideal COP of the system to be equal to 1.6 while the peak actual COP was 0.55.

Boehm [66] developed a solar assisted absorption system (single-effect with ideal cooling capacity of 10 ton) with storage tank (0.45 m^3), solar collector (63.7 m^2). Economic analysis was performed for this system and the result showed reduction from $3,448 to $1,737 annually more than the normal 8 ton vapor compression refrigeration

Attribute	Vapor Absorption	Vapor Compression
Method of compression.	Absorption of the refrigerant by the absorbent like LiBr absorbed water vapor and circulating pump used to raise the system pressure.	By Compressor.
Power consumption devices	Circulation Pump, the power consuming device is very less compared to compressor.	Compressor is the major consuming of electricity.
The amount of power required	Requires very small amount.	Requires large amount.
Type of energy required	Runs mainly on the waste heat in the plant or using hot water from solar collector or hot water from boiler.	Runs by electrical power, either from main grid or any renewable energy source like solar, wind or geothermal energy.
Running cost	Relatively Very less as it depends if waste heat or renewable energy source.	Relatively Very high as it depends on electric power.
Foundations required and noise	Relatively less noisy and does not require strong foundation.	Relatively more noisy and require heavy foundation.
Maintenance	Requires little maintenance for small pumps that fails rarely.	Compressor requires a maintenance.
Capacity control	Step less capacity control and zero capacity when there is no demand.	Stepwise capacity control by compressor, it consumes power even there is no demand.
Type of refrigerant used and its cost	Ammonia and water which are cheap refrigerant.	Halocarbons refrigerants, which are very expensive refrigerant.
Leakage of refrigerant	The leakage very less.	There is leakage relatively more than absorption system as the system pressure more.
Greenhouse effect	No refrigerant produces the greenhouse effect, it is guaranteed for future use.	Most of the halocarbon refrigerants are producing greenhouse effect.
Initial capital cost	Very High compared to vapor compression.	Very less compared to vapor absorption.
Corrosive nature	LiBr is corrosive and it will reduce the life span of the system.	No corrosive material and it has longer life.
Low working pressures	Very low and no need for expansion valve.	Can work at low pressure.
Coefficient of Performance (COP)	It's relatively low, a range 0.8 ~ 1.1.	It's relatively higher a range 4~5 and can be higher if the system combined with evaporative cooling.
Heat rejection	Heat rejection factor is high and it can be around 2.5, and heat rejection will be from condenser and absorber.	Heat rejection only from the condenser, so the heat rejection factor is small, which is about 1.25
Capacity	The system can be design for capacity higher than 1,000 tons of refrigeration in a single units.	The system can produce up to 2,500 tons of refrigeration in a single unit (Centrifugal chiller).
Sound Pressure Level	Relatively Low.	Relatively high and can be more than 80 dB (A).

Table 3: Comparison between Vapor Absorption Refrigeration with Vapor Compression Refrigeration System.

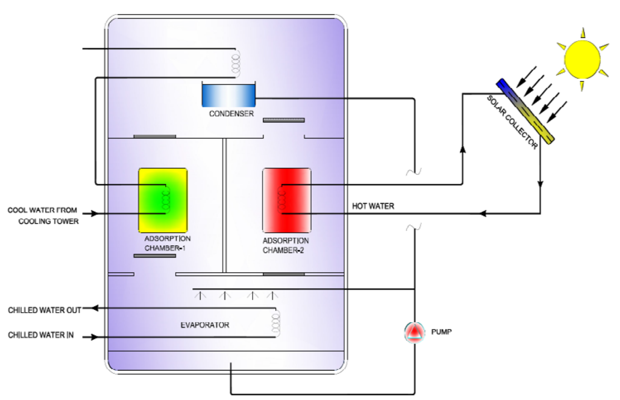

Figure 16: Schematic of Solar Adsorption System.

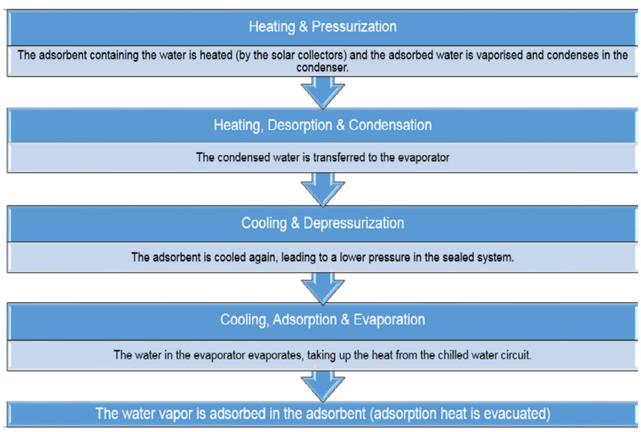

Figure 17: The process in adsorption system can be summarized.

system. The analysis showed the payback periods are 1.5 to 3 years based on the performance of the solar collector and rate of electricity difference. The system showed capability to supply more than 5.5 ton of actual cooling continuously for 8 hours on a summer day. Comparison between Vapor Absorption Refrigeration with Vapor Compression Refrigeration System Shown in Table 3.

Adsorption Cooling System

Adsorption cooling is a one of thermal driven system. The energy source can be either solar energy or waste heat from power plant.

Figure 16 shows the major components of adsorption refrigeration system which consists of a thermal compressor, condenser, evaporator and expansion valve.

The operation principle of an adsorption cooling device can be described as follows:

Solar Heating System supply hot water to regenerate the sorbent in chamber 2, the hot water can be supplied from the external heat source like waste heat. The silica gel desorbed by hot water. The water vapor from the sorbent flows to the condenser where it is then condensed to a liquid state.

The condensed water with high pressure flows through tubes and after reaching pressure level equal to that in the evaporator, so the water enters the evaporator where a system of nozzles is spraying water on the tubes of chilled water system.

The water vapor entering from evaporator to adsorption chamber 1 through open valve at the bottom of the chamber. However to ensure vapor flow towards the reactors (absorbers), the pressure inside the chamber should be lower than that in the evaporator, therefore the chamber precooled and the cooling required to remove the heat added by the adsorption process.

If the adsorbent in the adsorption chamber is fully saturated with water vapor, the chambers function is switched over. The process in adsorption system can be summarized as follow in Figure 17.

The below table and figure shows the difference between absorption and adsorption as follow:

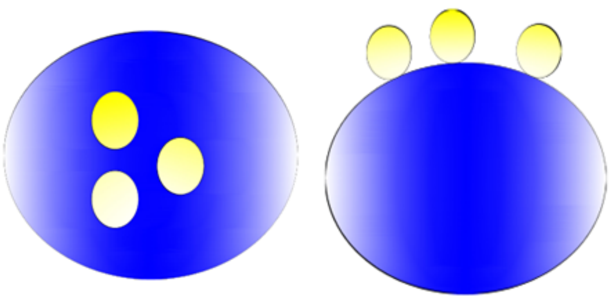

Figure 18: Difference between Absorption and Adsorption.

Absorption is when one molecule completely enters inside of a volume of other molecules. It becomes a part of it. This can be a chemical (reaction) or physical process.

Absorption occurs when the physical state of the molecules has changed as a gas turns into a liquid, or a liquid into a solid.

For example, LiBr can be absorbed into water – this is an example of a chemical absorption since a reaction occurs. Another example for a physical absorption is air dissolving into water this is since the air is entering into the water, driven by pressure difference.

Adsorption, is a surface process when one molecule not entering completely inside of a volume of other molecules, its only attracting the molecules of a substance on the surface of a liquid or a solid that increasing the concentration of the molecules on the surface.

This can be a chemical reaction (Chemisorption) chemical bonds used in sticking the adsorbate to the adsorbent or physical process (Physisorption -Van der Waals interactions) (Figure 18). For example, The CO_2 molecules just sit on the surface of the solid adsorbent. Table 4 shows Comparison between Absorption and Adsorption systems:

*An endothermic reaction occurs when energy is absorbed from the surroundings in the form of heat. Conversely, an exothermic reaction is one in which energy is released from the system into the surroundings.

Chemical and Physical Adsorption

Adsorption and chemical reaction adsorption cycles are similar to each other. The difference between these cycles is the processes which occur in the cycles. The force causing the adsorption process is a physical adsorption force; and the force causing the chemical adsorption process is a chemical adsorption force. Differences between both types of adsorption processes are described in Table 5.

Comparison Criteria	Adsorption System	Absorption System
Initial Cost	Almost similar	Almost similar
Phenomenon	It is a surface phenomenon	It is a bulk phenomenon
Heat exchange*	Exothermic process	Endothermic process
Temperature	It is favored by low temperature	It is not affected by temperature
Rate of reaction	It steadily increases and reach to equilibrium	It occurs at a uniform rate
Concentration	Concentration on the surface of adsorbent is different from that in the bulk	It is same throughout the material.
Example	(i) Water vapors adsorbed by silica gel. (ii) NH_3 is adsorbed by charcoal.	i) Water vapors absorbed by anhydrous $CaCl_2$. (ii) NH3 is absorbed in water forming NH_4OH
Continuous Operating	More than 8,000 hours per year	Require daily shutdown for dilution of lithium bromide solution.
Life Span	The silica gel up to 30 years.	10 years.
Maintenance	Replacement vacuum pump every 5 years, annual cleaning of condenser tubes.	Require more preventative maintenance for pumps, heat exchanger replacement, controls, and air leakage.
Refrigerant	Water	Water or ammonia.
Adsorbent/absorbent	Silica Gel	Lithium bromide or water
COP	0.7 ~ 0.8	0.8 ~1.1
Corrosion	None.	Lithium bromide are corrosive in nature.
Crystallization	None.	Yes, can occur in Low temperature cooled water.
Frequent Replacement Adsorbent/absorbent	Not necessary	Every 5 years.
Required Hot Water Temperature	Variable 50 to 100°C	Variable 80 to 120°C, Back-up heat is required if the temperature below 80°C to prevent crystallization.
Cooling water Requirement	30 to 4 °C, lower temperature increase system capacity	It should be between 18 to 30 °C.
Chilled Water Output	3 to 9 °C.	Higher than 9 °C.

Table 4: Shows Comparison between Absorption and Adsorption systems.

Attribute	Physical adsorption	Chemical Adsorption
Adsorption process Forces	Van Der Waals Force.	Covalent or ionic bonds, these forces are stronger than van der waals force.
The thermodynamic operation of the cycle.	Reversible process, heat is required to increase the temperature of adsorbent and complete adsorption and desorption cycle.	Very difficult to reverse. More heat is required to complete the cycle, and more heat is required to achieve high efficiency of reaction.
Working Media	Several pairs can be used: ▪ Activated carbon/methanol or ammonia. ▪ Silica gel/water.	Several pairs can be used: Ammonia Salts with alkaline compounds. Hydrogen and Methal hydrides.
Number of the adsorbers	One is enough for the base cycle, the number can be increased in order to enhance the efficiency.	Two are required.

Table 5: Comparison between Physical and Chemical adsorption.

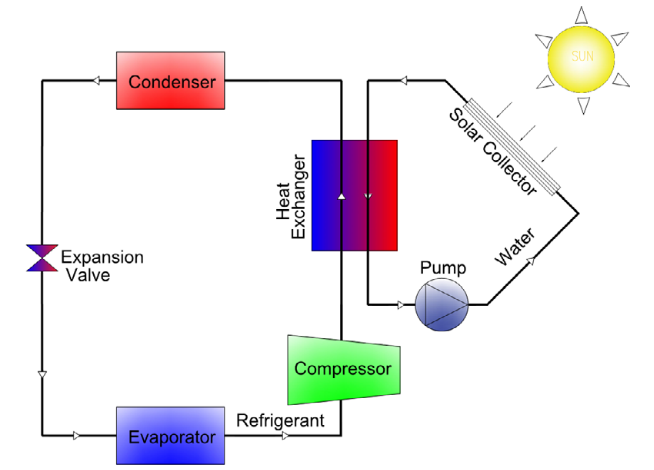

Figure 19: Schematic of Solar refrigerant Cooling system.

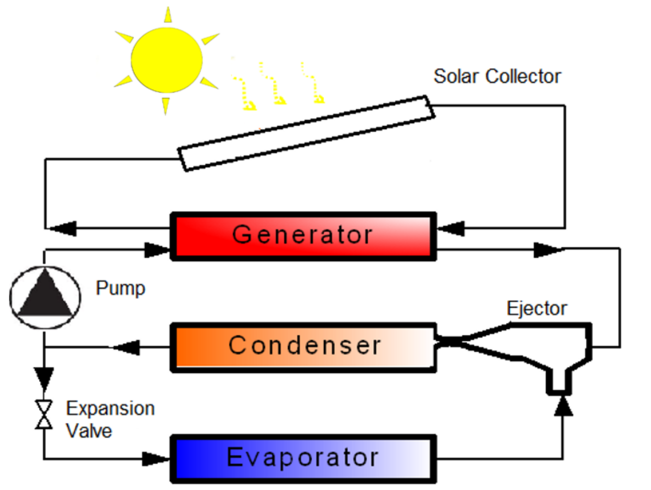

Figure 20: Schematic of ejector refrigeration system.

No moving parts and low evaporation temperatures during operation is the main advantages of chemical reaction cooling system. While as low COP, high weight of adsorbent makes it not sufficient for large application.

System design complexity due to adsorber volume change through chemical reaction and difficulty to achieve system tightness during operation at low pressure and temperature, all the above demerits limiting its use.

Lemmini [67] investigated the performance of adsorptive solar assisted cooling system and compare it with normal solid adsorption system. The comparison proved that the performance of solar powered system highly depends on the absorptivity of the solar collector and the insulation on the back side of the solar collector.

Pons and Guilleminot [68] carried out a study on solar assisted solid adsorption ice maker. The result revealed clearly the system COP is 0.12 which makes this machine one of the highest efficient solar ice makers.

Wang et al. [69] investigated a solar assisted adsorption system with activated carbon and water with solar collector (area 2 m^2), the result showed that the system are able to produce daily 10 Kg of ice with 90°C hot water (around 60 kg).

Energy Storage in Solar Cooling System

Schweigler et al. [70] modeled solar assisted absorption system with phase change material (PCM) for latent heat storage in order to guarantee a low operating temperature of the system. In the study, the latent heat storage was based Calcium Chloride Hexahydrate, whose melting temperature starting from 27°C up to 29°C. Standard lithium bromide and water absorption system cannot provide cold chilled water at 6°C/12°C with LiBr/Water system but in this system the condenser and absorber were air cooled combined with PCM latent storage, so the system can provide 6/12°C of chilled water from the absorption system due to reduction of the temperature of the rejected heat by 5°C to 8°C.

Solar Refrigerant Cooling System

Refrigerant is circulated by the compressor to the condenser through water-refrigerant brazed plate heat exchanger, the hot water is supplied from the solar collector to increase the temperature of refrigerant. The heated refrigerant is hot and at high pressure due to expansion and the further increase in the temperature and pressure reduced back pressure on the compressor; these phenomena will increase the cooling capacity of the system without increasing the power consumption resulting in high COP shown in Figure 19.

Thermo-mechanical Solar Cooling

Unlike conversion solar energy to thermal energy, in the thermo-mechanical system the solar energy converts to the thermal energy then converted to the mechanical power which can be used to provide the required cooling.

Steam Ejector Cycle

Steam ejector cooling is one of the popular thermo-mechanical cooling system used in refrigeration and air conditioning, the system consist of solar collector, generator, condenser, evaporator, expansion valve, ejector and pump (Figure 20) [71].

The working and operation principle of ejector cooling system are described in Figure 17. The saturated vapor primary fluid (can be water or other refrigerant) enters the nozzle of the ejector at high pressure and temperature supplied from boiler or generator.

This primary fluid expand and leaves the nozzle at a very high velocity and a low pressure which draws working fluid vapor (secondary fluid) from the evaporator and maintains the vacuum necessary for operation. When the mixing of the two streams is completed, the pressure increased in the diverging section and the mixture slow down, the ejector will be able to discharge the mixture of primary and secondary fluid at a pressure that is higher than the entering pressure. So, the ejector is boosting the pressure of the primary entering fluid.

A low energy grade energy source that can be used for this system and low cost of operation and construction are the main advantages of steam ejector solar cooling system, while as high initial cost, low COP, complicated design of the ejector and the difficulty to operate in a wide range of ambient temperatures are the challenges in this system.

Wang et al. [72,73] performed a study of ejector cooling system consist of multi-function generator that provides the required hot water for ejector cycle operation and can work as heat pump. In this study R141b considered as working refrigerant and the ejector design modified to work with other refrigerant like R365mfc to enhance COP of the system and R141b phased out, and R365mfc ODP was close to zero. The ejector cooling system with multifunction generator operating at full-cycle using R141b and the cooling capacity of 0.75 kW, ejector area ratio of 7.73 at 90°C generator temperature, condenser temperature 37°C and evaporator temperature 8.5°C. Operating coefficient of performance can reach 0.225 at full cycle while using R141b therefore it conclude that R365mfc can replace R141b without affecting the system overall efficiency and performance as long as the design of ejector optimized.

Pollerberg [74] investigated solar assisted steam ejector chiller for whole year in Bochum, Germany. The system includes experimental step with cooling capacity 1 kW and two types of collector a parabolic trough (PTC) and a vacuum tube collector (VTC). The effect of the operating temperatures and pressures on the efficiency of the solar collectors and the COP of the system are studied. Then, the annual mean efficiency of the solar collector, the annual mean COP of the solar ejector cooling system are determined by using simulation tools as well the annual mean total efficiency of the system for different locations worldwide are investigated. The direct horizontal solar radiation reached maximum value of 550-600 W/m^2, absorber area of 10.5 m^2, COP of the system investigated based on condenser temperature ranging from 15-35°C and evaporator temperature of 7, 13 and 17°C, with decreasing condenser temperature and increasing evaporator temperature COP of the system rises.

The simulation result showed that the PTC are more suitable for large application and collector fields and the ratio of direct insolation to global insolation for a particular zone had influenced on the economy aspect of the system.

Many researchers carried out experimental study [75-85] to investigate the performance of steam ejector refrigeration system with different working fluids and characteristic. A numerical study [86,87] also performed to find the optimum design condition of steam ejector refrigeration system. Good results were obtained from these numerical study such as better pressure recovery for small diffuser angle, the weight fraction recovery was higher for low angle and smaller droplet size yield to better diffuser performance.

Selvaraju et al. [88] investigated the performance of vapor ejector refrigeration system when the ejector operates at choking-mode. When operating conditions are changed, the critical performance parameters of the system get shifted to different critical values. The effect of factors studied in this paper were a specific heat of the working fluid and friction at the constant-area mixing chamber and internal irreversibility of the ejector to validate the model, the effect of compression ratio, driving pressure ratio on the critical entrainment ratio and critical COP of the ejector system are studied. The result from simulation compared with the experimental data from the literature, the effects of operational parameters and ejector configurations of the system are studied and find out the effect in the performance. The results showed decreasing the entrainment ration and COP due to increase compression ration while as entrainment ration and COP increases with rising driving pressure. Also, comparison of performance of the system with environment friendly refrigerants, R134a, R152a, R290, R600a and R717 is made. Among working fluid considered, the system with R134a gives better performance.

Solar Combined Power/Cooling Systems

The solar energy can be converted to thermal energy that drive power generation device therefore the produced power can be used to run refrigeration cycle which provides the required cooling and refrigeration effect.

Goswami and Lu [89] made first law efficiency analysis of the combined power and refrigeration cycles, the system includes the solar collector can supply hot water at 90°C temperature. The results showed that thermodynamic efficiency (first law) reached maximum 15.7% and minimum 10.5% based on the ambient temperature variation from 7°C-27°C.

Rankine cycle and a vapor compression cycle can be combined together. It uses the high-pressure vapor fluid to drive a turbine in the power cycle. Consequently, work from the turbine drives the compressor in the refrigeration cycle. Many option of working fluid can be used in rankine cycle (Figure 21).

The COP of the refrigeration cycle is as high as that of conventional vapor compression systems powered from grid electricity but the efficiency of the power cycle is quite low (about 10%). This system is quite complex and only suitable for large air conditioning applications. Solar Rankine air-conditioning systems were suggested in the United

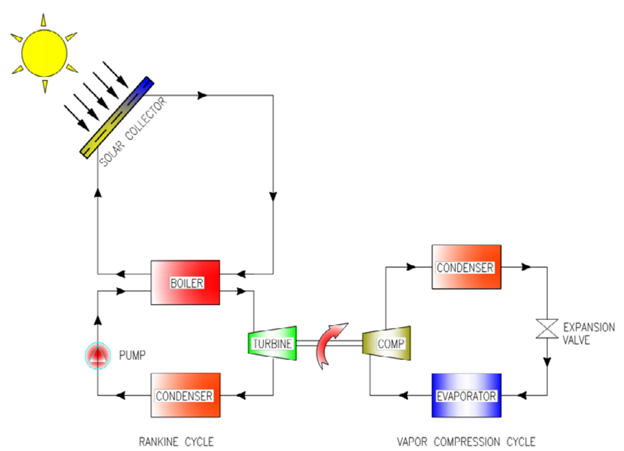

Figure 21: Combined Rankine and vapor compression cycle.

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States in 1975-1980 during the oil crisis. Numerous efforts have been Made to develop similar solar cooling systems. The systems were not economically competitive compared with conventional systems.

Wali [90] suggested that only halocarbon compounds and the fluorinated compounds fulfilled safety requirements. Subsequently, the working media which were previously recommended were found not to be environmentally benign. Thus, the development of this system was detained until interest returned in the 21st century with new proposed cycles combining power and cooling cycles.

Kane, Larrain et al. [91] proposed an Organic Rankine Cycle (ORC) including a hermetic scroll expander-generator and solar tracking equipment.

The advantages of Combined Rankine and vapor compression cycle are suitable for high capacity systems and suitable for integration into poly generation systems (heat, electricity and refrigeration).

High installation cost, large system and Regular maintenance required due to complications and many moving parts reduce the demand of this system.

Agrawal et al. [92], investigated the triple effect refrigeration cycle with a cascaded vapor compression cycle (N_2O natural refrigerant), absorption cycle (LiBr/Water system) with an ejector refrigeration cycle. The main disadvantage of N_2O is its higher GWP compared to other refrigerant; however it is significantly more favorable in terms of toxicity.

The results showed that some influenced factors as waste flue gas temperature, ejector evaporator temperature, turbine inlet and outlet pressure and discharge pressure of the compressor are having significant effects on the refrigeration outputs of proposed cycles in term of energy efficiency and thermal efficiency.

Fan et al. [93], investigated of a solar assisted ejector-absorption technologies and shows the other feature that these cycle can be used for, not only to provide the required cooling and refrigeration effect but can be used for environmental protection.

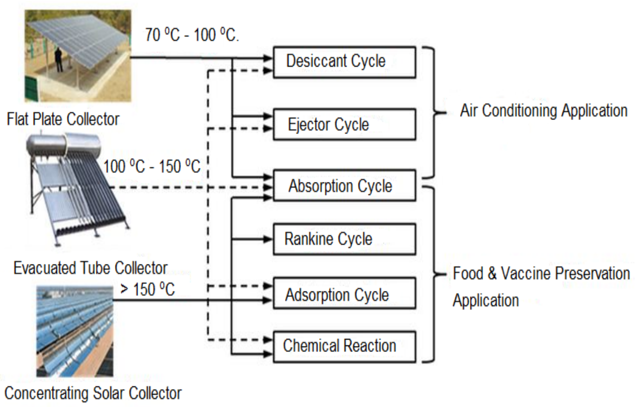

Figure 22: Solar Collector temperature ranges serving different Cooling application.

Abdul Khaliq et al. [94], performed energy and exergy analyses of a triple effect solar assisted refrigeration system. The results clearly revealed that thermodynamic investigations based on energy analysis is not enough and the exergy analysis must be considered to find out the imperfection component and work it out to enhance the system overall performance.

Rajesh Kumar et al. [95], performed the thermodynamic analysis of a solar assisted multi-effect refrigeration cycles. The result showed that highest irreversibility occurs in the central receiver and the heliostat field represents the second highest irreversibility. Furthermore, the first law efficiency is 11.5% while as second law efficiency is 2%, these results are another proof that the first law analysis is not accurate alone and hence, more accurate analysis shall be considered the second law analysis.

Solar Cooling Technologies Comparison based on Driving Temperature

The solar thermal cooling technologies performance change based on the hot water temperature.

The Thermal-Driven system consists of three kinds of solar system types including flat plate collector, delivering output temperature of around 70°C to 100°C, evacuated tube collector, delivering temperature in the range of 100°C to 150°C, and Concentrating Solar Collector, delivering temperature of over 150°C. The heat generated by the panels will be transmitted into the heat transformation cycle and produce two ranges of temperature, 8°C fits for air conditioning system and 0°C to 8°C which is applicable for food and vaccine preservation as shown in Figure 22.

Solar Collector temperature ranges serving different Cooling Cycles (Figure 23). The below graph shows the serval technology COP by varying driving hot water temperature. COP of Different solar cooling technologies and hot water temperature [96,97] shown in Figure 24. Table 6 some common used solar cooling technologies efficiency and cost ranges for 5 TR AC units (R-22).

Conclusion

Many solar energy technology used to achieve refrigeration effect are investigated in this paper. This paper providing the useful indicators of these technologies performance.

The paper presented the merits and demerits of the solar cooling technologies, a number of observations can be made as follow:

1. All sorption cycles including chemical sorption are in the process beginning with research laboratory to the market, but much more work is needed on cost minimization, design and packaging.

2. Small-scale absorption cycles driven by solar thermal energy have been recently launched in the market by several companies.

Sr.	Solar Cooling Technology	Cost Range per 5 TR AC unit	COP
1	Solar Assisted Vapor Compression System	$10,503 [100]	3-6 [98-99]
2	Solar Assisted Absorption System (LiBr/H_2O)	$20,000 [103]	0.76-0.83 [101-105]
3	Solar Assisted Absorption System (H_2O/NH_3)	$5,000 [107]	0.57-0.62 [101,102,104-107]
4	Solar Assisted Adsorption System	$20,000 [108]	0.40-0.61 [101,108]
5	Solar Assisted Solid Desiccant System	$25,000 [109]	1.06-1.22 [101,109]

Table 6: Some common used solar cooling technologies efficiency and cost ranges for 5 TR AC units (R-22).

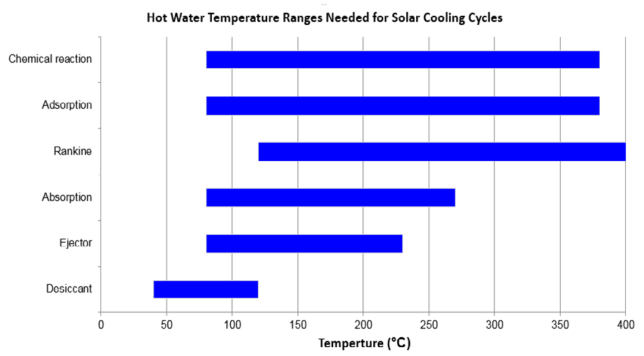

Figure 23: Solar Collector temperature ranges serving different Cooling Cycles.

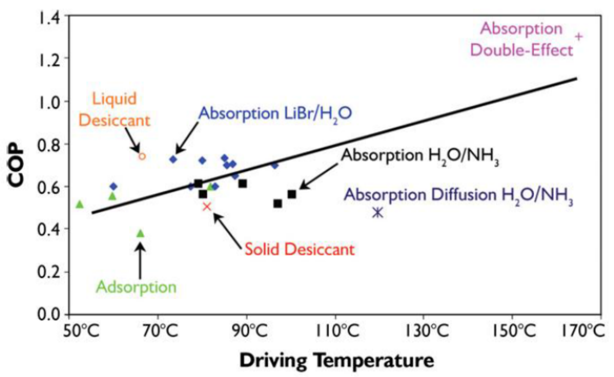

Figure 24: COP of Different solar cooling technologies and hot water temperature [96,97].

3. Adsorption and chemical adsorption cycles appear to function well in small scale applications such as small refrigerators; however, these cycles need to solve refrigerant/ adsorbent problems due to corrosion and crystallization.

4. An interesting option for the future is to integrate the desiccant cooling cycles into the ventilation system and rendering the system to become more popular.

5. The combined Rankine cycle is suitable for high cooling capacities.

where a large number of moving parts in the cycle, and the implied regular maintenance can be accepted.

6. The ejector refrigeration cycle has the benefit of being simple, reliable and feasible to operate with a low grade energy source. The cycle COP is low, but only slightly lower than other heat operated cycles.

7. The Multi effect refrigeration cycles are the best way to provide cooling at different magnitude and temperature ranges using renewable energy like solar energy that could produce required refrigeration effect.

8. Many researchers are working now to develop peltier cooler with low cost and high efficiency.

It is obvious that each refrigeration cycle described has its own niche in application, advantages and disadvantages therefore a proper decision of system selection must be taken according to aforementioned solar cooling system merit and demerit.

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